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Application of Pickering emulsion-based coatings/films stabilized with chitosan nanoparticles for the preservation of fresh postharvest commodities

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Postharvest losses of fresh produce remain a persistent challenge. Application of coatings/films have been extensively investigated as sustainable preservation strategies. This review highlights the role of chitosan nanoparticle (ChiNP)-stabilized Pickering emulsions in enhancing the functional performance of such coatings for maintaining fruit and vegetable quality. The findings indicated that ChiNP offer some advantages, including antimicrobial properties due to their cationic nature, while their nanoscale size contributes to emulsion stability by improving interfacial adsorption. Their incorporation enhances gas and water vapor barrier properties through a dense structural configuration at the oil–water interface, effectively suppressing ethylene biosynthesis and delaying cell wall degradation, thereby slowing ripening. Moreover, ChiNP demonstrate synergism with essential oils (EO), significantly improving the antimicrobial efficacy. However, further research is needed to improve stability, understand interactions with biopolymer matrices, assess wettability, ensure safety, and optimize delivery performance. In industrial context, the optimization of formulation parameters and sensory evaluations should be prioritized, thereby supporting the potential implementation of ChiNP as an effective and sustainable approach for fresh postharvest commodities preservation.

KEYWORDS

packaging, shelf life, postharvest, edible, quality

1 Introduction

Fruits and vegetables are valued globally for their nutrients but are highly perishable, even under cold storage (Ding et al., 2024). Postharvest losses, caused mainly by respiration, transpiration, and poor handling, account for about 14% of global food waste (FAO, 2019; Punia Bangar et al., 2022; Udayanga et al., 2013). To reduce deterioration and contamination, coatings/films have been developed for various fresh fruits and vegetables. Made from edible polymers like polysaccharides, proteins, and lipids, these films offer protection against mechanical and microbial damage, maintain biochemical quality, antioxidant capacity, and storage life of the fresh produces (Jung et al., 2020; Wardana et al., 2021; Lin et al., 2017). However, ongoing research aims to enhance their functional properties due to current limitations.

Pickering emulsion is an emulsion that utilizes solid particles for stabilization rather than traditional surfactants (Tan et al., 2022; Zhang et al., 2024). It has recently emerged as a promising alternative to conventional surfactants like Tween 20, Tween 80, and sodium dodecyl sulfate for food applications due to its potential to enhance the functional properties of edible films and coatings (Wang et al., 2013; Murray, 2019; Sarkar and Dickinson, 2020). These emulsions offer several advantages, including safety, biodegradability, stability, and cost-effectiveness, which make them particularly appealing for use in packaging systems (Ortiz et al., 2020). Furthermore, the overuse of synthetic surfactants can cause allergic reactions and may carry potential carcinogenic risks (Jiang et al., 2020a; Shah et al., 2021). Pickering emulsions are stabilized by solid particles or nanofibers that adsorb at the interface between water and oil phases (Lou et al., 2023). Functionalized polysaccharide, particularly ChiNP, have been used as stabilizers in the preparation of Pickering emulsions, which can then be incorporated into polymer matrices to produce food packaging films or coatings (Naji-Tabasi et al., 2024). Among polysaccharide-based particles, ChiNP demonstrated strong functional characteristics, serving effectively in antimicrobial roles and enhancing functional attributes as a nanofiller (Wardana et al., 2023a; Wardana et al., 2023b).

The use of Chi-based stabilizers in the development of emulsified biomaterials is rapidly increasing, as evidenced by 470 published studies on the topic referring to the Scopus-indexed database (Figure 1). In addition to being renewable and sustainable, Chi can be easily chemically functionalized to customize its properties for specific applications in the food systems (Pandey and Mathur, 2024), including aminoethyl Chi (Tamer et al., 2024), carboxymethyl Chi (Nicolle et al., 2021), quaternized Chi (Nicolle et al., 2021), and thiolated Chi (Sacco et al., 2020). Significant progress has been made in bio-based food packaging films, driven by the development of biopolymer nanomaterial-stabilized Pickering emulsions. This article reviews recent advancements in Pickering emulsions stabilized by ChiNP, which can be incorporated into polymer matrices to produce packaging materials aimed at preserving the freshness of postharvest commodities. The antimicrobial properties, barrier performance, and overall effectiveness of these ChiNP-stabilized Pickering emulsion films are also discussed.

2 ChiNP as stabilizer agent of Pickering emulsion

Pickering emulsions are stabilized by solid colloidal particles instead of traditional emulsifiers like surfactants or proteins (Tan et al., 2022), as shown in Figure 2A. First described by Ramsden (1903) and Pickering (1907), they offer enhanced stability, reduced health risks, and eco-friendly components (Albert et al., 2019). These emulsions are increasingly used in edible films and coatings that carry functional lipids (Deng et al., 2018; Jung et al., 2020). Their stability is explained by two main theories: (1) solid particles forming a barrier at the oil–water interface to prevent coalescence (Aveyard et al., 2003), and (2) particle networks creating viscoelastic structures that increase viscosity (Chen et al., 2020). Key influencing factors include particle type, concentration, pH, and temperature. Polysaccharide-based particles, in natural or modified forms, are among the most studied stabilizers. They are often integrated into polymer matrices for edible coatings. Their use improves emulsion resistance to environmental stressors such as heat and ionic strength, enhancing performance as barriers to light, water, and gases (Qiao et al., 2020). Moreover, the incorporation of nanomaterials allows controlled release of bioactive compounds, offering functional benefits for preserving food quality during storage (De Farias et al., 2025).

ChiNP is nanoscale particle derived from Chi, a biopolymer obtained from chitin primarily sourced from the shells of crustaceans such as shrimp and crabs (Abere et al., 2022; Ali et al., 2022), as seen in Figure 2B. It can be formed through various methods, including ionic gelation, emulsification, nanoprecipitation, and ionotropic gelation. In most cases, the synthesis of ChiNP was carried out using a Chi solution or using chitin directly from seafood sources via cross-linking by tripolyphosphate anions at room temperature (Sawtarie et al., 2017; Sreekumar et al., 2018; Ali et al., 2022). This method,

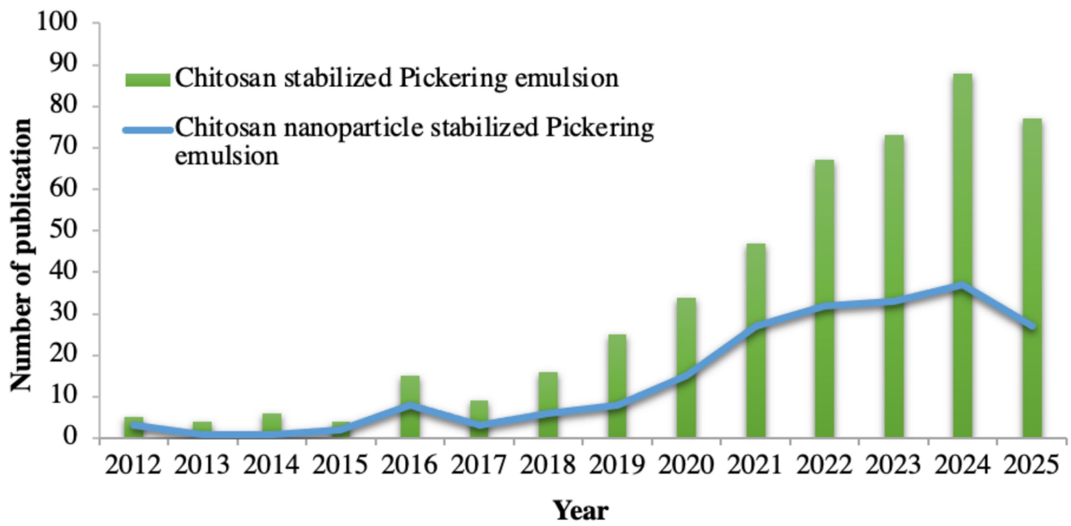

FIGURE 1
Annual publications (2009–2025) on "chitosan Pickering emulsion" and "chitosan nanoparticle Pickering emulsion" (Scopus, May 2025).

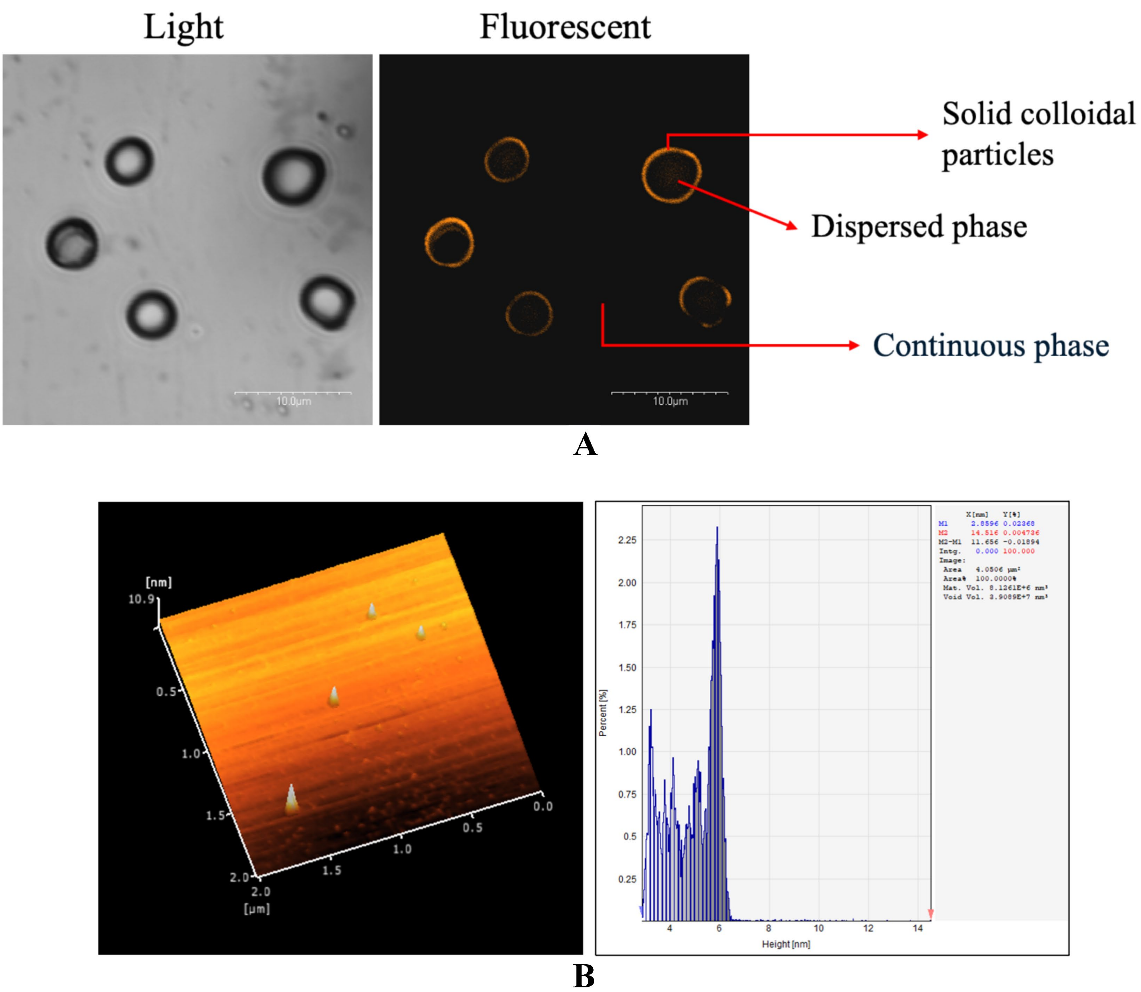

FIGURE 2
(A) Polysaccharide-based Pickering emulsion stained with acridine orange under confocal laser scanning microscopy (CLSM); **(B)** 3D ChiNP image and height profile observed with atomic force microscopy.

which is commonly called ionic gelation, allowed the preparation of ChiNP with range from 50 nm to 100 nm in diameter. It is not water soluble, hindering its direct application in aqueous systems, requiring dispersion aids, or emulsifiers to ensure uniform distribution and it often require acid solubilization to improve its solubility. Most methods based on ionic gelation involve the presence of 1% acetic acid to dissolve Chi. This nanoparticle has been gaining significant interest in various fields, including food science, due to their unique properties and potential applications. In the food field, ChiNP have been explored for several purposes, including use as a food additive (Stefanowska et al., 2023), food packaging material (Stefanowska et al., 2023; Wardana et al., 2024; Hamid et al., 2025) and solid stabilizer for Pickering emulsion (Wardana et al., 2023a).

ChiNP are effective stabilizers in Pickering emulsions, offering enhanced barrier and antimicrobial properties for preserving postharvest commodities (Ngo et al., 2021; Ren et al., 2020). Their role as nanofillers improves functional performances, such as antimicrobial (Wardana et al., 2023b), barrier (Ashraf et al., 2025a) and mechanical properties (Ashraf et al., 2025b), especially when the coating solution's pH remains above their pKa (~6.3), ensuring insolubility and stability (Lim and Hudson, 2004; Ahmed et al., 2021). While Chi's antimicrobial action is often linked to its positive charge in acidic conditions, studies have shown increased activity at higher pH. For example, N-alkylated Chi derivatives exhibited stronger effects against *E. coli* from pH 5 to 7.5 (Yang et al., 2005), suggesting that factors beyond charge contribute to its activity, which remains unclear under neutral or alkaline conditions (Kong et al., 2010).

3 Antimicrobial features

Microbial spoilage of fresh postharvest produce poses global challenges, affecting quality and safety. While synthetic antimicrobials have long been used, concerns over toxicity have shifted interest toward natural alternatives. Biodegradable antimicrobial coatings, especially Pickering emulsions, offer stability, controlled release, and bioactive compatibility. The ChiNP are particularly effective as emulsion stabilizers and antimicrobial carriers. The ChiNP-stabilized Pickering emulsions have shown promise as coating systems for postharvest preservation (Ahmed and Ikram, 2016; Wardana et al., 2023a; Thungphotrakul and Prapainainar, 2024). Their performance in microbial control supports continued research into their application for maintaining the postharvest quality of fresh commodities, as illustrated in Table 1.

The antibacterial mechanisms of ChiNP-stabilized Pickering emulsions are not yet fully understood. Studies showed that ChiNP stabilizer alone had no inhibitory effect on *E. coli* or *Staphylococcus aureus* (Thungphotrakul and Prapainainar, 2024). ChiNP are not effective antimicrobials in neutral to alkaline pH due to reduced solubility and weaker interaction with microbial membranes (Quan et al., 2021). However, incorporating clove essential oil (EO) enhanced antibacterial activity in a dose-and species-dependent manner. For example, 2.5% clove EO inhibited *E. coli* but not *S. aureus*, while 10% EO produced the highest inhibition zones (13.33 mm for *E. coli* and 11.33 mm for *S. aureus*) (Thungphotrakul and Prapainainar, 2024). This suggests that phenolic compounds in clove EO and controlled release via ChiNP encapsulation contribute to effectiveness. Similarly, Ran et al. (2024) reported that ChiNP-based emulsions with cinnamon EO inhibited *E. coli*, *S. aureus*, *Bacillus subtilis*, and *Pseudomonas fluorescens* by disrupting ATPase activity and chitin synthesis. *B. subtilis* was most affected. Microscopic staining confirmed increased bacterial death, highlighting the strong antimicrobial potential of these EO-loaded Pickering emulsions for food preservation.

Rhizopus stolonifer and *Penicillium digitatum* are major fungal pathogens causing postharvest rot in fruits and vegetables. Wardana et al. (2023a) examined the antifungal efficacy of cajuput EO stabilized with cellulose nanofibers and ChiNP against these fungi. Tangerines and tomatoes were inoculated with fungal spores, respectively 5 and 3 μL, and treated with EO-based Pickering emulsions. By day 3, lesions were absent in coated tangerines under storage temperature ~18°C and RH ~ 48%, while controls had 2.4 mm lesions. By day 6, lesion sizes in coated fruits were significantly smaller (22.41 mm in tangerines, 4.72 mm in tomatoes) than in uncoated controls (42.15 mm and 10.21 mm). The results showed that ChiNP-stabilized Pickering emulsions effectively suppressed fungal growth, with differing impacts across fruit types due to synergistic effects of EO and stabilizers. Mottaki et al. (2025) evaluated clove EO/ChiNP-stabilized emulsions against *P. digitatum in vitro* and *in vivo*. Treated samples showed significantly reduced fungal growth. Oranges coated with the formulation had minimal decay after 60 days, while uncoated fruits decayed entirely. The antifungal effect was comparable to commercial agents, likely due to increased hydrogen peroxide release and activation of plant defense enzymes. Bioactive compounds in clove EO, such as punicalagin and gallic acid, contributed to fungal inhibition (Wardana et al., 2021).

4 Preservation effect on fresh postharvest commodities

4.1 Light, gas, and water vapor barrier properties

The incorporation of ChiNP into Pickering emulsions enhances barrier properties, aiding postharvest preservation. ChiNP significantly reduce oxygen and water vapor permeability compared to conventional chitosan, especially when combined with pectin (Ngo et al., 2021). These emulsions maintain fruit quality by inhibiting enzymes and creating tortuous microstructures that slow moisture transmission and extend shelf life (Yu et al., 2021; Pan et al., 2024). Stabilizer particles at the oil–water interface form dense layers, minimizing evaporation and oxidation while reducing gas permeability (Jiang et al., 2020b). Light-blocking and UV-filtering effects are enhanced by certain nanoparticles like lignin-based types, making them suitable for food and cosmetic applications (Dai et al., 2019; Wu et al., 2024). These structural and antimicrobial properties support their potential in sustainable packaging (Lu and Tian, 2021; De Farias et al., 2025). The surface characteristics and hydrophilicity of stabilizers influence emulsion stability. Greater hydrophilicity improves particle adsorption, strengthening barriers against water and gases (Chakrabarty and Teramoto, 2020). Overall, ChiNP-stabilized Pickering emulsions present an eco-friendly strategy for extending the freshness of perishable foods, aligning with the demand for biodegradable, high-performance packaging (Ghavidel and Fatehi, 2020).

4.2 Postharvest physiology

Climacteric fruits continue to respire after harvest, releasing ethylene gas that drives ripening. Ethylene stimulates enzymes that break down pectin in the cell wall, leading to reduced firmness and increased soluble solids (Zhu et al., 2019). Chi has been reported to suppress ethylene accumulation, potentially through downregulating the expression or enzymatic activity of ACS (1-aminocyclopropane-1-carboxylic acid synthase) and ACO (1-aminocyclopropane-1-carboxylic acid oxidase). Edible coatings using Pickering emulsions stabilized by ChiNP have shown effectiveness in slowing respiration, as presented in Table 1. One of mechanisms is the inhibition of pectin-degrading enzymes like polygalacturonase (PLG) and pectate lyase (PLY), which normally break down the colloidal layer of the cell wall (Wantat et al., 2021). Research confirms ChiNP's enzyme-inhibiting effect. Yu et al. (2021) found that ChiNP-based coatings on mangoes suppressed PLG and PLY activity for up to 9 days, especially on day 6. This helped maintain fruit firmness, reducing the loss by only 47% in coated samples versus 87% in uncoated ones over 12 days. Similarly, Yang et al. (2025) reported that ChiNP-coated strawberries had better firmness and lower total soluble solids (TSS), indicating slower polysaccharide hydrolysis. The effectiveness of ChiNP is largely due to its function as a gas exchange barrier. The emulsion creates a dense, stable, and hydrophobic layer that limits the diffusion of water vapor and gases. This restricts ethylene biosynthesis and pectin-degrading enzyme activity, thereby slowing ripening and reducing TSS accumulation. Moreover, ChiNP coatings helped preserve fruit color and prevent browning by minimizing moisture loss (Ali et al., 2022). Hence, ChiNP-stabilized Pickering emulsions are a promising postharvest strategy to delay ripening by inhibiting enzyme activity and enhancing the fruit's barrier properties against gas and moisture exchange.

5 Challenges and limitations

There have been growing interest in Pickering emulsions stabilized by ChiNP for fresh fruit and vegetable applications, as stated in previous section, due to their biofunctionality and ability

TABLE 1 Summary of ChiNP-stabilized Pickering emulsion in preserving fruit and vegetable.

No	Continous phase	Dispersed phase	Stabilizer	Application	Effect	Ref.
1	Chi solution	Canola oil	ChiNP and α-pinene with diameter size 2–5 nm	Bell pepper	• The ChiNP and edible coating maintained the bell pepper shelf life during cold storage and kept its physicochemical quality	Hernández-López et al. (2020)
2	Chi solution	*Heracleum persicum* (Persian hogweed) EO	ChiNP with diameter size 40–80 nm	Bell pepper	• The samples treated with EO-ChiNP demonstrated general acceptance until day 24 of storage, while untreated samples lost acceptability by day 18	Taheri et al. (2020)
3	Water	Beeswax	Cellulose nanofibrils with 33.3 nm (width) and 3.7 nm (height), length <10 μm and carboxymethyl Chi	Berry fruits	• Inhibited the growth of *S. aureus* or *E. coli* • Had a potency as antiseptic and fresh keeping fruits	Xie et al. (2020)
4	Chi solution	*Saturejahortensis* (Summer savory) EO	ChiNP with diameter size 109.1 ± 39.2	Pomegranate arils	• The coated fruits preserved phytochemicals and water content while reducing microorganisms counts during storage • The total phenol content and antioxidant activity diminished over the storage period	Amiri et al. (2021)
5	Chi solution	Cinnamon EO	Chi and cellulose nanocrystals	Mango	• Improved the appearance of mangoes at 25° C for 12 d by reducing yellowing and dark spots, and delayed water loss • Maintained the postharvest quality of fruit including hardness, total soluble solid, titratable acid, and ascorbic acid	Yu et al. (2021)
6	Chi solution	Guava leaf extract	ChiNP-guava leaf with treatment of laster sterilization, semi-spherical particles, 21.92 nm (average size)	Strawberry	• Reduced fungal degradation compared to 50% control • Reduced weight loss to 4.68% from 27.35% in control • Treated strawberry had the highest anthocyanin and vitamin C	Ali et al. (2022)
7	Chi solution	Cajuput EO	Co-stabilizer cellulose NP with 68.49–90.28 nm (width), 1–2 μm (length) and ChiNP with 43.77–70.61 nm (diameter)	Orange and tomatoes coating	• Improved the antifungal activities of Chi againts *P. digitatum* and *R. stolonifera, respectively,* on orange and tomato	Wardana et al. (2023a)
8	Water	Thyme EO	ChiNP	Strawberries	• Prevented undesirable phenomena including weight loss, a decrease in firmness, an increase in pH, and microbial growth • Extended the shelf life of fruit	Li et al. (2024)
9	Water	Cinnamon EO	Chi and soy protein isolate colloidal particle with dimension, 8.98 μm–14.18 μm.	Banana	• Had intelligent sterilization capabilities by bacteria-mediated release of oils • Released essential oils effectively delayed banana spoilage	Ran et al. (2024)
10	Polyvinyl alcohol solution	Citral	Chi and self-made carboxymethyl glucan self-assembled nanoparticles with dimension, from 333.3 ± 8. 35 nm to 981.2 ± 15.23 nm (length)	Strawberries	• Improved the compatibility of citral in composite film substrate • Extended the antibacterial time of packaging materials • Prolonged the shelf life of fruit	Gao et al. (2024)

(Continued)

TABLE 1 (Continued)

No	Continous phase	Dispersed phase	Stabilizer	Application	Effect	Ref.
11	Water	Clove EO	ChiNP with average size < 100 nm (97.79 nm of width), contact angle < 90° and a positive zeta potential	Oranges	• Minimum fungicidal concentration against *P. digitatum* was equal to 2% • No significant difference between *in situ* inhibitory effects comparing with Xedamix (a commercial fungicide) on the target fungus in spiked orange	Mottaki et al. (2025)
12	Chi nanowhisker solution	Beeswax	Chi nanowhisker, sodium alginate, carboxymethyl cellulose, and guar with dimension, 18.7 ± 8.4 nm (width) 104.8 ± 53.7 nm (length)	Bananas and strawberries	• Improved hydrophobicity and dispersibility of costing solution • Significantly extended the shelf life of bananas and strawberries	Kim et al. (2025)
13	Arachin amyloid-like fibrils and Chi solution	Cinnamon EO	Arachin amyloid-like fibrils, Chi, and betanin	Berried, strawberries, grapes	• Possessed stronger $DPPH^{\bullet -}$ and $ABTS^{\bullet +}$ radical scavenging activities (77.16, 89.01%) • Inhibited rate for *E. coli* (99.34%), *S. aureus* (99.62%) and *B. cinerea* (99.04%) • Preserved and maintained a better quality of fruit	Yang et al. (2025)
14	Water	Beeswax	Carboxymethyl Chi and TEMPO-oxidized nanocellulose with length of 1–5 μm	Blueberries, strawberries, persimmon, grapes	• Preserved fruits by slowing their decay rate • Improved hydrophobicity and possessed a certain bacteriostatic • Improved antimicrobial properties against *S. aureus*	Huang et al. (2025)

to replace synthetic surfactants harmful to health and the environment. Incorporating edible polymers such as gelatin, alginate, or starch can enhance the mechanical and flexible properties of ChiNP-based systems, especially in hydrogels and films (Luo et al., 2022). Despite their potential, challenges still remain, particularly in improving emulsion stability under varying environmental conditions such as temperature, pH, ionic strength (Gonzalez Ortiz et al., 2020; Meng et al., 2023). Limited research exists on how ChiNP-based emulsions interact with complex film/coating biomatrices. Furthermore, limited data are available regarding the contact angle measurements of ChiNP-based materials proposed as novel Pickering stabilizers (Sharkawy et al., 2020). Gaining deeper infromation into their wettability would clearly support the enhancement of stability and barrier properties in chitosan-based Pickering emulsion systems. As a pH-sensitive cationic polysaccharide, ChiNP is ideal for stimuli-responsive delivery of bioactive compounds (Zhao et al., 2022), however more studies are needed to understand its dynamic behavior and bioavailability in both *in vitro* and *in vivo* models. Toxicological assessments are also necessary to ensure food safety (Meng et al., 2023). Finally, further exploration is essential to fully harness the functional potential of ChiNP-based Pickering emulsions.

6 Conclusion and future perspective

The use of ChiNP-stabilized Pickering emulsion shows promising potential in extending fruit shelf life by preserving quality and preventing microbial contamination. Its nanoparticle size offers effective stabilization and compatibility, enabling the encapsulation and controlled release of bioactive compounds. It is important to note that although ChiNP holds promise in various food applications, further research is ongoing to fully explore their potential and ensure their safety and regulatory compliance. Several mechanisms of action of ChiNP as an antimicrobial agent and barrier properties also need to be investigated thoroughly. This allows further understanding for future research on the formulation and development process (e.g., encapsulation efficiency, in vivo release kinetics) in allowing the modification of emulsion to combat specific microbial contamination (Ashraf et al., 2025b). Concerns related to allergenicity, and sustainability arise from the sourcing of Chi from crustaceans, prompting researchers to explore alternative sources, such as fungi and insects, for Chi production (Peng et al., 2022). Moreover, sensory evaluations play a vital role in determining consumer acceptance, yet this aspect remains insufficiently investigated in recent research. For food applications, higher concentrations of EO are often required, leading to undesirable tastes and odors. Encapsulating EO in ChiNP could offer a potential approach for achieving sustained release (Bakr et al., 2024). Overall, ChiNP-based stabilization of Pickering emulsion offers a wide range of possibilities for improving food quality, safety, and sustainability.

Author contributions

AAW: Funding acquisition, Writing – review & editing, Supervision, Writing – original draft, Validation, Methodology,

Conceptualization. VM: Writing – original draft, Writing – review & editing, Conceptualization. LPW: Writing – review & editing, Writing – original draft, Conceptualization. FNN: Writing – review & editing, Writing – original draft. FuminT: Resources, Writing – review & editing, Writing – original draft. FumihT: Writing – original draft, Writing – review & editing, Resources. RHBS: Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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