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Stabilization of emulsified edible coating using cellulose nanomaterials for fruit preservation

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Fruit losses during postharvest handling remain a major global challenge. Edible coatings, particularly those stabilized by cellulose nanomaterials (CNM), offer a sustainable solution to enhance fruit preservation. This review aims to explore the role of CNM-stabilized Pickering emulsions in improving coating stability, antimicrobial activity, and barrier properties. The findings indicate that CNM possess a high aspect ratio, enabling them to create a compact and efficient interfacial layer at the oil-water interface. Incorporating CNM as a stabilizer enhances the barrier properties of emulsion-based coatings, effectively delaying fruit ripening by slowing the respiration rate through mechanisms such as improved inhibition of gas exchange, reduced oxygen availability, and suppression of ethylene production. The effectiveness in reducing microbial growth is attributed to the sustained-release capability of the active components by CNM in the Pickering emulsion coating. Its antimicrobial activity against Gram-positive and Gram-negative bacteria, yeast, and fungi at appropriate concentrations. The optimization of CNM-based Pickering emulsions should be tailored to the specific requirements of the intended application, particularly considering the potential of CNM to serve as a growth medium for microbes. Future work should focus on formulation optimization for industrial application and on sensory evaluations to ensure consumer acceptance, paving the way for CNM as a viable strategy in sustainable fruit preservation.

KEYWORDS

nanocomposite, food, lipid, quality, shelf life, packaging, postharvest

1 Introduction

Fruit losses occur at various stages, from production through postharvest handling, storage, and transportation, significantly reducing the amount of food available for human consumption. According to the FAO (2019), ∼14% of global food is lost between harvest and retail. These substantial losses are primarily attributed to mishandling, ineffective transportation methods, and contamination by fungi and bacteria (Udayanga et al., 2013). The application of edible films or coatings, particularly for highly perishable products such as fruits, has been reported as an alternative strategy to preserve food quality and protect against undesirable mechanical, physical, chemical, and microbiological damage (Falguera et al., 2011; Jung et al., 2020; Wardana et al., 2021). Those are typically fabricated from renewable polymers, including polysaccharides, proteins, lipids, or their mixtures, which serve as the primary matrix for forming a thin protective layer (Lin et al., 2017). However, due to the inherent limitations of these biopolymer matrices, ongoing research efforts are focused on enhancing their functional properties.

Emulsification, a technique involving the mixing of two or more immiscible phases, has received considerable attention for its ability to improve the functional properties of edible films and coatings. However, emulsion-based systems often face challenges such as phase separation and long-term instability, which can adversely affect coating functionality (Taherian et al., 2011; Wang et al., 2013). Moreover, excessive use of synthetic surfactants may trigger allergic reactions and pose potential carcinogenic risks (Jiang et al., 2020; Shah et al., 2021). The Pickering emulsion technique represents a promising approach to improving the performance of emulsion-based biomaterials, particularly with respect to stability, safety, barrier properties, and antimicrobial activity (Ma et al., 2019; Nkede et al., 2023). Solid particles adsorbed at the oil–water (o/w) interface, along with interactions among particles and between particles and droplets, contribute to enhanced system stability, often outperforming conventional surfactants (Monégier du Sorbier et al., 2015; Jiang et al., 2025). The use of cellulose-based stabilizers in the development of emulsified biomaterials is gaining momentum, with 1,091 studies reported on the subject (Figure 1). In addition to being renewable and sustainable, cellulose nanomaterials (CNM) can be readily modified through chemical functionalization to tailor their properties for specific applications, making them a versatile component for a wide range of Pickering emulsion systems (Lu et al., 2021; Seo et al., 2021). This review focuses on CNM as stabilizers in Pickering emulsions and their application in the preservation of fresh fruit.

2 Potency of CNM for Pickering emulsion coating

Pickering emulsions are stabilized by solid colloidal particles instead of traditional emulsifiers like surfactants, proteins, or phospholipids (Tan et al., 2022). First introduced by Ramsden (1903) and Pickering (1907), they offered an enhanced stability, eco-friendly stabilizers, and lower health risks (Albert et al., 2019). Applications include edible films and coatings with functional lipids (Deng et al., 2018; Jung et al., 2020). Two theories explain their stabilization: the solid particle interface film theory, where particles form a rigid layer at the oil–water interface preventing coalescence (Aveyard et al., 2003); and the three-dimensional viscoelastic particle network theory, where particle networks increase viscosity and inhibit droplet merging (Lagaly et al., 1999; Chen et al., 2020). Stability is influenced by particle wettability, concentration, electrolytes, temperature, pressure, and pH (Chen et al., 2020).

The CNM have gained significant attention in recent years as potential stabilizers. They are tiny, natural, hydrophilic particles, but their crystalline form reveals amphiphilic properties, derived from cellulose, the earth's most abundant organic polymer. According to Technical Association of the Pulp and Paper Industry (TAPPI) WI 3021, CNM is defined as materials with nanoscale external dimensions or internal structures (Teo et al., 2022). They are often produced from cellulose extracted from various plant sources, such as softwood, hardwood, cotton, agricultural resides/wastes, grasses, or other fibrous materials (Figure 1) (Hassan et al., 2018). The CNM includes nanostructured materials and nanofibers. Cellulose microcrystals and microfibrils fall under nanostructures, while cellulose nanocrystals (CNC), cellulose nanofibrils (CNF), and bacterial cellulose (BC) are nanofibers (Trache et al., 2020). Though chemically similar, these nanofibers differ in morphology, crystallinity, and flexibility due to varying sources and extraction methods (Phanthong et al., 2018).

The CNM have a high aspect ratio, allowing them to form a dense and effective interfacial layer at the oil-water interface (Napso et al., 2018; Dominguez et al., 2024). This dense packing of particles helps in stabilizing the emulsion by preventing coalescence and Ostwald ripening (Liu et al., 2019). However, due to the abundance of hydroxyl groups on its surface, nanocellulose tends to aggregate in non-polar solvents, restricting its applications and usage (Trache et al., 2020). The surface chemistry of CNM can be modified to enhance their compatibility with different oil and water phases such as esterification, etherification, silylation, grafting and others (Abitbol et al., 2016; Afrin and Karim, 2017; Kamel et al., 2020). Functionalization of CNM can improve their ability to stabilize Pickering emulsions in a wider range of systems. Furthermore, CNM provide emulsions with good mechanical and thermal stability, which is important in various industrial applications, including food products (Gong et al., 2017). Therefore, the formulation and optimization of CNM-based Pickering emulsions should be tailored to the specific requirements of the intended application.

3 Effect of CNM-stabilized Pickering emulsions on antimicrobial activity

The antimicrobial activity is important parameter of biomaterial especially for food, pharmaceutical, and cosmetics application. In recent years, several studies have evaluated the potentials of CNM as Pickering emulsion stabilizer in various biomatrices in the terms of antimicrobial action improvement (Wardana et al., 2021; Bangar et al., 2022; Zhou et al., 2024). The main discoveries of those of related works, describing antimicrobial activity against bacteria (G^+ and G^-), yeast, and fungi, are summarized in Table 1. However, naturally, cellulose can be used by microbes as a growth medium, hence the appropriate of the concentration is essential.

Zhou et al. (2024) investigated the antibacterial properties of Pickering emulsion coatings made from konjac glucomannan-loaded bacterial cellulose nanofibers (BCN), silver nanoparticles (AgNPs), and thyme EO against *Staphylococcus aureus* and *Escherichia coli*. Their findings showed that the Pickering emulsion films produced larger zones of inhibition compared to other treatments, indicating superior antibacterial activity. Specifically, the inhibition zones measured 1.12 cm for *S. aureus* and 1.07 cm for *E. coli*. This effectiveness was attributed to the sustained-release capability of the active components in the Pickering emulsion films. Similarly, Bangar et al. (2022) incorporated clove bud oil (CBO)/CNC-based PE into pearl millet starch (PMS) films to combat *S. aureus* ATCC 29213 and *E. coli* ATCC 25922. While PMS and PMS/CNC films showed no antibacterial activity, the

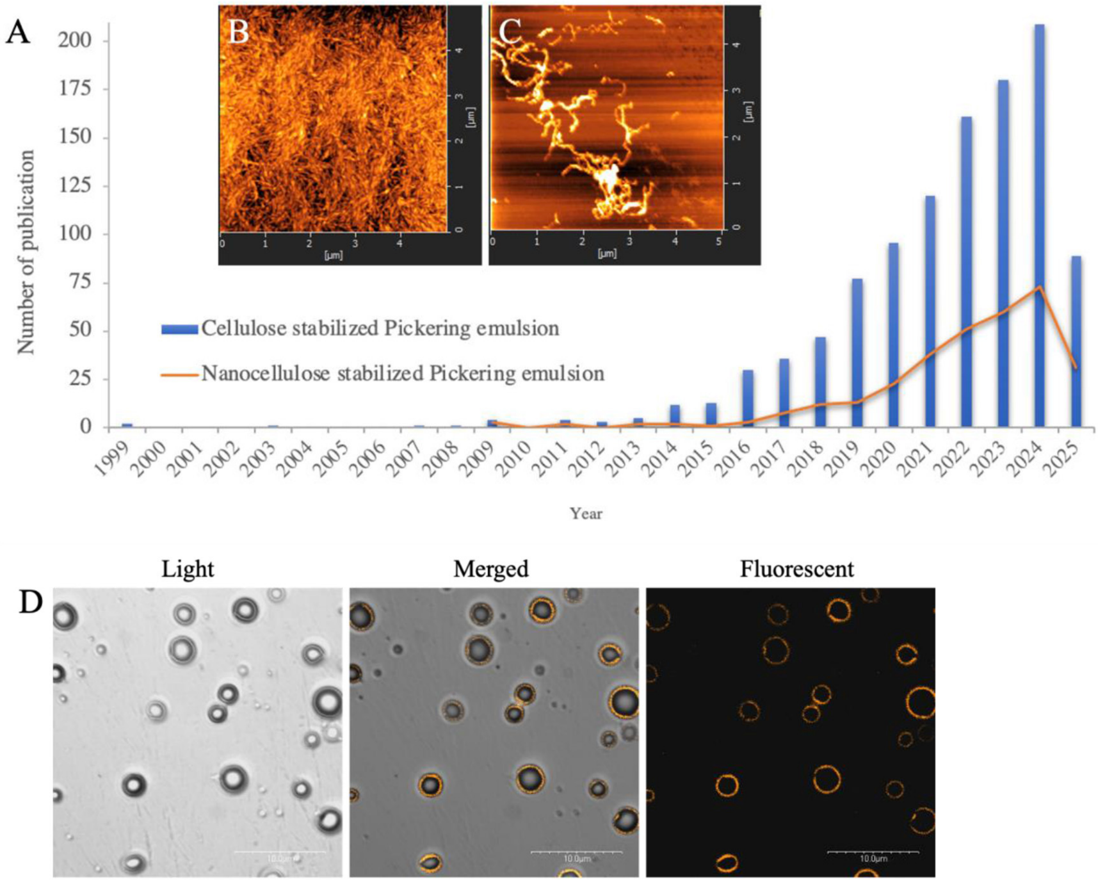

FIGURE 1
(A) Number of annual reports and documents by subject area by search keywords "cellulose Pickering emulsion" and "nanocellulose Pickering emulsion" over the past 26 years. Indexed by Scopus, update-March 2025; **(B)** Atomic force microscopy photograph of CNC and **(C)** CNF; **(D)** Pickering emulsion system stabilized with Cellulose Nano Materials (CNM) observed with Confocal Laser Scanning Microscopy (CLSM). The CNM was stained with fluorescence dye, acridine orange.

addition of CNC/CBO-PE significantly enhanced antimicrobial performance. Clear zones formed around the film disks indicated inhibition, with *S. aureus* exhibiting a larger inhibition diameter (21.5 mm) compared to *E. coli* (16.6 mm). This suggests that the active films were more effective against Gram-positive bacteria, likely due to the extra protective outer membrane in Gram-negative bacteria, which hinders the penetration of antimicrobial compounds. The strong antibacterial effect of the CNC/CBO-PE films was credited to the phenolic compounds in CBO, which disrupt bacterial cell membranes, damage cell walls, inhibit respiration, and ultimately lead to cell death.

Nkede et al. (2023) developed active coatings using chitosan (CH), CNF, and lemongrass oil (LGO) in a Pickering emulsiom system to preserve tomatoes. The formulations included CH, CH/1% LGO PE, and CH/2% LGO PE. Antifungal activity was tested against fruit fungal pathogen, *Botrytis cinerea,* on inoculated tomatoes. Results showed that tomatoes coated with LGO-PE films had significantly smaller lesion diameters compared to uncoated or CH-coated tomatoes. After 9 d of storage, the CH/2% LGO PE treatment achieved the smallest lesion diameter (10.64 mm), corresponding to a 57.44% inhibition rate, indicating effective suppression of *B. cinerea*. This was attributed to citral and neral, active compounds in LGO that penetrate fungal cell walls, disrupt metabolic processes, and lead to fungal death. In another study, Wardana et al. (2023) explored the antifungal potential of alginate/LGO/CNF PE coatings against *Penicillium italicum* and *Penicillium digitatum*. Various *in vitro* assays revealed that 0.75% LGO PE significantly enhanced antifungal activity. Spore germination was inhibited by 88.28% for *P. digitatum* and 91.94% for *P. italicum*; germ tube elongation was reduced by 89.28 and 90.13%, respectively; and membrane integrity was disrupted by 41.67% (*P. digitatum*) and 63% (*P. italicum*). The antifungal effect was attributed to geranial and neral in LGO, which compromise fungal cell membrane integrity, ultimately leading to cell death.

4 Effect of CNM-stabilized Pickering emulsions on barrier properties

Fruit ripening is one of the most important indicators of fruit quality, with its effect determining the fruit's edibility and quality. The biggest factor contributing to fruit ripening, especially

TABLE 1 Summary of CNM-stabilized pickering emulsion in preserving fruits and vegetables.

No	Main matrix	Dispersed phase	Stabilizer	Application	Effect	References
1	Chitosan	Oleic acid	CNC, 156 ± 4 nm (diameter)	Pear coating	• Delayed fruit ripening • Reduced senescence scalding • Improved adhesiveness on fruit surface with smooth texture and few voids	Deng et al., 2018
2	Chitosan	Oleic acid	CNC	"Bartlett" Pear coating	• Inhibited ethylene production • Delayed fruit ripening and superficial scald	Jung et al., 2020
3	Chitosan	Oleic acid	CNC	"Bartlett" Pear coating	• Maintain peel chlorophyl • Delayed respiration rate and ethylene production • maintained equivalent titratable acidity (~0.23 g/100 mL) and total soluble solids	Rosenbloom et al., 2020
4	Chitosan	Chinnamon EO	CNC	Mangoes at the green stage of maturity coating	• Improved the appearance of mangoes at 25°C for 12 d by reducing yellowing and dark spots • Reduced water loss, membrane lipid peroxidation • Improved hardness, total soluble solid, titratable acid, and ascorbic acid	Yu et al., 2021
5	Chitosan	Sandalwood EO	CNF, 24.86 ± 10.01 nm (width average)	Apple and orange coating	• Delayed the *Penicillium digitatum* decay on orange and *Botrytis cinerea* on apple	Wardana et al., 2021
6	Starch	Beeswax	CNC or CNC modified with DDSA	Banana, strawberry, and fresh cut apple coating	• Reduced oxygen activities • Prevented moisture losses	Trinh et al., 2022
7	Starch	Clove bud oil	CNC derived from Kudzu (*Pueraria montana*) vine, 219.11 ± 36.5 nm (length) and 33.14 ± 8.78 nm (width)	Red grapes film	• Extended the shelf life of fruit up to 15 d at 5°C • Maintained the weight, firmness, and soluble solids	Bangar et al., 2022
8	Chitosan	Cajuput EO	Co-stabilizer CNF 68.49–90.28 nm (width), 1–2 µm (length) and Chitosan 43.77–70.61 nm (diameter)	Orange and tomatoes coating	• Improved the antifungal activities of chitosan againts *P. digitatum* and *Rhizopus stolonifera*, respectively, on orange and tomato	Wardana et al., 2023
9	Pregelatinized corn starch	Basil EO	CNF, 3–4 nm (width)	Mandarin orange coating	• Selected 5% pregelatinized corn starch, 3% basil EO, 0.5% CNF as optimum formulation through TOPSIS method • Achieved in lowering losses of citric acid • Maintained the color density and polymer	Wigati et al., 2023a
10	Pregelatinized corn starch	Basil EO	CNF, 3–4 nm (width)	Mandarin orange coating	• Prolonged the shelf life of the mandarin orange • Minimized weight loss and color changes of fruit stored at room temperature for 12 d	Wigati et al., 2023b
11	CNC	Rice bran oil with or without aloe vera extract	CNC, ±200–300 nm (length), ±5–10 nm (width)	Banana, lime coating	• Maintained visual freshness and pH of fruit at 5°C for 12 d • Prevented the lime peel's decay	Singkhonrat et al., 2023
12	Chitosan	Lemongrass EO	CNF, 3–4 nm (width)	Tomato coating	• Showed the better weight loss and color appearances of the sample stored at 20°C and 60% RH for 15 d • Improved antifungal activity against *B. cinerea*, stored at 25°C and 60% RH	Nkede et al., 2023
13	Sodium alginate	Thyme, clove EO	CNC, 260 ± 31.4 nm	Guava coating	• Clove EO coatings showed higher antioxidant and antifungal activity than thyme EO coatings • Maintained ascorbic acid and firmness compared to uncoated fruit during 12 days in ambient condition	Mahapatra et al., 2024

(Continued)

TABLE 1 (Continued)

No	Main matrix	Dispersed phase	Stabilizer	Application	Effect	References
14	Sodium alginate	Ylang-ylang EO	CNC 4–10 nm (width), 100–260 nm (length)	Mandarin (*Citrus reticulata*) coating	• Lowered the weight loss of fruit • Suppressed the growth of *P. italicum* and *P. digitatum* inoculated on sample	Nkede et al., 2024
15	Konjac glucomannan	Thyme EO	Bacterial CNF coupled with Ag nanoparticles	Tangerine coating	• Displayed excellent fresh-keeping properties for tangerine	Zhou et al., 2024
16	Sodium alginate	Ginger EO	CNC, 4–10 nm (diameter), 100–500 nm (length)	Mango coating	• Delayed postharvest senescence of sample • Maintained long-term bioavailability of fruit	Zhang et al., 2024
17	Carboxymethyl chitosan	Beeswax	TEMPO-oxidized CNM	Cellulosic paper coating	• Preserved fruits by slowing their decay rate	Huang et al., 2025
18	Coconut wax	Lactonic, acidic sophorolipids	CNF	Cherry tomato coating	• Remained the freshness of fruit during 12 d at room temperature • Reduced the weightloss and increased vitamin C content after 15 d of storage • Inhibited microbial growth	Li et al., 2025
19	Carboxymethyl chitosan enriched with tannic acid	Cinnamaldehyde	CNF, 6.39 ± 1.07 nm (diameter)	Mango coating	• Minimized weight loss and enzymatic activities • Retarded senescence • Extended fruit shelf life at ambient condition	Wang et al., 2025

CNC, cellulose nanocrystals; CNF, cellulose nanofibers; CNM, cellulose nanomaterials; DDSA, (2-Dodecen-1-yl) succinic anhydride; EO, essential oil; TOPSIS, technique for order of preference by similarity to ideal solution; TEMPO, 2,2,6,6-tetramethyl-1-piperidinyloxy.

in climacteric fruits, is the respiration process due to ethylene production. The production of ethylene mainly results in growth and physiological processes in plants, with the ripening process being one of the crucial parts. Therefore, controlling ethylene concentrations by reducing ethylene production and inhibiting ethylene receptors becomes the key interest in delaying fruits from ripening (Ebrahimi et al., 2022). Although commercial ethylene scavengers and synthetic coating have been developed throughout the year to combat the problem, CNM has been researched as an alternative for controlling ethylene levels, with recent research showing similar or even better results compared to commercial coating (Deng et al., 2018; Jung et al., 2020; Rosenbloom et al., 2020; Trinh et al., 2022). CNM mainly contributes on delaying the respiration rate through mechanisms such as inhibiting gas exchange and reducing oxygen activities during respiration (Chen et al., 2020; Yan et al., 2017). These mechanisms inhibited fruit ripening by indirectly reducing the ethylene content inside the coated fruits with controlling the circulation of O_2 and CO_2 content being its main mechanism (Rosenbloom et al., 2020). Studies from Deng et al. (2018) and Jung et al. (2020) show the usage of coating using CNC as the stabilizer with the Pickering emulsion technique for Bartlett pears delay the ripening process by increased hydrophobicity, which resulted in maintained fruit structure firmness and retained chlorophyll content. As Pickering emulsion was more stabilized, the coating improved its hydrophobic properties, which results in a stable and less permeable gas barrier. This phenomenon resulted in much less oxygen entering the system and remaining inside for ethylene biosynthesis to produce ethylene in larger quantities (Riaño et al., 2022).

Research conducted on the physical mechanism of cellulose films and coatings showed that blends of CNM with other biopolymers, such as chitosan, could effectively block UV radiation. For instance, films containing cellulose and chitosan exhibit reduced transmittance of UV light, thereby offering protection against oxidative reactions that could compromise product integrity (Cazón et al., 2019; Davoodi et al., 2020). The interaction between CNM and other polymers enhances the mechanical strength and water barrier properties while effectively limiting moisture transfer through the packaging (Cazón et al., 2020; Zhao et al., 2021). Such compositions enabled the production of edible films and coatings, which are vital for sustainable applications in food and material sciences. Furthermore, recent studies indicate that CNC and CNF can significantly enhance the water vapor barrier properties of films due to their high surface area and hydrophilic nature, which creates robust biofilms capable of controlling moisture transmission (Fotie et al., 2017; Rampazzo et al., 2017). By forming hydrogen bonds in the biofilm, these cellulose structures minimized voids where water molecules can permeate, thus improving the overall barrier efficiency (Zhao et al., 2021). The functionality of these cellulose-based biofilms is particularly beneficial in food packaging, where maintaining product freshness and extending shelf life are critical.

Finally, the use of CNM-stabilized Pickering emulsions has emerged as a promising strategy to enhance the postharvest quality and longevity of fresh fruits and vegetables. By integrating CNM such as CNC and CNF into edible coatings, often in combination with biopolymer matrices like chitosan, starch, or alginate and natural essential oils, these emulsions form protective features that significantly delay ripening, reduce microbial spoilage, and preserve visual and nutritional quality. The coatings have demonstrated a broad range of benefits, including maintaining firmness, color, chlorophyll content, and ascorbic acid levels, while minimizing weight loss and oxidative degradation. Moreover, the antifungal and antioxidant properties delivered through essential oil incorporation further enhance the preservation effects. Collectively, these findings highlight the considerable potential of CNM-based emulsions as a sustainable, functional, and effective solution for prolonging shelf life and ensuring the safety and appeal of fresh produce during storage and distribution.

5 Future prospects

The Pickering emulsion technique, using CNM as a stabilizer, shows promise for food preservation. CNM coatings enhance structural stability, add functional properties, and extend shelf life, as confirmed by studies on fruits and vegetables. These positive results suggest CNM's potential for industrial-scale application. Further research should optimize formulations for upscaling and explore the compatibility between dispers phases and stabilizers to improve emulsion coherence. Additionally, sensory evaluations are crucial to assess consumer acceptance, an area still underexplored in recent studies.

Data availability statement

All data are available within this article and no datasets were generated or analyzed during the current study.

Author contributions

AAW: Funding acquisition, Writing – review & editing, Supervision, Writing – original draft, Validation, Methodology, Conceptualization. VM: Writing – original draft, Conceptualization, Data curation. LPW: Writing – original draft, Data curation, Conceptualization. FNN: Writing – review & editing, Writing – original draft. FuminT: Resources, Writing – review & editing, Data curation. FumihT: Supervision, Writing – review & editing, Resources.

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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.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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