Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Food Science

Recent advances in Pickering emulsions for inhibiting foodborne bacteria

Chuye Ji and Yixiang Wang

Foodborne bacteria pose significant risks to public health and economic conditions. Natural antibacterial agents have proven effective against foodborne bacterial contamination but often suffer from harsh environmental and processing conditions. Pickering emulsions, recognized for good stability, high loading capacity, sustained release, cost-effectiveness, low toxicity, biocompatibility, and sustainability, have emerged as efficient carriers for natural antibacterial agents and shown great promise in preserving fruits, vegetables, meats, seafood, and other foods by either direct coating or incorporation in active packaging films. With the growing interest in Pickering emulsions loaded with natural antibacterial agents, in this review, we highlight recent advances in their applications for inhibiting foodborne bacteria. The mostly investigated foodborne bacteria and the compositions and antibacterial mechanisms of natural antibacterial agents loaded Pickering emulsions are summarized, and food-related applications are spotlighted. Despite challenges, such as scalability and regulatory approval, antibacterial Pickering emulsions show great potential as sustainable preservatives for food preservation.

Address
Department of Food Science and Agricultural Chemistry, McGill University, Ste Anne de Bellevue, Quebec H9X 3V9, Canada

Corresponding author: Wang, Yixiang (yixiang.wang@mcgill.ca)

Current Opinion in Food Science 2025, **61**:101265

This review comes from a themed issue on **Food Bioprocessing**

Edited by **Xing Chen**

For complete overview of the section, please refer to the article collection, "Food Bioprocessing 2025"

Available online 17 December 2024

https://doi.org/10.1016/j.cofs.2024.101265

Introduction

Foodborne diseases caused by pathogenic bacteria impose a substantial burden on public health and economic systems. Foodborne bacteria can be transmitted to the host body through physical contact, resulting in systemic infections — the main cause of global mortality and morbidity. In 2023, the U.S. Food & Drug Administration reported 232 food and beverage recalls. Canadian Food Inspection Agency oversaw approximately 164 food recalls annually from 2018 to 2023, with over a quarter attributed to contamination from microorganisms [1].

Besides the development of rapid detection and photodynamic inactivation technologies for foodborne pathogenic bacteria [2,3], special attention has recently been paid to natural antibacterial agents for inhibiting bacterial growth and preventing outbreaks of foodborne infections and diseases; however, these bioactive compounds are sensitive to harsh conditions, such as elevated temperatures, extreme pH levels, and light exposure. One potential strategy to address their environmental sensitivity is the encapsulation of natural antibacterial agents. Pickering emulsions are stabilized by solid colloidal particles, which protect and control the release of encapsulated bioactive compounds. According to the search results of the Web of Science, 4370 research papers on Pickering emulsions have been published between 2020 and 2024, with 419 papers investigating their antimicrobial activities. Notably, these 419 papers account for about 86.6% of the total 484 papers on antimicrobial applications, indicating a significant research interest in the last five years. Antibacterial Pickering emulsions can be applied by either direct spray coatings on food surfaces (e.g. encapsulation of essential oils) or as components of active food packaging (e.g. films incorporating antibacterial Pickering emulsions [4]). However, their commercialization remains challenging due to insufficient investigation regarding scalability, cost-performance balance, and consumer acceptance.

With the growing interest in Pickering emulsions loaded with natural antibacterial agents, there is a lack of review of recent advances in Pickering emulsions for inhibiting foodborne bacteria and their applications in the food industry. This paper focuses on the recently reported antibacterial Pickering emulsions, providing a summary of the most investigated foodborne bacteria, the commonly employed natural antibacterial agents and mechanisms, and the food-related applications. It aims to offer insights into future research directions to fully harness the potential of antibacterial Pickering emulsions.

Foodborne bacteria

Foodborne bacteria are responsible for over 200 diseases, primarily caused by ingesting pathogenic bacteria and/or their produced toxins. The most common foodborne pathogenic bacteria, such as *Campylobacter jejuni*, *Salmonella* spp., *Listeria monocytogenes* (*L. monocytogenes*), *Escherichia coli* (*E. coli*), *Staphylococcus aureus* (*S. aureus*), *Bacillus cereus*, *Clostridium perfringens*, *Clostridium botulinum*, *Shigella* spp., *Vibrio* spp., and *Yersinia enterocolitica*, deteriorate food quality and pose serious health risks, leading to intestinal infections, urinary tract infections, and food poisoning, with considerable implications for public health and economic conditions [5]. In 2023, foodborne infections increased in the United States, with *Campylobacter* and *Salmonella* being the primary causes of intestinal infections. The incidences of *Campylobacter*, *Salmonella*, *Listeria*, Shiga toxin-producing *E. coli* (STEC), *Vibrio*, and *Yersinia* infections exceeded the target rates established by Healthy People 2030 goals. In the European Union (EU), campylobacteriosis, caused by *Campylobacter*, also has been the most prevalent gastrointestinal disease, with more than 246 000 cases reported annually, primarily resulting from the consumption of contaminated food products such as poultry, pork, and beef [6]. Salmonellosis, the second most frequently reported zoonotic disease in the EU, affects over 91 000 people annually, primarily due to the consumption of contaminated foods such as eggs and raw meat from pigs, turkeys, and chickens [7]. More recently, increasing concern has emerged regarding *L. monocytogenes*, an intracellular bacteria pathogen capable of surviving and proliferating under harsh environmental conditions, which was associated with a prolonged multicountry outbreak linked to fish product consumption between 2012 and 2024 [8,9].

In recent years, novel detection technologies, such as culture-independent biorecognition-based biosensors, have been employed to ensure food safety. Besides early detection, natural antibacterial agents have been widely studied for their ability to resist bacterial contamination [10], while *S. aureus* and *E. coli* are commonly selected as model Gram-positive and Gram-negative foodborne bacteria to investigate the antibacterial activities and mechanisms of antibacterial agents.

Pickering emulsions loaded with natural antibacterial agents

Natural antibacterial agents

The recently reported natural antibacterial agent-loaded Pickering emulsions for inhibiting foodborne bacteria are summarized in Table 1. The currently used antibacterial agents are primarily natural essential oils and other extracts from plants, animals, and microorganisms. There is a growing interest in applying natural antibacterial agents instead of synthetic ones to target foodborne bacteria, driven by the broad-spectrum antibacterial activity and good biocompatibility of natural extracts, as well as rising concerns over the potential risks of synthetic chemicals and the emergence of drug resistance [11]. The antibacterial mechanisms of different substances vary: acidic and basic substances can disrupt bacterial cell walls and induce cell protein coagulation, whereas alcohols can denature cell proteins and interfere with cell metabolism [11]. Pickering emulsions have been customized to enhance antibacterial effectiveness by increasing the penetration of antibacterial agents through targeted bacterial cell walls (e.g. acidic and basic substances) or enabling controlled release of alcohol-based agents for prolonged protection.

Essential oils, composed of secondary metabolites such as phenolic compounds, alcohols, and terpenes, have strong germicidal properties and long-term efficacy. The antibacterial activity of essential oils is primarily attributed to phenolic substances such as cinnamaldehyde, carvacrol, eugenol, and thymol. The various chemical compositions of essential oils enable them to target multiple sites within bacterial cells, and their hydrophobic properties facilitate penetration of the cytoplasmic membrane [10]. It was reported that the emulsified cedarwood essential oil directly interacted with bacterial cell membranes, facilitating the interaction and improving the antibacterial activity [12]. Other bioactive extracts, such as curcumin and resveratrol, also exhibit significant antibacterial effects against foodborne bacteria and have positive effects on human health. Liu et al. found that curcumin exhibited inhibitory effects on *S. aureus* and *Bacillus subtilis* by disrupting cell membranes, with its antibacterial activity extended through the protection with Pickering emulsions [4]. Antibacterial peptides can effectively inhibit a broad spectrum of foodborne pathogens and do not easily develop resistance, but their applications remain limited due to high production costs, potential toxicity, and susceptibility to protease degradation [11]. The Pickering emulsions encapsulated with antibacterial peptide SA6 (derived from salted *P. vannamei*) significantly prolonged bacterial inhibition time, reducing the *S. aureus* count to 2.83 CFU/mL after 5 days of storage [13].

Pickering emulsions

The encapsulation of natural antibacterial agents provides an effective way to improve their stability and bioavailability. For Pickering emulsions, solid particles instead of surfactants are adsorbed at the oil/water interface and form a physical barrier that shields the encapsulated ingredients from the external environment and enables controlled release [14]. Pickering emulsions exhibit inherent stability against coalescence and environmental stress due to the high energy barrier required to displace adsorbed particles from the interface. Despite generally larger droplet sizes and lower surface coverage compared to conventional emulsions, Pickering emulsions provide effective and sustained protection for natural antibacterial agents, offering favorable advantages, including cost-effectiveness, high loading capacity, high stability, sustained release, low toxicity, biocompatibility, and sustainability. Moreover, by selecting suitable particle stabilizers of Pickering

Table 1

Summary of recently reported natural antibacterial agents in Pickering emulsions for inhibiting foodborne bacteria.

Antibacterial agents		Pickering emulsion formulation		Target foodborne bacteria	Method of microbiological analysis	Refs.
		Stabilizer	Oil [oil to water ratio]			
Essential oil	Cinnamaldehyde	OSA-modified cellulose nanocrystals	Canola oil [10:90] (v/v)	*S. aureus* ATCC 6538, *E. coli* K12, *P. aeruginosa* PA14	Minimal inhibitory concentration (MIC), minimal bactericidal concentration (MBC), inhibition zone (well diffusion method)	[14]
	Cinnamaldehyde and tea polyphenol	Chitosan/zein nanoparticles	Soybean oil [5:95], [20:80] (v/v)	*S. aureus* 10,201, *E. coli* 10,032	Inhibition zone method	[27]
	Cinnamon essential oil	Lignocellulose nanocrystals/tannic acid	Mixture of sunflower oil and cinnamon essential oil, [50:50] (v/v)	*S. aureus*, *E. coli*	Visual bacterial growth	[39]
	Carvacrol	Nanocellulose bearing both aldehyde and carboxylic acid groups	Hexadecane [20:80] (v/v)	*E. coli* K12, *S. aureus* 25,923	Inhibition zone method, colony counting method	[40]
	Cassia oil	Halloysite nanotubes	Hexadecane [10:90] (v/v)	*S. aureus*, *E. coli*	Inhibition rate, live/dead bacterial viability assay	[41]
	Clove essential oil	Whey protein isolate/inulin	Clove essential oil [10:90] (v/v)	*S. aureus*, *E. coli*	Inhibition zone method	[28]
	Grapefruit essential oil	Corn nanostarch	Grapefruit essential oil [10:90] (w/w)	*S. aureus*, *E. coli*	Inhibition zone method	[42]
	Ginger essential oil	TEMPO-oxidized cellulose nanocrystals	Ginger essential oil [11:89], [22:78], [33:67] (v/v)	*S. aureus*, *E. coli*	Inhibition zone method	[43]
	Lavender essential oil	Gelatin	Lavender essential oil [8:92] (v/v)	*E. coli* ATCC 25922, *S. aureus* ATCC 25923	Bactericidal ratio	[44]
	Oregano essential oil	Carboxylated cellulose nanocrystals	Oregano essential oil [20:80] (v/v)	*S. aureus*, *E. coli*	Circular disc dispersion approach	[45]
	Peppermint oil	Chitosan-decorated silica nanoparticles	Peppermint oil [10:90] (v/v)	*S. aureus*, *E. coli*	MIC, inhibition zone method	[46]
	Tangerine peel essential oil and purple corncob anthocyanin	Esterified modified starch	NR	*E. coli* ATCC 25922, *S. aureus* ATCC 25923	Inhibition zone method	[30]
	Thyme essential oil	Soybean lipophilic protein	Mixture of 95% soybean oil and 5% thyme essential oil	*S. aureus*, *E. coli*	Growth inhibition rate	[33]
	d-Limonene	APS oxidized cellulose nanofibers	d-Limonene [NR]	*E. coli* ATCC 25922, *S. aureus* ATCC 653	Inhibition zone (disk diffusion assay), bacteriostatic activity (shaking bottle method)	[23]
Other extracts	Carnosic acid	Bacterial cellulose nanocrystal/ε-polylysine/carnosic acid	NR	*S. aureus* ATCC 27660, *L. monocytogenes* ATCC 19114, *Salmonella enteritidis* ATCC 13076	Plate count method and agar diffusion assay	[37]
	Cannabidiol	Soy protein isolate/chitosan	Tributyrin oil [10:90] (v/v)	*S. aureus*, *E. coli*, *C. albicans*, *B. subtilis*	MIC, MBC, inhibition zone (the Kirby-Bauer method)	[47]
	Curcumin	Succinylated soy protein isolate	Corn oil [10:90] (v/v)	*S. aureus*, *E. coli*	Inhibition zone method	[48]
	Red roselle extract	Persimmon pectin/β-cyclodextrin	*Litsea cubeba* oil	*L. monocytogenes*	Inhibition zone method	[22]
	Resveratrol	Zein/pectin	Peppermint oil [5:95] (w/w)	*S. aureus* CGMCC 1.1861, *S. Typhimurium* CMCC 50115	MIC	[49]
	Vitamin E	Whey protein isolate–vanillin	Corn oil [40:60], [50:50], [60:40] (v/v)	*S. aureus*, *E. coli*	MIC, MBC, inhibition zone	[50]
	Peptide SA6	Soybean isolate protein	Soybean oil [70:30] (v/v)	*S. aureus*	MIC	[13]

NR = not reported.

emulsions, the modulated permeation rates and enhanced adhesion to bacterial cells can be achieved to disrupt cell function and improve antibacterial efficacy.

The design of Pickering emulsions for inhibiting foodborne bacteria involves the selection of stabilizing particles, the encapsulation of antibacterial agents, and the manipulation of interfacial properties and environmental sensitivity to ensure the stability of emulsions and the encapsulation and controlled release of antibacterial agents. Proteins (e.g. zein, whey protein isolate, soy protein isolate) and polysaccharides (e.g. chitosan, pectin, cellulose) are commonly used as Pickering emulsion stabilizers for food applications and have good encapsulation efficiency for antibacterial agents that target foodborne bacteria. The properties of stabilizers and the preparation methods of Pickering emulsions determine the particle size and surface charge of emulsion droplets, which significantly influence the effectiveness against foodborne bacteria [2,12]. For instance, smaller particles possess a larger surface area that may enable stronger interactions with bacteria and enhance antibacterial efficacy, while larger particles usually have prolonged release of antibacterial agents. In general, the rigid barrier network formed by particle stabilizers provides protection and controlled release of antibacterial agents. When emulsion droplets come into contact with bacterial cells, their small size and low interfacial tension allow for rapid attachment and penetration through cell membranes, resulting in improved antibacterial performance [15]. Moreover, the electrostatic attractions between the typically charged bacterial cell walls and the surface-charged emulsion droplets can mediate localized binding at the targeted sites. For example, the emulsion droplets coated with positively charged chitosan could target bacterial cells through electrostatic interactions [16], while the Pickering emulsions stabilized by positively charged cellulose-based nanoparticles exhibited enhanced antibacterial properties due to the electrostatic attraction, facilitating bacterial decomposition and subsequent dying [17]. Furthermore, Pickering emulsions can be tailored to respond to environmental factors such as pH or temperature, enabling the targeted release of antibacterial agents under specific conditions that promote bacterial inhibition and reduce the potential for resistance. This stimulated response can be particularly beneficial in site-specific delivery systems; for example, Pickering emulsion stabilized by chitosan-tripolyphosphate nanoparticles enabled higher curcumin release at pH 2 that relates to gastric conditions compared to basic pH 7.4 that corresponds to blood fluid [18].

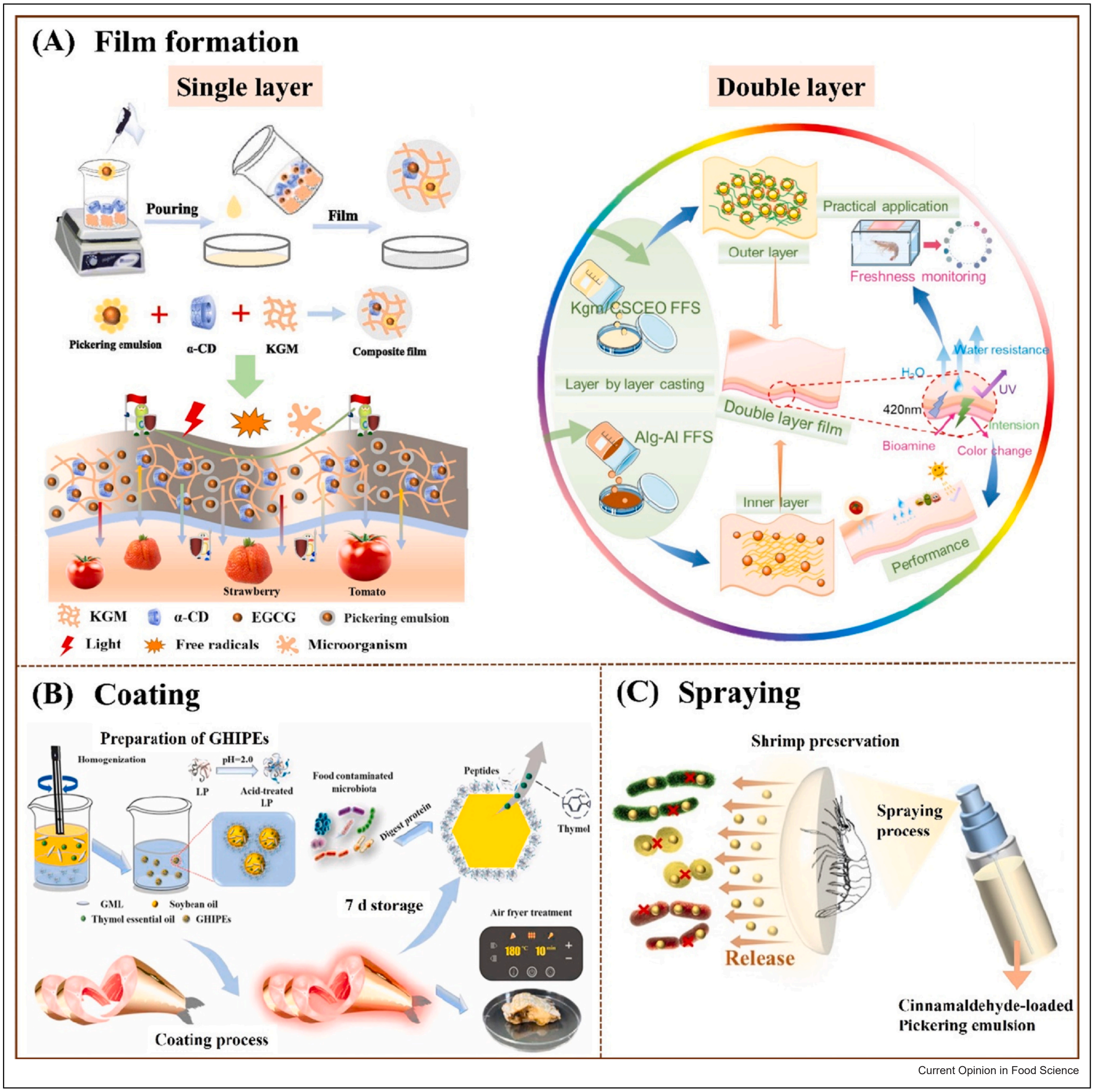
Food applications

Pickering emulsions can enhance the stability and enable the controlled/targeted release of loaded bioactive compounds, making them valuable for potential applications, including drug delivery systems, wound healing materials, and functional components for food packaging. With growing concerns over foodborne bacteria outbreaks and the possible health risks posed by synthetic food preservatives, there has been increasing attention towards applying natural antibacterial Pickering emulsions for food preservation. Recent research has demonstrated their effectiveness in preserving various food types, including vegetables, fruits, meat, seafood, dairy products, and baked products. Packaging films and coating materials based on Pickering emulsions containing natural antibacterial agents are the most common application methods (Figure 1). The treatments have shown significant effects on extending the shelf life of food products, improving food nutritional value and safety, minimizing food waste, and reducing reliance on synthetic preservatives. The results align with the public's demand for ready-to-eat foods with high nutritional value and minimal processing, demonstrating the potential to revolutionize food preservation practices.

Fruits and vegetables

Fruits and vegetables are highly perishable due to their high moisture content and nutrient-rich compositions. Pickering emulsions containing natural antibacterial agents as an effective preservation solution can be applied through dipping, spraying, or film formation, creating protective barriers that minimize air exposure, water loss, and bacterial contamination. Li et al. investigated the preservation of strawberries and tomatoes using α-cyclodextrin/konjac glucomannan composite films loaded with epigallocatechin gallate (EGCG) encapsulated Pickering emulsions [19]. The improved loading efficiency and sustained release of EGCG from the films effectively inhibited the growth of *S. aureus* and *E. coli* by disrupting cell membranes, extending the shelf life of strawberries and tomatoes to 7 days. Cinnamon essential oil nanoemulsions stabilized by hydroxypropyl-β-cyclodextrin (HPCD) and lecithin were incorporated into konjac glucomannan/pullulan composite films for the preservation of cherries and mushrooms [20]. Increasing the concentration of HPCD resulted in greater film thickness, which extended the pathway for essential oil release and effectively improved the retention rate. The retention rate and release speed of cinnamon essential oil determined the films' antibacterial activity, and the high barrier properties enabled by Pickering emulsions slowed down the browning in mushrooms (maintaining a lightness value > 80 until day 12) and reduced weight loss in mushrooms and cherries. Similar results were observed by incorporating anise essential oil Pickering emulsions in corn starch/cassia gum composite films, which delayed the browning and spoilage of mushrooms and maintained their texture and color after 5 days of storage [21]. Mangos, as a climacteric fruit, are also prone to enzymatic browning and spoilage

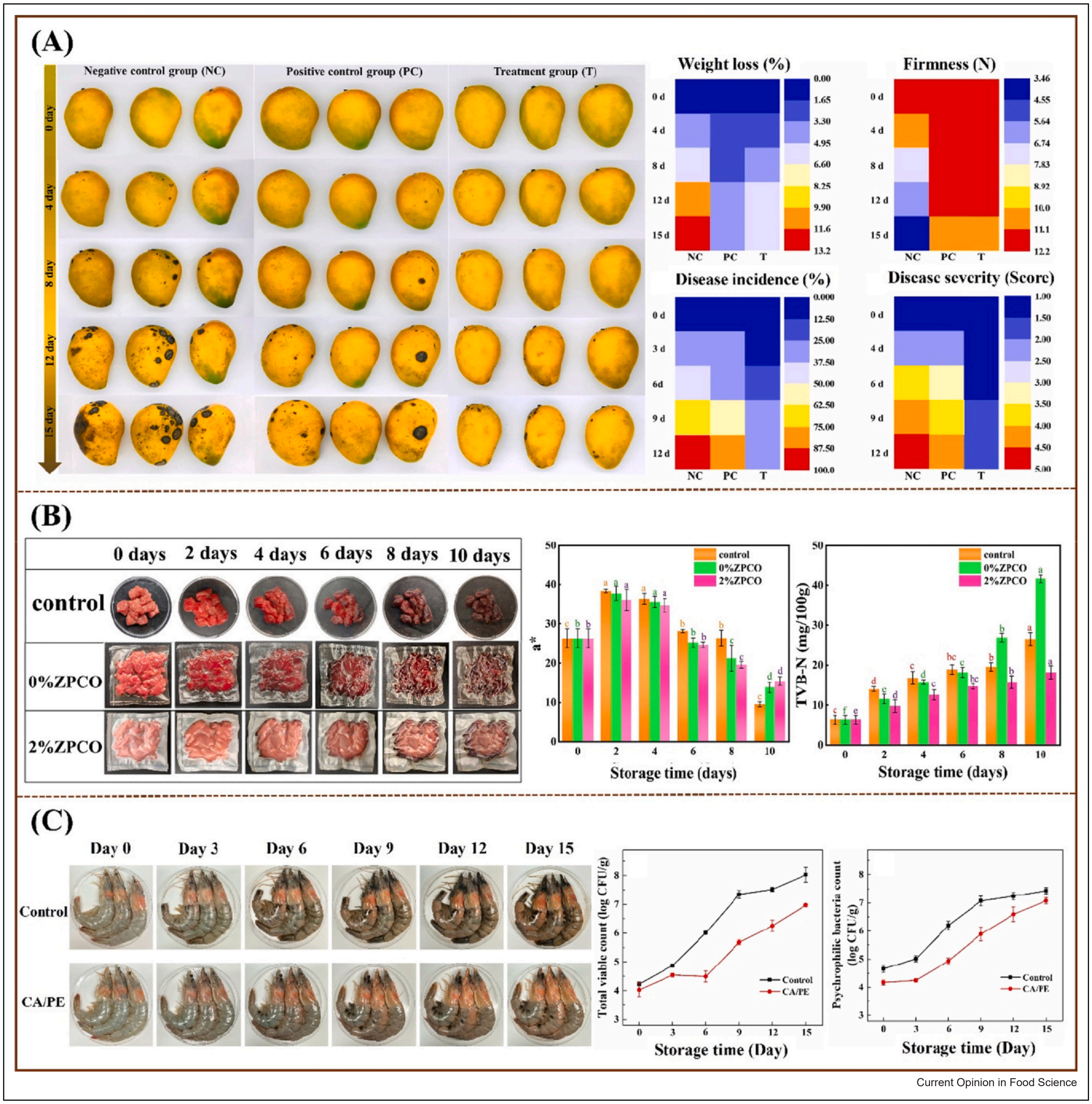
Figure 1



Schematic diagram of application methods of antibacterial Pickering emulsions for food preservation.
Reprinted with permission from the works cited in Refs. [14,19,33,35].

due to their rapid ripening and susceptibility to post-harvest diseases. The combination of gelatin films, *Litsea cubeba* oil Pickering emulsion (LCON), and ZnO nanoparticles effectively controlled the postharvest quality of mangos, reducing black spots, limiting weight loss to 6.18%, and maintaining firmness of 10.81 N after 15 days (Figure 2a) [22]. The high preservation performance was due to the excellent biological (antibacterial inhibition zone: 31.24 mm), mechanical (tensile strength: 42.03 MPa), and barrier (water vapor permeability: 18.01 g mm·m^{-2}·kPa^{-1}·h^{-1}) properties of the optimized films. Notably, the synergistic effect of LCON and ZnO enhanced the inhibition of *L. monocytogenes* growth by regulating reactive oxygen metabolism and disrupting cell membranes. Besides the active packaging films, an antibacterial coating was developed through dipping to

Figure 2



(a) Effects of different treatments on the appearance quality, weight loss, firmness, disease incidence, and disease severity of mango during the storage period. (NC: negative control group, PC: positive control group, T: treatment group). **(b)** Digital photos of beef samples in the control group (samples without package), 0% ZPCO group (samples packed with film without ZPCO), and 2% ZPCO group (samples packed with film with 2% ZPCO), and changes in a* and TVB-N values of beef samples at various time intervals. **(c)** Changes in appearance quality, total viable count, and psychrophilic bacteria count of shrimp treated without (Control) and with cinnamaldehyde-loaded Pickering emulsion stabilized (CA/PE) during storage.
(a) Reprinted with permission from the work cited in Ref. [22]. **(b)** Reprinted with permission from the work cited in Ref. [29]. **(c)** Reprinted with permission from the work cited in Ref. [14].

preserve the sensory and nutritional qualities of strawberries [23]. The coating solution was formulated with oxidized cellulose nanofibers stabilized D-Limonene Pickering emulsions and chitosan. The strong antibacterial activity against *S. aureus* and *E. coli* was primarily attributed to D-Limonene, which induced cell protein denaturation, disrupted membrane integrity, and altered cell permeability.

Meat

The U.S. Department of Agriculture reported 89 recalls of meat and poultry products in 2023 — a 31% increase compared to 2022. Meat products, rich in protein and fat, are more prone to pathogenic bacteria contamination than fruits and vegetables [24]. The spoilage of meat products results in changes in total viable count (TVC), pH, color, and total volatile basic nitrogen (TVB-N) values. Their transport and storage require a strict low-temperature environment and the use of broad-spectrum preservatives to inhibit foodborne bacterial growth (e.g. *Staphylococcus* spp., lactic acid bacteria, *Enterococcus* spp.) and slow down biochemical changes [25]. Similarly, Pickering emulsions are commonly used in active films or coatings to help retain moisture, control bacterial growth, and prevent texture and flavor degradation of meat. Pickering emulsions loaded with various essential oils have been widely employed in active food packaging due to their distinguished antibacterial activity and ability to enhance the mechanical and barrier properties of the packaging materials. Additionally, the incorporation of antioxidants and freshness indicators has been particularly applied in meat preservation. An active and smart gelatin/chitosan film was developed by incorporating curcumin and cinnamon oil Pickering emulsions, demonstrating great potential for pork preservation and as a freshness indicator [26]. Introducing Pickering emulsions enhanced the antibacterial activity of films (inhibition zones: *E. coli* = 150.47 mm^2; *S. aureus* = 173.72 mm^2) and reduced water absorption by 336.27%. The effective encapsulation facilitated the controlled release and provided a sustained antibacterial effect, which improved the fresh-keeping effect of pork (TVB-N content = 30.52 mg/100 g after 3 days). The chitosan films containing Pickering emulsions loaded with tea polyphenol and cinnamaldehyde demonstrated enhanced antibacterial activity (inhibition zones: *E. coli* = 265.62 mm^2; *S. aureus* = 193.59 mm^2) and extended the shelf life of pork from 2 days to 8 days (TVC < 10^6 CFU/g) [27]. In starch-based films, Pickering emulsions containing clove essential oil provided effective protection for pork, prolonging its shelf life to 10 days (TVC = 5.33 log CFU/g, TVB-N content = 14.70 mg/100 g, pH = 6.08 on day 10) [28]. Wu et al. reported that chayote tuber starch films allowed the sustained release of cinnamon essential oil from the incorporated Pickering emulsions, and the release duration was prolonged in fatty foods and at low temperatures (Figure 2b) [29]. The obtained composite films with the broad antibacterial spectrum and strong antioxidant properties significantly slowed down TVB-N formation (18.2 mg/100 g after 10 days) in fresh beef. Chen et al. developed corn starch–based films with purple corncob anthocyanin and Pickering emulsions containing tangerine peel essential oil, which had significant antibacterial activity (inhibition zones: *E. coli* = 191.15 mm^2; *S. aureus* = 269.25 mm^2) to contribute to pork preservation and enabled visual freshness monitoring [30]. In gelatin-based films, the synergistic antibacterial effect of oregano essential oil Pickering emulsions combined with ε-polylysine exhibited excellent inhibition efficacy against targeted bacteria (inhibitory rate: *E. coli* = 100%; *S. aureus* = 97.32%), thereby effectively extending the shelf life of beef with significantly decreased TVC and TVB-N formation [31].

Seafood

Seafood products are highly valued for their nutritional benefits, such as the polyunsaturated omega-3 fatty acids in salmon, and the rich minerals and vitamins in shrimp [32]. However, they are highly perishable and susceptible to bacterial and chemical spoilage during processing and storage, which can significantly reduce their commercial value [24]. Antibacterial Pickering emulsions can enhance preservation effectiveness by addressing specific challenges, such as delicate texture and complex surface structures that complicate disinfection [14,33]. High internal phase Pickering emulsions enriched with thyme essential oils have demonstrated smart sensing and targeted release ability [33]. The gel structure extended the release time of essential oils with a retention of 87.18% after 14 days, thereby prolonging the antibacterial effects against foodborne pathogens (*S. aureus* and *E. coli*). The emulsions achieved ‘smart sensing’ controlled release of essential oils, triggered by the digestion of wall materials by pathogenic bacteria, and extended the shelf life of fish (*Cololabis saira*) to 7 days in direct surface coating mode. The cinnamaldehyde-loaded Pickering emulsions stabilized by modified cellulose nanocrystals could be directly sprayed on the shrimp surface, resulting in an extended shelf life (TVC = 6.26 log CFU/g on day 12) (Figure 2c) [14].

Pickering emulsion–loaded packaging films can also monitor the freshness of seafood by associating colors change with the degree of spoilage. The combination of collagen films and cinnamon essential oil-loaded Pickering emulsions with oxidized mulberry extract acting as an enhancer exhibited strong antibacterial activity against *E. coli* and *Pseudomonas fluorescens*, extending the shelf life of fish by 4 days and exhibiting a visible color change from red (day 0) to blackish green (day 12) [34]. A unique double-layer packaging structure consisting of a high-barrier antibacterial layer (konjac glucomannan matrix incorporating cinnamon essential oil Pickering emulsion) and a pH/NH_3-responsive layer (alginate matrix containing alizarin as an indicator) was designed to monitor and preserve the freshness of shrimp (TVB-N = 18.65 mg/100 g after 3 days) [35]. Tang et al. prepared 3D printing inks from curcumin/oregano oil Pickering emulsions, potato starch, and polyvinyl alcohol to create pH-sensitive packaging films [36], which showed good inhibitory effects on *E. coli* and *S. aureus* and exhibited color changes corresponding to pH and TVB-N levels during fish preservation.

Other foods

Recently, Pickering emulsions containing natural antibacterial agents have also been applied for the preservation of dairy products [37] and baked goods [38]. For example, gelatin films incorporating three-phase Pickering emulsions could preserve fresh (acid-coagulated) and mozzarella cheese due to the complete inhibition of pathogenic bacteria (*S. aureus*, *L. monocytogenes*, and *S. enteritidis*) and the delay of lipid peroxidation [37]. Composite films based on ginger essential oil Pickering emulsions prolonged the shelf life of packaged bread slices from 4 to 30 days because of the sustained release of antibacterial ingredients and the emulsion protective layer that slowed down evaporation and staling [38].

Conclusions and perspective

Natural antibacterial agents have attracted great attention as sustainable food preservatives due to the rising infections and outbreaks caused by foodborne pathogenic bacteria, addressing the increasing concerns about the potential health risks posed by synthetic preservatives, as well as the demand for minimally processed and ready-to-eat food products with high nutritional value. Pickering emulsions have shown great potential to be effective carriers for antibacterial agents, attributed to their cost-effectiveness, high loading capacity, high stability, sustained release, low toxicity, biocompatibility, and sustainability. Pickering emulsions containing various natural antibacterial agents can be customized to meet the specific preservation requirements of perishable food products through dipping, spraying, or active film formation, creating protective barriers that inhibit bacterial growth and contamination and ensuring enhanced food safety and quality retention.

Currently, most attention has been paid to the incorporation of antibacterial Pickering emulsions in active food packaging films. This strategy not only prolongs the antibacterial effect but also improves the mechanical and barrier properties of packaging films; however, the integration of active films in practical packaging systems should be further considered. Direct coating suggests a facile way to apply Pickering emulsions, especially for food products with complex structures, but the type of food may affect the antibacterial efficacy, and the dipping/spraying processes may change the sensory and texture of food. Emerging techniques such as electrospinning and 3D printing provide exciting opportunities to construct novel carrier structures, which will lead to future investigation. The adoption of natural antibacterial agents represents a sustainable solution, but at the same time, navigates significant regulatory hurdles, such as rigorous compliance requirements, and should address economic considerations to align production costs with market demands and consumer willingness. In recent years, concerns regarding the potential biotoxicity of nanomaterials have led to increased research into the toxicity of Pickering emulsions. However, studies on the cellular toxicity and *in vivo* metabolism of antibacterial agent-loaded Pickering emulsions remain limited, as most existing research mainly focuses on formulation design and antibacterial performance. Additionally, there is a lack of precise study on the effects of food matrix components on the antibacterial activity of Pickering emulsions. The simultaneous incorporation of various natural antibacterial agents into Pickering emulsions has shown promise for improving preservation performance, and more research works on the synergistic effects and interactions of different bioactive compounds can be expected. Future research should also pay attention to the potential resistance of foodborne bacteria, such as *Acinetobacter*, *Pseudomonas*, and species of *Enterobacterales*, to various antibacterial Pickering emulsions.

Data Availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no conflicts of interest to this work.

Acknowledgements

We would like to acknowledge financial support from the Natural Sciences and Engineering Research Council of Canada (NSERC RGPIN-2019-04498, NSERC DGECR-2019-00472).

C.J. would like to thank the financial support from China Scholarship Council (NO. 202106790028) and Centre de Recherche sur les Systèmes Polymères et Composites à Haute Performance (2023-RS6-309014).

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest.

1. Canadian Food Inspection Agency: **Statistics: Food Recall Incidents and Food Recalls**; 2023.

2. Bahrami A, Delshadi R, Cacciotti I, Faridi Esfanjani A, Rezaei A, Tarhan O, *et al*.: **Targeting foodborne pathogens via surface-functionalized nano-antimicrobials**. *Adv Colloid Interface Sci* 2022, **302**:102622, https://doi.org/10.1016/j.cis.2022.102622

3. Li Y, Tan L, Liu F, Li M, Zeng S, Gui Y, *et al*.: **Effects of soluble Antarctic krill protein-curcumin complex combined with**

photodynamic inactivation on the storage quality of shrimp. *Food Chem* 2023, **403**:134388, https://doi.org/10.1016/j.foodchem.2022.134388

4. Liu D, Dang S, Zhang L, Munsop K, Li X: **Corn starch/polyvinyl alcohol based films incorporated with curcumin-loaded Pickering emulsion for application in intelligent packaging**. *Int J Biol Macromol* 2021, **188**:974-982, https://doi.org/10.1016/j.ijbiomac.2021.08.080

5. Sohrabi H, Majidi MR, Khaki P, Jahanban-Esfahlan A, de la Guardia M, Mokhtarzadeh A: **State of the art: lateral flow assays toward the point-of-care foodborne pathogenic bacteria detection in food samples**. *Compr Rev Food Sci Food Saf* 2022, **21**:1868-1912, https://doi.org/10.1111/1541-4337.12913

6. European Food Safety Authority: **EFSA explains zoonotic diseases - Campylobacter**; 2024.

7. European Food Safety Authority: **Campylobacter and Salmonella cases stable in EU**; 2021.

8. European Food Safety A: **Prolonged multi-country outbreak of *Listeria monocytogenes* ST173 linked to consumption of fish products**. *EFSA Support Publ* 2024, **21**:8885E, https://doi.org/10.2903/sp.efsa.2024.EN-8885

9. European Food Safety A: **Prolonged multi-country outbreak of *Listeria monocytogenes* ST1607 linked to smoked salmon products**. *EFSA Support Publ* 2024, **21**:8810E, https://doi.org/10.2903/sp.efsa.2024.EN-8810

10. Falleh H, Ben Jemaa M, Saada M, Ksouri R: **Essential oils: a**
• **promising eco-friendly food preservative**. *Food Chem* 2020, **330**:127268, https://doi.org/10.1016/j.foodchem.2020.127268.
This review highlighted current knowledge of the antibacterial activity and food preservative properties of essential oils, supporting their use as natural, eco-friendly, safe, and biodegradable agents for food preservation.

11. Chen C, Chen L, Mao C, Jin L, Wu S, Zheng Y, *et al*.: **Natural**
•• **extracts for antibacterial applications**. *Small* 2024, **20**:2306553, https://doi.org/10.1002/smll.202306553.
This paper provided a comprehensive review of recent advances in natural extracts from plants, animals, and microorganisms for antibacterial applications, which is beneficial for researchers to have an advanced understanding of natural extracts, the corresponding antibacterial mechanisms, and their future development.

12. Huang K, Liu R, Zhang Y, Guan X: **Characteristics of two cedarwood essential oil emulsions and their antioxidant and antibacterial activities**. *Food Chem* 2021, **346**:128970, https://doi.org/10.1016/j.foodchem.2020.128970

13. Yang S, Dai J, Aweya JJ, Lin R, Weng W, Xie Y, *et al*.: **The antibacterial activity and Pickering emulsion stabilizing effect of a novel peptide, SA6, isolated from salt-fermented *Penaeus vannamei***. *Food Bioprocess Technol* 2023, **16**:1312-1323, https://doi.org/10.1007/s11947-023-03000-9

14. Ji C, Wei J, Wang Y: **Cinnamaldehyde-enriched Pickering**
• **emulsions stabilized by modified cellulose I and II nanocrystals recycled from maple leaves for shrimp preservation**. *Carbohydr Polym* 2024, **326**:121590, https://doi.org/10.1016/j.carbpol.2023.121590.
The authors used cinnamaldehyde-enriched Pickering emulsions as a spraying material to extend the shelf life of shrimps that were hard to disinfect due to their complicated surface structure.

15. Nwabuife JC, Omolo CA, Govender T: **Nano delivery systems to the rescue of ciprofloxacin against resistant bacteria "*E. coli*; *P. aeruginosa*; *S. aureus*; and MRSA" and their infections**. *J Control Release* 2022, **349**:338-353, https://doi.org/10.1016/j.jconrel.2022.07.003

16. Krogsgård Nielsen C, Kjems J, Mygind T, Snabe T, Schwarz K, Serfert Y, *et al*.: **Enhancing the antibacterial efficacy of isoeugenol by emulsion encapsulation**. *Int J Food Microbiol* 2016, **229**:7-14, https://doi.org/10.1016/j.ijfoodmicro.2016.04.002

17. Meng Q, Xue Z, Chen S, Wu M, Lu P: **Smart antimicrobial Pickering emulsion stabilized by pH-responsive cellulose-based nanoparticles**. *Int J Biol Macromol* 2023, **233**:123516, https://doi.org/10.1016/j.ijbiomac.2023.123516

18. Shah BR, Li Y, Jin W, An Y, He L, Li Z, *et al*.: **Preparation and optimization of Pickering emulsion stabilized by chitosan-tripolyphosphate nanoparticles for curcumin encapsulation**. *Food Hydrocolloid* 2016, **52**:369-377, https://doi.org/10.1016/j.foodhyd.2015.07.015

19. Li H, Tan W, Hou M, Yang S, Liu C, Han M, *et al*.: **Multi-strategy**
• **dynamic cross-linking to prepare EGCG-loaded multifunctional Pickering emulsion/α-cyclodextrin/konjac glucomannan composite films for ultra-durable preservation of perishable fruits**. *Carbohydr Polym* 2024, **338**:122205, https://doi.org/10.1016/j.carbpol.2024.122205.
In this paper, the EGCG-loaded Pickering emulsion/α-cyclodextrin/konjac glucomannan composite film had favorable thermal stability, mechanical properties, barrier properties, and antioxidant and antibacterial activity, which held promise as a multifunctional antimicrobial preservation material with sustained-release properties and biodegradability for perishable food applications.

20. Zhou F, Yu L, Liu Y, Zeng Z, Li C, Fang Z, *et al*.: **Effect of hydroxypropyl-β-cyclodextrin and lecithin co-stabilized nanoemulsions on the konjac glucomannan/pullulan film**. *Int J Biol Macromol* 2023, **235**:123802, https://doi.org/10.1016/j.ijbiomac.2023.123802

21. Zhao P, Yan X, Cheng M, Wang Y, Wang Y, Wang K, *et al*.: **Effect of Pickering emulsion on the physical properties, microstructure and bioactivity of corn starch/cassia gum composite films**. *Food Hydrocolloid* 2023, **141**:108713, https://doi.org/10.1016/j.foodhyd.2023.108713

22. Yang Z, Li M, Li Y, Li Z, Huang X, Wang X, *et al*.: **Improving properties of *Litsea cubeba* oil Pickering emulsion-loaded gelatin-based bio-nanocomposite film via optimizing blending ratio: application for mango preservation**. *Food Hydrocolloid* 2023, **145**:109052, https://doi.org/10.1016/j.foodhyd.2023.109052

23. Yue X, Miao M, Feng X: **Incorporating of oxidized cellulose nanofibers@d-limonene Pickering emulsion into chitosan for fully biobased coatings toward fruits protection**. *ACS Sustain Chem Eng* 2023, **11**:15102-15113, https://doi.org/10.1021/acssuschemeng.3c04396

24. Odeyemi OA, Alegbeleye OO, Strateva M, Stratev D:
• **Understanding spoilage microbial community and spoilage mechanisms in foods of animal origin**. *Compr Rev Food Sci Food Saf* 2020, **19**:311-331, https://doi.org/10.1111/1541-4337.12526.
This article reviewed the spoilage microbiota and mechanisms in foods such as meat, dairy products, and seafood, which is beneficial for researchers to understand the food spoilage mechanisms and develop robust technologies to prevent food spoilage and waste.

25. Coombs CEO, Holman BWB, Friend MA, Hopkins DL: **Long-term red meat preservation using chilled and frozen storage combinations: a review**. *Meat Sci* 2017, **125**:84-94, https://doi.org/10.1016/j.meatsci.2016.11.025

26. Liu J, Li K, Chen Y, Ding H, Wu H, Gao Y, *et al*.: **Active and smart**
• **biomass film containing cinnamon oil and curcumin for meat preservation and freshness indicator**. *Food Hydrocolloid* 2022, **133**:107979, https://doi.org/10.1016/j.foodhyd.2022.107979.
This research paper provided an attractive universal strategy to construct active and smart composite films for meat packaging applications. The combination of cinnamon oil-loaded Pickering emulsions and curcumin enables customized performance.

27. Wang Z, Zhang M, Liang S, Li Y: **Enhanced antioxidant and antibacterial activities of chitosan/zein nanoparticle Pickering emulsion-incorporated chitosan coatings in the presence of cinnamaldehyde and tea polyphenol**. *Int J Biol Macromol* 2024, **266**:131181, https://doi.org/10.1016/j.ijbiomac.2024.131181

28. Zhao Z, Liu H, Tang J, He B, Yu H, Xu X, *et al*.: **Pork preservation by antimicrobial films based on potato starch (PS) and polyvinyl alcohol (PVA) and incorporated with clove essential oil (CLO) Pickering emulsion**. *Food Control* 2023, **154**:109988, https://doi.org/10.1016/j.foodcont.2023.109988

29. Wu H, Wang J, Li T, Lei Y, Peng L, Chang J, *et al*.: **Effects of cinnamon essential oil-loaded Pickering emulsion on the structure, properties and application of chayote tuber starch-based composite films**. *Int J Biol Macromol* 2023, **240**:124444, https://doi.org/10.1016/j.ijbiomac.2023.124444

30. Chen Q, Zhang P, You N, Xu Y, Zhang Y, Luan P, *et al.*: **Preparation and characterization of corn starch-based antimicrobial indicator films containing purple corncob anthocyanin and tangerine peel essential oil for monitoring pork freshness**. *Int J Biol Macromol* 2023, **251**:126320, https://doi.org/10.1016/j.ijbiomac.2023.126320

31. Zhuang D, Li R, Wang S, Ahmad HN, Zhu J: **Reinforcing effect of ε-polylysine-carboxymethyl chitosan nanoparticles on gelatin-based film: enhancement of physicochemical, antioxidant, and antibacterial properties**. *Int J Biol Macromol* 2024, **255**:128043, https://doi.org/10.1016/j.ijbiomac.2023.128043

32. Karageorgou D, Rova U, Christakopoulos P, Katapodis P, Matsakas L, Patel A: **Benefits of supplementation with microbial omega-3 fatty acids on human health and the current market scenario for fish-free omega-3 fatty acid**. *Trends Food Sci Technol* 2023, **136**:169-180, https://doi.org/10.1016/j.tifs.2023.04.018

33. Sun Y, Zhang P, Hou Y, Cheng S, Tan M, Zhu B, *et al.*: **Enhanced stability and antibacterial efficacy of edible oleogels-in-water high internal phase emulsions prepared from soybean lipophilic protein**. *Food Hydrocolloid* 2024, **154**:110058, https://doi.org/10.1016/j.foodhyd.2024.110058

34. Ran R, Xiong Y, Zheng T, Tang P, Zhang Y, Yang C, *et al.*: **Active and intelligent collagen films containing laccase-catalyzed mulberry extract and pickering emulsion for fish preservation and freshness indicator**. *Food Hydrocolloid* 2024, **147**:109326, https://doi.org/10.1016/j.foodhyd.2023.109326

35. • Li S, Hu X, Zhang S, Zhao J, Wang R, Wang L, *et al.*: **A versatile bilayer smart packaging based on konjac glucomannan/alginate for maintaining and monitoring seafood freshness**. *Carbohydr Polym* 2024, **340**:122244, https://doi.org/10.1016/j.carbpol.2024.122244.

This is an interesting study that used a bilayer intelligent, active packaging system to monitor and maintain seafood freshness. The authors integrated cinnamon essential oil Pickering emulsion and alizarin into a three-dimensional polysaccharide matrix through hydrogen bonding interactions and dehydration condensation.

36. Tang T, Zhang M, Mujumdar AS, Li C: **3D printed curcumin-based composite film for monitoring fish freshness**. *Food Packag Shelf Life* 2024, **43**:101289, https://doi.org/10.1016/j.fpsl.2024.101289

37. • Xia, Sun J, Jia X, Li L P, Xu K, Cao Y, *et al.*: **Multifunctional sustainable films of bacterial cellulose nanocrystal-based, three-phase pickering nanoemulsions: a promising active food packaging for cheese**. *Chem Eng J* 2023, **466**:143295, https://doi.org/10.1016/j.cej.2023.143295.

The authors introduced natural pigments into the bacterial cellulose nanocrystal-stabilized Pickering nanoemulsion delivery systems to realize the manufacturing of intelligent packaging that integrated antibacterial and antioxidant properties and monitored the change of cheese freshness.

38. Fasihi H, Noshirvani N, Hashemi M: **Novel bioactive films integrated with Pickering emulsion of ginger essential oil for food packaging application**. *Food Biosci* 2023, **51**:102269, https://doi.org/10.1016/j.fbio.2022.102269

39. • Dai H, Chen Y, Chen H, Fu Y, Ma L, Wang H, *et al.*: **Gelatin films functionalized by lignocellulose nanocrystals-tannic acid stabilized Pickering emulsions: influence of cinnamon essential oil**. *Food Chem* 2023, **401**:134154, https://doi.org/10.1016/j.foodchem.2022.134154.

This research paper focused on the influence of different volume proportions of mixed oils (sunflower oil and cinnamon essential oil). The cinnamon essential oil proportion regulated the color, morphology, mechanical properties, barrier properties, and functional characteristics of the emulsion films.

40. Tavakolian M, Koshani R, Tufenkji N, van de Ven TGM: **Antibacterial Pickering emulsions stabilized by bifunctional hairy nanocellulose**. *J Colloid Interface Sci* 2023, **643**:328-339, https://doi.org/10.1016/j.jcis.2023.04.033

41. Tan C, Zhao P, Zhou Y, Liu M: **Hydrophobic halloysite nanotubes via ball milling for stable Pickering emulsions: implications for food preservation**. *ACS Appl Nano Mater* 2022, **5**:11289-11301, https://doi.org/10.1021/acsanm.2c02410

42. Deng N, Hu Z, Li H, Li C, Xiao Z, Zhang B, *et al.*: **Physicochemical properties and pork preservation effects of lotus seed drill core powder starch-based active packaging films**. *Int J Biol Macromol* 2024, **260**:129340, https://doi.org/10.1016/j.ijbiomac.2024.129340

43. Chen Q, You N, Liang C, Xu Y, Wang F, Zhang B, *et al.*: **Effect of cellulose nanocrystals-loaded ginger essential oil emulsions on the physicochemical properties of mung bean starch composite film**. *Ind Crops Prod* 2023, **191**:116003, https://doi.org/10.1016/j.indcrop.2022.116003

44. • Wang J, Sun X, Zhang H, Dong M, Li L, Zhangsun H, *et al.*: **Dual-functional intelligent gelatin based packaging film for maintaining and monitoring the shrimp freshness**. *Food Hydrocolloid* 2022, **124**:107258, https://doi.org/10.1016/j.foodhyd.2021.107258.

The authors developed gelatin films incorporating lavender essential oil Pickering emulsions and alizarin, which demonstrated a sensitive, reversible, and rapid response to pH and NH_3. These films showed potential for real-time monitoring and maintaining the freshness of shrimp.

45. Yang W, Zhang S, Hu Y, Fu Q, Cheng X, Li Y, *et al.*: **Pectin-based film activated with carboxylated cellulose nanocrystals-stabilized oregano essential oil Pickering emulsion**. *Food Hydrocolloid* 2024, **151**:109781, https://doi.org/10.1016/j.foodhyd.2024.109781

46. Lai H, Liu Y, Huang G, Chen Y, Song Y, Ma Y, *et al.*: **Fabrication and antibacterial evaluation of peppermint oil-loaded composite microcapsules by chitosan-decorated silica nanoparticles stabilized Pickering emulsion templating**. *Int J Biol Macromol* 2021, **183**:2314-2325, https://doi.org/10.1016/j.ijbiomac.2021.05.198

47. Han X, Duan C-J, Wei Z-F, Xu J, Nie C-D, Chang Y-H, *et al.*: **Pickering extremulsion rich in lipophilic phytochemicals: preparation, characterization and application**. *J Food Eng* 2024, **370**:111960, https://doi.org/10.1016/j.jfoodeng.2024.111960

48. Liu Y, Chen G, Yang Y, Wu R, Zhang L, Mu X, *et al.*: **Fabrication of chitosan-based smart film by the O/W emulsion containing curcumin for monitoring pork freshness**. *J Food Eng* 2024, **379**:112115, https://doi.org/10.1016/j.jfoodeng.2024.112115

49. Cheng H, Khan MA, Xie Z, Tao S, Li Y, Liang L: **A peppermint oil emulsion stabilized by resveratrol-zein-pectin complex particles: enhancing the chemical stability and antimicrobial activity in combination with the synergistic effect**. *Food Hydrocolloid* 2020, **103**:105675, https://doi.org/10.1016/j.foodhyd.2020.105675

50. Zhao S, Wang X, Zhang H, Li W, He Y, Meng X, *et al.*: **Bacteriostatic Pickering emulsions stabilized by whey protein isolate–vanillin nanoparticles: fabrication, characterization and stability in vitro**. *Food Chem* 2023, **429**:136871, https://doi.org/10.1016/j.foodchem.2023.136871