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Review article

A review of Pickering emulsions-based delivery systems: Encapsulation, enhancing the stability and bioavailability of bioactive compounds

Mona Miran *, Farzaneh Kamandloo

Department of Food Science and Engineering, College of Agriculture and Natural Resources, University of Tehran, Karaj Campus, Karaj, Iran

ABSTRACT

Pickering emulsions are surfactant-free mixtures consisting of two immiscible fluids stabilized by solid particles. These emulsions offer prolonged stability to liquid droplets and resistance to coalescence. In recent decades, interest in Pickering emulsions has surged due to their superior properties compared to conventional emulsions, particularly their exceptional stability and versatility across various applications. The compatibility of stabilizing particles, along with their capacity to encapsulate and release active components, has led to diverse applications in the biomedical, pharmaceutical, nutraceutical, food, and cosmeceutical industries. With their unique structure, Pickering emulsions provide stability, biocompatibility, and environmental friendliness, making them promising candidates for drug delivery. Given the emphasis on the biocompatibility of particle stabilizers, the use of Pickering emulsions has increasingly focused on encapsulation and delivery, particularly for oral and topical administration. These emulsions can enhance the bioavailability of poorly soluble bioactive compounds in oral delivery systems while providing controlled release mechanisms. This review briefly explains the physicochemical properties, preparation methods, and characterization techniques of Pickering emulsions, highlighting their suitability for delivering bioactive compounds. We delve into recent advancements in the stability and formulation of Pickering emulsions and their applications for both oral and topical administration. The review discusses challenges encountered and identifies opportunities for future research, emphasizing their potential to improve stability and release during gastrointestinal digestion.

Keywords: Pickering emulsion; Emulsion delivery system; Bioactive compounds; Encapsulation.

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1. Introduction

Emulsions are a dispersed system consisting of several immiscible liquids, with one liquid present in the form of tiny droplets dispersed within another. Typically, these emulsions comprise water and oil (L. Chen et al., 2020). Since emulsions are inherently thermodynamically unstable, they are susceptible to degradation over time due to processes such as coalescence, flocculation, creaming, sedimentation and Ostwald ripening (Mwangi et al., 2020; Xia et al., 2021). Therefore, it is essential to use appropriate stabilizers to ensure their formulation and long-term stability (Albert et al., 2019).

Emulsions stabilized by solid particles are known as Pickering emulsions (Albert et al., 2019; J. Wu & Ma, 2016), a term derived from the pioneering research of Pickering (Pickering, 1907). The concept was initially introduced by Ramsden in the early 1900s (Deng et al., 2022; Ramsden W, 1903). Pickering emulsions have naturally existed for many years, as seen in milk and chylomicrons formed during digestion, which are stabilized by lactoprotein granules and enzyme- or lipoprotein granules, respectively. Significant research efforts have been devoted to understanding the

*Corresponding author.
E-mail address: *mona.miran@ut.ac.ir* (M. Miran).
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complexities of particle-stabilized interfaces and developing mathematical models to explain the thermodynamics and kinetics involved since the late 1970s. The interfacial structures of emulsions stabilized solely by solid particles were first visualized in 2002, thanks to advancements in low-temperature field emission scanning electron microscopy and confocal imaging (Ming et al., 2022). Since 2000, there has been a marked increase in publications focused on "Pickering emulsions" within the broader category of "emulsions," reflecting the growing interest in the unique properties these emulsions exhibit (Albert et al., 2019).

Pickering emulsions are stabilized by colloidal solid particles that prevent droplet coalescence (Harman et al., 2019; Peito et al., 2022). When these colloidal particles adsorb onto the surface of droplets, they form an irreversible interfacial barrier that inhibits droplet aggregation, thereby enhancing the stability of the system (Peito et al., 2022). For an effective Pickering emulsion system, the average size of the colloidal particles should be 10 to 100 times smaller than that of the emulsion droplets (Araiza-Calahorra et al., 2018).

Pickering emulsions can demonstrate remarkable stability, largely due to their strong resistance to coalescence and Ostwald ripening (Xia et al., 2021). These emulsions do not require surfactants, as micro- or nanoparticles can significantly reduce or eliminate the need for synthetic surfactants (Deng et al., 2022; Tai et al., 2020). Compared to traditional emulsions stabilized with surfactants, Pickering emulsions generally exhibit greater stability and offer several advantages, including reduced manufacturing costs, lower toxicity, fewer adverse effects and satisfactory biocompatibility (Y. Yang et al., 2017).

The versatility of Pickering emulsions allows for tailoring specific applications, thanks to the wide variety of potential combinations of different particle types as well as the aqueous and oily phases used (Albert et al., 2019). Their increasing use can be attributed to a broad spectrum of applications across various fields, including food (L. Chen et al., 2020; Xia et al., 2021), material science (Bao et al., 2022; H. Zhao et al., 2022; Zia et al., 2020) and biomedical/pharmaceutical areas (Beladjine et al., 2023; de Carvalho-Guimarães et al., 2022). These emulsions serve various purposes in the food industry, including fat replacement, food packaging and as bioactive delivery vehicles (C. Wu et al., 2025). Although numerous reviews have addressed the general characteristics and key parameters influencing the properties of Pickering emulsions (Gauthier & Capron, 2021; Keramat et al., 2022; J. Wu & Ma, 2016), some have specifically focused on their pharmaceutical applications (Frelichowska et al., 2009; Harman et al., 2019; Marto et al., 2016; Peito et al., 2022), drug delivery systems and encapsulation of bioactive compounds (Cahyana et al., 2022; G. V. C. Ramos et al., 2025; Teixé-Roig et al., 2023).

It is important to note that Pickering emulsions present a promising alternative in food and pharmaceutical formulations. They enhance overall product characteristics, provide desirable viscosity and promote long-term stability. For example, these emulsions offer an effective solution for preparing topical drugs and facilitating drug delivery to the skin (de Carvalho-Guimarães et al., 2022; Marto et al., 2016). Furthermore, due to their capacity for effective cargo encapsulation and release, Pickering emulsions have become valuable tools. Their unique structure confers stability, biocompatibility and environmental friendliness, making them particularly promising for drug delivery applications (Deng et al., 2022; Tai et al., 2020).

This review emphasizes the significance of Pickering emulsions in drug delivery, especially encapsulation of bioactive compounds. It aims to explain the advancements in their formulation and application, with special attention given to biocompatible particles such as polysaccharides, lignin, proteins, cyclodextrins and fat crystals, which enhance the stability and functionality of these emulsions. Moreover, this review discusses how Pickering emulsions improve the bioavailability of poorly soluble bioactive compounds.

2. Physicochemical properties of Pickering emulsions

2.1. Formation of Pickering emulsion

Pickering emulsions are created by homogenizing an aqueous phase with solid particles that adsorb at the oil-water interface. This process requires the solid particles to have partial wettability with both phases (de Carvalho-Guimarães et al., 2022; Gauthier & Capron, 2021). These particles enhance the interfacial area and reduce the energy between the immiscible liquids, contributing to emulsion stability by preventing coalescence and sedimentation through the formation of a three-dimensional particle network (McClements & Rao, 2011; Perrin et al., 2020; Shi et al., 2020).

Unlike traditional emulsions that use surfactants to lower interfacial energy, Pickering emulsions rely solely on a layer of solid particles (de Carvalho-Guimarães et al., 2022). The properties of these solid particles significantly influence the emulsion's stability, type, classification, and morphology (Y. Yang et al., 2017). Key characteristics of these particles including wettability, size, surface properties, and concentration, which are crucial in determining the stability and type of emulsion, whether it is water-in-oil (W/O) or oil-in-water (O/W) (Low et al., 2020; Tai et al., 2020; J. Wu & Ma, 2016).

Wettability, measured by the contact angle (θ) between the particle and the interface, plays a significant role in emulsion formation. Particles that are optimally wetted by both phases can effectively stabilize the emulsion. The most stable Pickering emulsions are generally formed when the three-phase contact angle is around 90°. This angle indicates an ideal balance in wettability, allowing solid particles to efficiently stabilize the interface between the oil and water phases. Particles with contact angles greater than 90° tend to form W/O emulsions due to their hydrophobic nature, while those with angles below 90° favor O/W emulsions because of their hydrophilic characteristics. Extreme contact angles close to 0° or 180° can hinder emulsion formation altogether (Deng et al., 2022; Harman et al., 2019; Low et al., 2020; Shi et al., 2020). Fig. 1 shows the position of a solid particle at the interface of a droplet and the contact angle of W/O and O/W emulsions.

The particle surface charge also affects interactions with the two phases, impacting emulsion stability. The formation of Pickering emulsions is influenced by critical factors such as the characteristics of the particles, the presence of various additives, and the properties of both the dispersed and continuous phases. Additionally, the size and shape of the particles can influence stabilization characteristics; smaller particles, for instance, can provide a larger surface area for stabilization (Gauthier & Capron, 2021; Low et al., 2020; D. Zhao et al., 2019). Other factors, like the pH of the aqueous phase, also play a vital role in emulsion stability (Low et al., 2020; Tai et al., 2020; J. Wu & Ma, 2016).

It is worth mentioning that modifying the interfacial properties for one aspect may sometimes conflict with another. For example, while improving wettability may enhance emulsion stability, it could also impair drug release. Similarly, positively charged particles may facilitate cellular uptake but limit tissue distribution due to

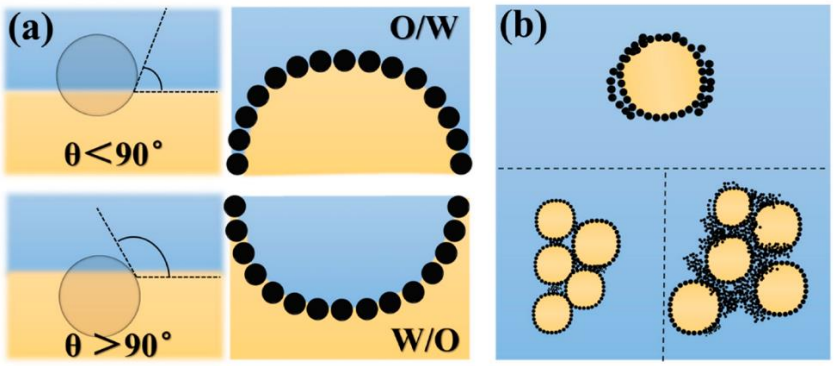


Fig. 1. This schematic illustrates the position of a solid particle at the interface of a droplet. (a) The contact angle (θ) is measured within the water phase (indicated as W in blue) for spherical particles located at the oil-water interface. In the upper part of the figure, there is an oil-in-water (O/W) emulsion (θ < 90°), while the lower part depicts a water-in-oil (W/O) emulsion (θ > 90°). The corresponding types of emulsions are labeled in the central section. (b) Structural characteristics of Pickering emulsions. This figure has been reproduced, with gratitude, from M. Zhang et al. (2023) and is used with permission under the Open Access Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

electrostatic interactions with cells at the injection sites. It is essential to note that optimizing interfacial properties for one aspect may conflict with another; enhancing wettability can improve droplet stability but may hinder drug release permeability (Ming et al., 2022).

2.2. *Solid particles for stabilizing Pickering emulsions*

A wide variety of inorganic and organic particles are utilized to stabilize Pickering emulsions. These include polysaccharides, lignin, and proteins (Albert et al., 2019). Specific examples of polysaccharides are starch (Ge et al., 2017; Marto et al., 2015; X. Song et al., 2020; F. Zhu, 2019), cellulose (Z. Li et al., 2018; Low et al., 2019; Tang et al., 2018), pectin (Cen et al., 2023), xylan (S. Yu et al., 2023) and chitin/chitosan (Ben Cheikh et al., 2021; Naji-Tabasi et al., 2024). Proteins, those derived from plants, can be found in the cotyledons of legume seeds and the endosperms of cereal grains. They are classified into categories such as water-soluble albumins, alcohol-soluble prolamins, salt-soluble globulins and acid/alkaline-soluble glutelins. Recent efforts have also focused on utilizing prolamin-rich cereals to generate colloidal particles (Sarkar & Dickinson, 2020). Common sources of these proteins include pea (S. Zhang et al., 2020), soy, flaxseed, quinoa, and lupin (Jiao et al., 2018; Ribeiro et al., 2021; Shi et al., 2020; H. Yang et al., 2020), along with commonly used proteins like gliadin, gluten (Mwangi et al., 2020) and zein (R. Meng et al., 2020). Animal proteins, such as lactoferrin (Sarkar et al., 2018), gelatin, whey protein, casein, β-lactoglobulin, and ovalbumin, are also used (Jiao et al., 2018; Ribeiro et al., 2021; Shi et al., 2020; H. Yang et al., 2020).

Additional categories of stabilizing particles include cyclodextrin (a family of cyclic oligosaccharides obtained from starch through enzymatic conversion) (Cheong et al., 2016; Jug et al., 2021; Kou et al., 2023; C. Liu et al., 2023; C. Yuan et al., 2021) and fat crystals (Rousseau, 2013; Tenorio-Garcia et al., 2023). There are also synthetic polymer-based particles that are biocompatible, such as polylactic acid, polyglycolic acid, and polyethylene oxide (Albert et al., 2019; Harman et al., 2019; Jiang et al., 2020). Other examples include drug nanocrystals/nanoparticles (Z. Wang et al., 2022; T. Yi et al., 2017; J. Zhang et al., 2024), as well as microbial cells like yeasts and probiotics (Firoozmand & Rousseau, 2015; Nejadmansouri et al., 2023). Natural clays (Calabrese et al., 2018; Lu et al., 2021) and silica (SiO_2) particles are also effective stabilizers for Pickering emulsions (Peito et al., 2022; Taherpour & Hashemi, 2018). A review of some solid particles currently used as stabilizing agents for Pickering emulsions can be found in Table 1.

Solid particles are capable of stabilizing not only traditional O/W and W/O emulsions but also more complex structures like water-in-water (W/W) (Dickinson, 2019; Gonzalez-Jordan et al., 2018) and oil-in-oil (O/O) emulsions (Zia et al., 2020). Multiple emulsions, including W/O/W and O/W/O, can be synthesized in one or two steps using different particles (Keramat et al., 2022; Peito et al., 2022; H. Zhao et al., 2022).

In W/O emulsions, hydrophilic compounds are encapsulated, while hydrophobic compounds are encapsulated in O/W emulsions. These multiple emulsions offer advantages like taste masking and controlled release; however, they may encounter stability challenges due to their complex structure and thermodynamic instability (Albert et al., 2019; Ming et al., 2022).

Notably, Pickering emulsions provide similar benefits to surfactant-stabilized emulsions, including easier preparation and long-term stability (Albert et al., 2019; H. Zhao et al., 2022). Additionally, high internal phase emulsions (HIPEs) (Gao et al., 2021; Kramer et al., 2021) and Pickering nanoemulsions (Ding et al., 2023; Kramer et al., 2021) have been developed. HIPEs feature a greater internal phase ratio than conventional emulsions, with ratios starting at 0.74. High internal phase Pickering emulsions (HIPPEs) offer improved properties, such as reduced stabilizer use, decreased environmental pollution, and enhanced sustainability (Gao et al., 2021; Shi et al., 2020; Silverstein, 2013).

3. Tools and methods for producing and analyzing Pickering emulsions

Traditional emulsification techniques, often reliant on synthetic emulsifiers. Conventional emulsifiers are mainly small-molecule surfactants; however, some of them can pose health risks, limiting their use in food and pharmaceuticals (L. Chen et al., 2020), driving demand for natural alternatives (Teixé-Roig et al., 2023). As a result, advances in technology have led to innovative methods designed to reduce reliance on traditional emulsifying agents (de Carvalho-Guimarães et al., 2022). Researchers can optimize Pickering emulsions for specific applications, such as delivering bioactive compounds, by incorporating solid particles into the suspension (Albert et al., 2019; J. Chen et al., 2023; T. Zhang et al., 2022).

Various emulsification methods can be employed; the most popular used to produce Pickering emulsions include:

- High-speed homogenization: Uses a rotor-stator to create high shear forces for particle dispersion (J. Chen et al., 2023; Kempin et al., 2020; D. M. Ramos et al., 2023).
- High-pressure homogenization: Forces the emulsion through a narrow gap, enhancing mixing and stability (Benetti et al., 2019; Z. Ren et al., 2020).
- Ultrasound processing: Employs cavitation bubbles to generate shear forces that stabilize the emulsion (Benetti et al., 2019; D. M. Ramos et al., 2023).

Innovative techniques such as membrane emulsification (Ekanem et al., 2022; Q. Yuan & Williams, 2016) and microfluidic emulsification (H. Li et al., 2023; Sun et al., 2021; W. Wang et al., 2023) offer precise control over droplet size and distribution.

To analyze the formation and stability of Pickering emulsions, researchers utilize various measurement methods, including laser diffraction, microscopy (optical, electron and atomic force microscopy) (Marto et al., 2016; Tai et al., 2020). Additionally, the evaluation of surface coverage, droplet charge and color can be considered for measurement. For instance, the zeta potential analysis of the droplets can indicate their stability; higher absolute values typically correlate with greater stability against coalescence (Gauthier & Capron, 2021; Low et al., 2020). Evaluating physical stability includes assessing coalescence and gravitational separation, using methods like accelerated coalescence tests and analytical centrifugation (Low et al., 2020; Marto et al., 2016; Tai et al., 2020).

Advanced imaging and characterization techniques, such as cryoelectron microscopy and super-resolution confocal imaging, enhance the understanding of single droplet behavior, aiding in the delivery of bioactive compounds (Ming et al., 2022).

4. Pickering emulsions in delivery systems

The applications of Pickering emulsions have gained significant interest due to advancements in particle synthesis and the discovery of new colloids with tunable surface properties. These emulsions are known for their stability, high payload capacity and the biocompatibility of particle stabilizers, making them valuable in the pharmaceutical and food industries. Their unique structure supports effective drug delivery through high-capacity encapsulation, stability and environmental friendliness (McClements, 2018; McClements et al., 2007).

In biomedical and pharmaceutical contexts, Pickering emulsions are primarily used for drug encapsulation and delivery, including topical and oral applications (de Carvalho-Guimarães et al., 2022; Marto et al., 2016; Ming et al., 2022). Their potential for enhancing drug loading, delivery and controlled release arises from optimizing particle characteristics and interfacial assembly, which is crucial for biological interactions (Beladjine et al., 2023; Chiappini et al., 2015; Keramat et al., 2022; Mwangi et al., 2020; Shi et al., 2020). The stability and aggregation of particles at the interface significantly influence the structure and functional properties essential for effective drug delivery (Ming et al., 2022; J. Wu & Ma, 2016).

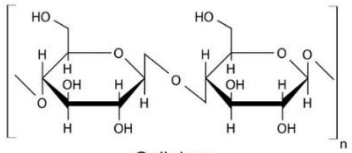
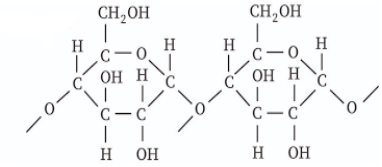
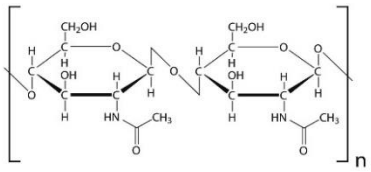
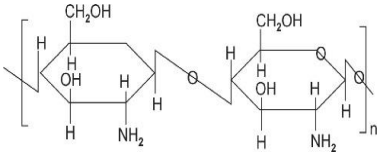
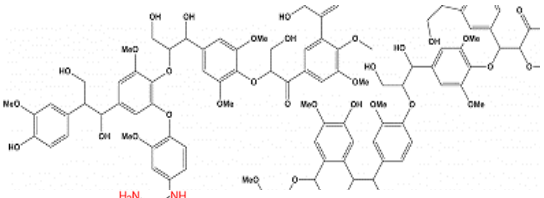
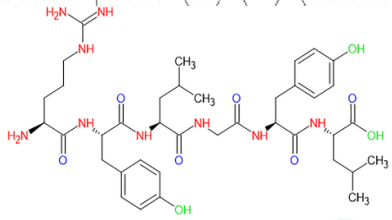
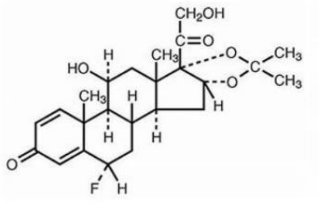
As natural, biodegradable and safe systems, Pickering emulsions show promise across various fields (Cahyana et al., 2022). Encapsulating bioactive compounds for food use and pharmaceutical (edible products) requires food-grade materials, primarily composed of protein/polysaccharide particles, lipid crystals, flavonoids and food-grade wax. The absence of surfactants enhances the eco-friendliness and acceptance of these encapsulation systems (Pickering emulsions). However, Pickering emulsions stabilized by inorganic particles should be avoided due to safety concerns (Boostani et al., 2024; C. Wu et al., 2025). Natural food-grade particles are abundant and can be easily extracted, allowing for diverse Pickering emulsions with various features. The selection of biocompatible, non-toxic oils for food-grade emulsions is also critical (Albert et al., 2019), such as olive oil (Sharkawy et al., 2020), sunflower oil (Sarkar et al., 2018; S. Zhang et al., 2020), red palm olein (Low et al., 2019), soybean oil, castor oil, coconut oil, glycerides (Albert et al., 2019), kenaf seed oil (Cheong et al., 2016), corn oil, camellia oil, lard oil and fish oil (C. Liu et al., 2023).

Recent advancements in drug delivery technologies have unveiled new pathways for delivering therapeutic agents, facilitating their passage through biological barriers and targeting specific organs or cells (Haji et al., 2022; Ming et al., 2022; Tai et al., 2020). Future developments in Pickering emulsions are expected to focus on a comprehensive design that integrates droplet formation, targeting, internalization and drug release for optimal effectiveness (Ming et al., 2022).

Bioactive compounds include diverse chemical structures such as polysaccharides, fibers, polyunsaturated fatty acids (PUFAs), phenolic compounds (e.g., curcumin, resveratrol and flavonoids), proteins, peptides, carotenoids and essential oils. Despite their health benefits, including reducing risks of cardiovascular diseases, cancer and diabetes, their application is limited due to low bioavailability and susceptibility to degradation (McClements, 2018; Mwangi et al., 2020; G. V. C. Ramos et al., 2025; Zabot et al., 2022). Encapsulation techniques can enhance their stability and functionality. Examples include nanoparticles, emulsions, hydrogels, bionanocomposite, nanofibers and liposomes (Kamandloo et al., 2026; McClements, 2018; Moghadam et al., 2024; Umar et al., 2025; Zabot et al., 2022). Emulsion-based delivery systems, including conventional emulsions, nanoemulsions, highly concentrated emulsions, double emulsions, gelled emulsions, multilayer emulsions and combination systems, which have been widely utilized. These delivery systems have shown high stability and improved bioaccessibility for embedded compounds (G. V. C. Ramos et al., 2025; Teixé-Roig et al., 2023). The following research highlights innovations in stabilizing emulsions using biocompatible materials, showcasing potential in the delivery of bioactive compounds.

Curcumin is a hydrophobic crystalline polyphenol known for its anti-inflammatory, anticancer and antioxidant properties, but its low solubility and extensive metabolization in the gastrointestinal tract limit its gastrointestinal absorption and bioavailability (Farshchi-Andisi et al., 2025; Miran et al., 2021; Saffarionpour & Diosady, 2022). The preparation of Pickering emulsions with stabilized nanoparticles may enhance curcumin's stability and controlled release. Nanoparticles from minerals, proteins and polysaccharides can stabilize curcumin emulsions, increasing their bioaccessibility. Recent studies highlight methods for preparing curcumin Pickering emulsions for applications in pharmaceuticals and food fortification (Saffarionpour & Diosady, 2022). In research by Kan et al. (2023), curcumin was encapsulated in hydrophilic bovine bone gelatin nanoparticles, resulting in high encapsulation efficiency (93.9%) and better emulsifying performance compared to standard methods, highlighting the importance of pH in droplet size and stability. This study suggests that the pH-cycle method may effectively develop protein nanoparticles for stabilizing Pickering emulsions (Kan et al., 2023). Additionally, hydrolyzed rice glutelin nanoparticles were fabricated using varying ethanol concentrations by Yang et al. (2023) to study their properties for stabilizing Pickering emulsions.

Table 1. Characterization of some solid particles as stabilizing agents, including polysaccharide-, lignin- and protein-based particles.

Stabilizing agents	Type	Structure	Potential application	Particle Size	References
Cellulose nanocrystals Pickering emulsions droplets in alginate beads	Polysaccharide	 Cellulose	Hydrophobic drug delivery	≈259.6 nm	(Yan et al., 2019)
Starch amphiphilic pH-sensitive starch nanoparticles	Polysaccharide		Drug carriers	≈140 nm	(Sufi-Maragheh et al., 2019)
Starch			Topical antibiotic delivery	-	(Marto et al., 2019)
Chitin nanocrystals	Polysaccharide		Replacement of synthetic surfactants		(Ben Cheikh et al., 2021)
Pistacia atlantica Pickering emulsion-filled chitosan gel	Polysaccharide		Targeted delivery of curcumin	-	(Naji-Tabasi et al., 2024)
Lignin/chitosan oligosaccharide particles	Biopolymer (lignin/ oligosaccharides)	-	Synergistic cancer therapy	≈176 - 790 nm	(K. Chen et al., 2021)
Lignin-based nanoparticles	Lignin (Complex organic polymers)		Controlled release of trans-resveratrol.	-	(Dai et al., 2019)
Casein-caffeic acid covalent nanoparticles	Protein-Polyphenol		Enhancing bioavailability of curcumin	≈171.11 nm	(B. Zhang et al., 2023)
Whey protein microgels	Protein		Delaying the rate of digestion fat	≈700-1200 nm	(S. Chen et al., 2022)
Camellia oleifera seed cake protein	Protein	-	Delivery system	≈1103 nm - 2302 nm	(Cui et al., 2023)

The optimal concentration for stability was found to be 50% ethanol, improving photochemical stability of curcumin-loaded emulsions. Another study focused on co-encapsulating curcumin and β-carotene in Pickering emulsions stabilized by complex nanoparticles. The optimal conditions were found at 2.0% particle concentration, 100 MPa pressure and 60°C temperature. Higher particle concentrations and temperatures reduced the bioaccessibility of the nutrients, while lower pressures enhanced lipolysis. This approach can show promise for the industrial production of functional foods and dietary supplements (Wei et al., 2022).

The application of antioxidant-loaded protein-polysaccharide nanoparticles for stabilizing and delivering curcumin in HIPPEs is limited. A study created resveratrol-loaded α-lactalbumin-chitosan nanoparticles for curcumin delivery, showing effective adsorption at the oil/water interface and forming a gel-like structure around oil droplets. These emulsions maintained excellent physical stability, with curcumin retention at 75.4% after 30 days, compared to 63.9% with α-lactalbumin-chitosan particles. However, both types of emulsions exhibited lower lipolysis compared to conventional emulsions, indicating that resveratrol may inhibit lipolysis (Fan et al., 2022).

W. Wang et al. (2025) developed stable oil-in-water Pickering emulsions with curcumin to enhance its stability and digestive characteristics. Using a Type 2 Diabetes mouse model, the curcumin-loaded emulsions demonstrated high encapsulation efficiency (96.7%) and improved bioavailability (25.5%–36.4%), showing enhanced antioxidant and hypoglycemic activity compared to oil-soluble curcumin. Animal studies revealed these emulsions improved glucose metabolism and supported tissue repair in the pancreas, liver and colon while reducing oxidative stress and activating the PI3K/Akt (phosphatidylinositol 3-kinase/Akt or protein Kinase B) pathway (W. Wang et al., 2025). In another study, alkali lignin was modified to synthesize quaternized alkali lignin, creating pH-responsive oil-in-water Pickering emulsions. These emulsions were stable at pH 5−9, but demulsified outside this range, allowing for reversible emulsification. Curcumin was used as a model drug, achieving a 50.08% encapsulation rate, with its release being pH-dependent. The lignin emulsion also protected curcumin from UV degradation (Y. Li et al., 2024).

A study focused on resveratrol encapsulated in Pickering emulsions stabilized by tea water-insoluble protein nanoparticles. It reported a high zeta potential and encapsulation efficiency over 85%. The bioavailability of resveratrol in these emulsions was doubled compared to unencapsulated forms after simulated digestion, highlighting the potential for using Pickering emulsions in delivering nutraceuticals (Z. Ren et al., 2023). Additionally, in another study by Noor et al. (2025), cellulose nanocrystals were used to stabilize hexadecane-water emulsions for encapsulating resveratrol, demonstrating that the molecular release could be controlled by particle surface coverage. The surface coverage correlated with resveratrol concentration instead of ionic strength, showing a linear relationship with release rates.

Rutin, a bioactive flavonoid with poor water solubility, was encapsulated in oil-in-water emulsions of varying particle sizes (small: 0.56 μm, medium: 0.73 μm, large: 2.32 μm) by Fu et al. (2023). Smaller particle sizes improved emulsion stability and reduced rutin loss during 28 days of storage. The loss of the flavonoid was mainly due to photodegradation. The degradation rate constant decreased and half-life increased with smaller droplets, indicating better light scattering and encapsulation (Fu et al., 2023). Additionally, Pickering emulsions stabilized with octenyl succinic acid-modified starch nanoparticles (from quinoa, maize and potato) effectively encapsulated rutin, showing stability without coalescence or Ostwald ripening. Studies confirmed strong interactions and retention of rutin, with high encapsulation efficiencies (99.3% for quinoa starch, 96.1% for maize and 97.2% for potato) after 31 days (Remanan & Zhu, 2023).

A study by L. Li et al. (2024) explored soy protein isolate-xanthan gum complexes as emulsifiers for Pickering emulsions delivering quercetin. Results showed that these complexes formed a gel network, stabilizing the emulsion and preventing droplet aggregation. Post-digestion analysis indicated increased bioaccessibility of quercetin in these complexes stabilized emulsions compared to those stabilized with only soy protein isolate, highlighting the Pickering emulsion as a promising delivery system.

β-carotene is valuable for its physiological functions but struggles with stability and bioavailability in functional foods. A study focused on HIPPEs stabilized by peanut protein isolate and cellulose nanocrystals for encapsulating β-carotene to prevent degradation. Cellulose nanocrystals enhanced the emulsifying capability of peanut protein isolate, with the peanut protein isolate/ACNCs (cellulose nanocrystals that were prepared by ammonium persulfate oxidation) complex showing the best stability after 30 days. These emulsions demonstrated excellent retention of β-carotene under thermal, UV and oxidative conditions (Nie et al., 2024).

Another study developed a Pickering emulsion delivery system using whey protein isolate (WPI) and proanthocyanidins to encapsulate β-carotene. The addition of proanthocyanidins significantly improved UV stability and encapsulation efficiency. *In vitro* digestion showed that the WPI- proanthocyanidins complex formed a more stable emulsion, reduced lipid hydrolysis and allowed for sustained β-carotene release. IEC-6 cell tests indicated that β-carotene-loaded emulsions enhanced cell viability and reduced intracellular reactive oxygen species (ROS), with oligomeric proanthocyanidins providing superior antioxidant effects (Qin et al., 2025). Research by Zhou et al. (2024) involved modifying zein with curcumin to create ternary nanoparticles with polysaccharides for antioxidant Pickering emulsions. The addition of curcumin significantly improved β-carotene retention and reduced lipid oxidation, while gum karaya enhanced the bioaccessibility of β-carotene during digestion (Zhou et al., 2024). Lastly, chitosan particles were explored for their potential to create Pickering emulsions with high encapsulation efficiency. The study evaluated the effects of various factors on emulsion stability, revealing that smaller droplet sizes improved β-carotene protection. Optimal conditions for preparing chitosan Pickering emulsions included a pH of 6.5 and a chitosan concentration of 1.0 wt%. Overall, these findings highlight the effectiveness of different protein and polysaccharide systems in developing stable emulsions for lipophilic bioactive compounds like β-carotene (Yin et al., 2024).

In a study, Pickering emulsions made from resveratrol-loaded gliadin nanoparticles and oxidized chitin nanocrystals protected fish oil from oxidation. Increasing gliadin nanoparticles/oxidized chitin nanocrystals concentrations reduced droplet size and improved emulsion stability regarding pH, ionic strength, temperature and storage time. These emulsions showed enhanced antioxidant capacity and maintained lower peroxide and acid values compared to controls during a 14-day oxidation test. They also protected fish oil from gastric juices, promoting absorption of omega-3 fatty acids, making them a promising option for food industry applications (Zeng et al., 2024).

Table 2. Studies on Pickering emulsions stabilized by polysaccharide-based, protein-based particles, fat crystals and cyclodextrin particles for encapsulation of bioactive compounds.

Particles			Emulsion	Bioactive compounds	Route of administration	References
Type of particles for stabilizing	**Composition**	**Characterization (Shape and size)**	**Characterization (Type, phase and droplet size)**			
Polysaccharide-based particles	Chitosan and multiple seaweed polyphenols (*Laminaria japonica* and *Ascophyllum nodosum* polyphenols)	≈100 - 1000 μm	O/W, Aqueous: water Oil: corn oil	β-Carotene	-	(W. Meng et al., 2024)
Polysaccharide/protein-based particles	Pea protein isolate / high methoxyl pectin	Spherical ≈379 nm	O/W, Aqueous: water Oil: corn oil	β-carotene	-	(J. Yi et al., 2021)
Polysaccharide-based particles	Carboxymethyl cellulose/ cationic chitosan	≈980, 1470 and 2320 nm	O/W, Aqueous: water Oil: coconut oil	Curcumin	-	(X. Zhu et al., 2021)
Polysaccharide -based particles	Hydrophobic modified calcium alginate	≈ 316-412 nm	O/W, Aqueous: water Oil: corn oil	Curcumin	Oral	(W. Zhang et al., 2018)
Protein-based particles	α-Lactalbumin self-assembled nanoparticles	Spherical ≈1 μm	O/W, Aqueous: water Oil: medium-chain triglyceride	Curcumin	Oral	(B. Liu et al., 2021)
Protein/ oligosaccharide-based particles	Glycated proteins and chitooligosaccharides	Spherical Dependent on the amount of protein, ≈132 - 1480 nm	O/W, Aqueous: water Oil: medium-chain triglyceride	Curcumin	-	(J. Yu et al., 2021)
Polysaccharide/-based particles	Nanocellulosic	Spherical ≈150 nm	O/W, Aqueous: water Oil: coconut oil	Coumarin and curcumin	-	(Asabuwa Ngwabebhoh et al., 2018)
α-cyclodextrin	Octenyl succinic anhydride modified α-cyclodextrins	Polygonal ≈400–800 nm	O/W, Aqueous: water Oil: medium chain triglyceride	Curcumin	-	(Hao et al., 2024)
Fat crystals	Crystal polymorphism solid lipid particles	Spherical	O/W, Aqueous: water Oil: corn oil	Curcumin	Oral	(Y. Song et al., 2023)
Fat crystals	Solid lipid nanoparticles using medium- and long chain diacylglycerol or glycerol tripalmitate as lipid matrix and three kinds of surfactants including Tween 20, quillaja saponin and rhamnolipid	Spherical MLCD-T20 (160.65 nm), MLCD-SQ SLNs (376.93 nm), respectively, TP-T20 (457.03 nm) and TP-SQ SLNs (514.03 nm)	O/W, Aqueous: water Oil: Soybean oil ≈ 200–500 nm	Curcumin	-	(Y. Yu et al., 2023)
Polysaccharide-based particles	Octenylsuccinate quinoa starch granule	Granule ≈25.60 - 43.90 μm	O/W, Aqueous: water Oil: corn oil	Lutein	-	(S. Li et al., 2020)
Polysaccharide-based particles	Chitosan nanoparticles	Spherical ≈38.4 nm	O/W, Aqueous: water Oil: soybean oil	Hesperidin	Topical	(Dammak & do Amaral Sobral, 2018)

Polysaccharide-based particles	Chitosan/gum arabic nanoparticles	Spherical ≈109 nm	O/W, Aqueous: water Oil: olive oil	Resveratrol	Topical	(Sharkawy et al., 2020)
Polysaccharide-based particles	Starch	Spherical ≈145.20 nm	O/W, Aqueous: water Oil: various oil	Resveratrol	Topical	(Bi et al., 2021)
Polysaccharide-based particles	OSA-modified starch granules	Granules ≈0.85 µm	O/W, Aqueous: water Oil: orange oil	Resveratrol	-	(Matos et al., 2018)
Polysaccharide-based particles	Waxy maize starch nanocrystal and chitosan	Colloidal ≈42 nm	O/W, Aqueous: water Oil: tricaprylin	Resveratrol	-	(Jo et al., 2021)
Protein/ polysaccharide-based nanoparticles	Zein/gum Arabic	Spherical ≈27.95 - 69.98 µm	O/W, Aqueous: water Oil: soybean oil	Thymol	-	(J. Li et al., 2018)
Polysaccharide/Protein-based nano-complexes	Almond gum / WPI nano-complexes	≈313 nm	O/W, Aqueous: water Oil: tricaprylin	Thymol	-	(Doost et al., 2019)
Cyclodextrin particles	β-Cyclodextrin/ vitamin E assembled shells	Sheet-like ≈1000 nm	O/W, Aqueous: water Oil: fish oil	PUFA	Oral	(Xi et al., 2019)

Continued.

G. Ren et al. (2023) fabricated antioxidant Pickering emulsions using resveratrol-grafted zein and quaternary ammonium chitosan. These emulsions demonstrated excellent stability and effective delivery of peppermint oil while retaining high antioxidant activity (G. Ren et al., 2023). Moreover, Pickering emulsions are a promising vehicle for essential oils like cinnamaldehyde, eugenol and limonene, which possess antifungal, antibacterial, antiviral and antioxidant properties. However, essential oils are prone to evaporation, light and oxygen degradation and low solubility, which limits their industrial use. Research indicates that essential oils in Pickering emulsions are less susceptible to evaporation and oxidation, exhibit enhanced antibacterial activity and have increased solubility (Cahyana et al., 2022). W. Li et al. (2023) aimed to create a new antimicrobial Pickering emulsion using star anise essential oil and bio-based nanoparticles made of zein and pectin loaded with thymol. The nanoparticles were produced as spherical particles with an average diameter of 200 nm. The study examined how nanoparticles' concentration, oil phase ratio and storage time influenced emulsion stability. Results showed that the Pickering emulsion significantly inhibited *Escherichia coli* and *Staphylococcus aureus*, achieving almost 7 log colony-forming unit/g reduction at 36 hours, twice the effectiveness of thymol or the individual essential oils (W. Li et al., 2023).

Table 2 summarizes research on using Pickering emulsions for encapsulation, highlighting their role in enhancing the bioavailability of poorly soluble compounds, such as curcumin and their applications across various administration routes. This table highlights innovative strategies and findings in the field, specifically focusing on Pickering emulsions stabilized by polysaccharide-based, protein-based particles, fat crystals and cyclodextrin particles.

5. Conclusion

Unlike traditional emulsions, Pickering emulsions employ solid particles as emulsifiers, which are irreversibly adsorbed at the oil-water interface, effectively preventing droplet coalescence. While simple emulsions remain the most common carriers for encapsulating bioactive compounds, bio-based emulsion systems like Pickering emulsions have emerged as effective colloidal delivery systems for encapsulation and controlled release.

Pickering emulsions enhance the stability and bioavailability of lipophilic active compounds, which often suffer from low solubility and instability during processing and digestion. The unique structure of Pickering emulsions, combined with their biocompatibility and environmental friendliness, makes them ideal for oral and topical delivery systems. Recent years have highlighted food-grade, particle-stabilized Pickering emulsions as promising candidates in the food and pharmaceutical industries (for edible usage) due to their superior stability and ability to encapsulate bioactive ingredients.

They offer stability, high payload capacity, and biocompatibility, effectively encapsulating both lipophilic and hydrophobic bioactive compounds, thus enhancing their solubility and bioavailability. Challenges remain in optimizing particle properties for enhanced stability and controlled release while ensuring the biocompatibility of both the particles and the oils used. Recent advancements in particle synthesis and imaging techniques have improved our understanding of their interactions and behaviors, paving the way for innovative applications in delivery systems. Future research can target a comprehensive design that integrates all aspects of the delivery process.

Conflict of interest

The authors declare that there is no conflict of interest.

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