

## Mini Review: The Effect Of Stabilizer Particle Types On The Characteristics Of Pickering Emulsion

I Made Fajar Juliantara\*, Ni Made Dwi Angga Yani

Department of Agricultural Industrial Technology, Faculty of Agricultural Technology, Udayana University

### ABSTRACT

Pickering emulsions are colloidal dispersion systems in which solid particles, rather than conventional surfactants, adsorb irreversibly at the oil–water interface to confer kinetic stability. The growing demand for biocompatible, non-toxic, and environmentally sustainable emulsification systems has driven substantial research interest in diverse categories of stabilizer particles. This literature review synthesizes findings from twenty-one primary research articles and review publications to critically evaluate how the type of solid stabilizer particle governs the physicochemical characteristics of Pickering emulsions, including droplet size, zeta potential, viscosity, and long-term stability. Particle types examined include polysaccharide-derived nanocrystals (cellulose nanocrystals and nanochitin), protein-based particles (chitosan, whey protein, zein, and soy protein isolate), starch nanoparticles, inorganic nanoparticles (silica and hydroxyapatite), and composite or hybrid particles. The review further examines how formulation variables—specifically particle wettability, particle size and concentration, pH, ionic strength, and mechanical emulsification conditions—modulate emulsion characteristics. Key findings indicate that particles with contact angles near 90° and intermediate wettability generate the most stable emulsions, that increasing particle concentration consistently reduces globule diameter, and that pH manipulation governs surface charge and aggregation behavior. Applications of Pickering emulsions in food encapsulation, active packaging, cosmetics, pharmaceutical delivery, and agriculture are discussed. Future research directions include scale-up feasibility, in vivo bioaccessibility validation, and the rational engineering of multi-functional hybrid particles.

**Keywords:** Pickering emulsion; solid particle stabilizer; emulsion stability; wettability; biopolymer nanoparticles.

### INTRODUCTION

An emulsion is a thermodynamically unstable system composed of two immiscible liquid phases—typically oil and water—in which one phase is dispersed as droplets within the other. Conventional emulsions rely on amphiphilic surfactants or macromolecular emulsifiers to reduce interfacial tension and delay phase separation. Surfactants adsorb at the oil–water interface and form a molecular monolayer that resists coalescence. However, synthetic surfactants carry well-documented drawbacks: they are susceptible to environmental conditions such as temperature, pH, and electrolyte concentration; they may cause adverse biological effects; and increasingly stringent regulatory frameworks limit their use in food and pharmaceutical products [2].

Pickering emulsions present a mechanistically distinct alternative. First documented systematically by

Pickering in 1907, these systems employ solid micro- or nanoparticles as the sole stabilizing agent. Solid particles adsorb at the oil–water interface with a detachment energy that can be several orders of magnitude greater than the thermal energy  $kT$ , rendering adsorption effectively irreversible under standard conditions [7]. This irreversibility translates into emulsions with markedly superior resistance to coalescence and Ostwald ripening compared to their surfactant-stabilized counterparts. Pickering emulsions also require smaller quantities of stabilizing agent, and many suitable particles originate from renewable, biodegradable, and food-grade biological sources—making them attractive for clean-label formulations [2,6].

Despite their conceptual simplicity, Pickering emulsions involve a complex interplay between particle properties—wettability, size, shape, concentration, and surface charge—and process

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

parameters such as homogenization energy, shear rate, oil-to-water ratio, pH, and ionic strength. The type of stabilizer particle is the primary determinant of emulsion characteristics because it dictates how particles position themselves at the interface, how densely they pack, and how robust the interfacial film becomes [7,10]. Biopolymer-derived particles such as cellulose nanocrystals (CNC), nanochitin, chitosan nanoparticles, starch nanoparticles, and protein aggregates have attracted particular attention because they combine functional emulsifying performance with biocompatibility and biodegradability. Inorganic particles—notably silica and hydroxyapatite—offer complementary advantages including tunable surface chemistry and high mechanical rigidity [7].

The scope of this literature review encompasses twenty-one peer-reviewed studies published between 2020 and 2025. The primary objective is to consolidate current knowledge on how different categories of stabilizer particles determine the physical and functional characteristics of Pickering emulsions, including droplet morphology, size distribution, zeta potential, rheological behavior, and storage stability. Secondary objectives are to analyze the mechanistic basis of stabilization, examine how formulation variables modulate emulsion performance, and survey current and emerging applications across food science, pharmaceuticals, cosmetics, and agriculture. The review closes with recommendations for future research targeting the remaining challenges in large-scale production, particle standardization, and *in vivo* efficacy validation

### Stabilization Mechanism Of Pickering Emulsions:

The stabilization of Pickering emulsions originates from the partial wettability of solid particles by both the oil and water phases. When a spherical particle of radius  $r$  adsorbs at an oil–water interface with interfacial tension  $\gamma_{ow}$ , the energy required to detach that particle from the interface is expressed by the Young equation relationship:

$$E = \pi r^2 \gamma_{ow} (1 \pm \cos\theta)^2$$

where  $\theta$  is the three-phase contact angle measured through the aqueous phase. This energy can reach values in the range of  $10^5$ – $10^7$  kT for particles with radii of 10–100 nm and contact angles approaching

$90^\circ$ , explaining why particle adsorption is effectively irreversible and why Pickering emulsions are kinetically far more stable than those stabilized by molecular surfactants [7,9].

Contact angle governs both the position of the particle at the interface and the type of emulsion formed. Hydrophilic particles with  $\theta < 90^\circ$  reside predominantly in the aqueous phase and preferentially stabilize oil-in-water (O/W) emulsions, while hydrophobic particles with  $\theta > 90^\circ$  favor the oil phase and tend to stabilize water-in-oil (W/O) emulsions [4,6]. Particles with  $\theta$  closest to  $90^\circ$  achieve the deepest penetration across the interface, maximizing the contact area with both phases and therefore generating the highest detachment energy and greatest stability [7]. Young's equation defines the contact angle as  $\cos\theta = (\gamma_{so} - \gamma_{sw})/\gamma_{ow}$ , where  $\gamma_{so}$  and  $\gamma_{sw}$  are the solid–oil and solid–water interfacial tensions, respectively [6].

In practice, biopolymer-derived particles are inherently hydrophilic due to abundant hydroxyl and amino surface groups. Their contact angles typically lie between  $20^\circ$  and  $70^\circ$ , placing them below the ideal value for maximum stability. Several studies have shown that surface modification—for example, acetylation of cellulose, adsorption of chitosan onto silica, or formation of protein–polysaccharide conjugates—shifts the contact angle toward  $90^\circ$  and markedly improves emulsifying performance [5,11,16]. Ebrahimi and co-workers demonstrated that CNC derived from hazelnut shells possessed amphiphilic character confirmed by contact angle and interfacial tension measurements, which enabled them to adsorb at the oil–water interface and form stable O/W Pickering emulsions without chemical modification [3].

Beyond contact angle, three additional mechanisms contribute to Pickering stabilization: (1) steric repulsion arising from the dense particle monolayer that physically blocks droplet approach; (2) electrostatic repulsion generated by the surface charge of particles dispersed in the continuous phase, which prevents flocculation; and (3) network formation when excess particles bridge adjacent droplets or form a gel-like matrix in the continuous phase [2,8]. The relative contribution of each mechanism depends on particle type, concentration, and environmental

conditions. At high particle concentrations, interfacial arrest—a rheological transition in which the particle-laden interface becomes solid-like—was reported by Guo and colleagues for CNC/nanochitin heteroaggregates under net cationic conditions, resulting in non-deformable droplets with no detectable creaming over nine months [5].

Mechanical emulsification methods also influence the adsorption kinetics and packing density of particles at the interface. Gao and co-workers systematically compared rotor–stator homogenization, ultrasonic emulsification, and their combination using nano-silica particles. They found that ultrasound generates intense cavitation forces that break oil into finer

droplets and simultaneously accelerate particle diffusion toward the nascent interface, resulting in smaller droplet sizes and narrower distributions than rotor–stator treatment alone [4]. The combination of both methods at optimized parameters produced the finest emulsions, demonstrating that process energy directly modulates interfacial coverage and thus emulsion quality [4].

### Types Of Stabilizer Particles:

Table 1 provides an overview of the principal stabilizer particle categories identified across the reviewed literature, including their origin, preparation method, and key functional properties.

Particle Type	Source / Preparation Method	Key Properties	Representative Reference
Chitosan NPs	Deacetylation of chitin; ionic gelation with tripolyphosphate (STPP)	Biodegradable, cationic, antimicrobial; contact angle $\sim 78^\circ$	Alehosseini et al. [1]; Ribeiro et al. [11]
Cellulose Nanocrystals (CNC)	Acid hydrolysis of microcrystalline cellulose or agricultural biomass; ultrasound treatment	High crystallinity ( $\geq 69.6\%$ ); needle-shaped; amphiphilic surface	Meirelles et al. [9]; Ebrahimi et al. [3]; Aw et al. [15]; Dong et al. [12]
Nanochitin (ChNCs)	HCl hydrolysis of $\alpha$ -chitin from crustacean shells	Rod-shaped; positive surface charge; amphiphilic character	Ben Cheikh et al. [10]
Starch Nanoparticles (SNPs)	Pullulanase hydrolysis (molecular weight reduction); nanoprecipitation	Non-allergenic, inexpensive; emulsification tunable by MW	Ko & Kim [8]; Guo et al. [13]
Zein Particles	Anti-solvent precipitation; composite with xanthan gum or CFG	Amphiphilic; contact angle $\sim 90^\circ$ with co-biopolymer; self-assembling	Molecules review [7]
Whey Protein	Heat denaturation/aggregation; glycation at $90^\circ\text{C}$ , pH 2.0	Food-grade; WPI nanofibrils; calcium cross-linked spherical NPs	Molecules review [7]
Soy Protein Isolate (SPI)	Maillard reaction conjugation; ultrasound with pectin	Globular; pH-responsive; freeze-thaw stable at pH 3.0	Molecules review [7]

Silica NPs (SiO <sub>2</sub> )	Fumed silica; surface-modified with chitosan	Tunable wettability; stable at varied pH; W/O emulsion capable	Gao et al. <sup>[4]</sup> ; Heidari et al. <sup>[16]</sup>
Hydroxyapatite (HAp)	Chemical precipitation; surface modification	Biocompatible; biomedical-grade; used in scaffold fabrication	Molecules review <sup>[7]</sup>
CNC + Nanochitin Complex	Electrostatic heteroaggregation of oppositely charged particles	Stable at net cationic or anionic charge; 9-month creaming resistance	Guo et al. <sup>[5]</sup>
Zein–Sodium Alginate (ZAS)	Anti-solvent precipitation + polyphenol adsorption + SA coating	High curcumin loading (81.65%); improved bioaccessibility	Zhang et al. <sup>[14]</sup>

**Table 1. Summary of Stabilizer Particle Types Used in Pickering Emulsions**

### Polysaccharide-Based Particles

Polysaccharide-derived particles dominate the Pickering emulsion literature because they are derived from the most abundant biopolymers on Earth—cellulose, chitin, and starch—and because their surface chemistry can be tuned to adjust wettability and charge <sup>[2]</sup>.

Cellulose nanocrystals (CNC) are rod-shaped nanoparticles prepared by acid hydrolysis of cellulose sources, followed by dialysis and ultrasound treatment. Their dimensions typically range from 100 to 500 nm in length and 3 to 15 nm in cross-section <sup>[9]</sup>. The needle-shaped morphology of CNC, as confirmed by atomic force microscopy (AFM) by Meirelles and co-workers, facilitates dense interfacial packing through geometric interlocking, creating a mechanically robust particle monolayer <sup>[9]</sup>. These authors showed that O/W emulsions stabilized by CNC prepared from microcrystalline cellulose were homogeneous, opaque, and kinetically stable for several days. Importantly, the stabilization mechanism was primarily electrostatic and steric repulsion between droplets, as the high surface charge (negative zeta potential) generated strong inter-droplet repulsive forces <sup>[9]</sup>. Ebrahimi and colleagues extended this work by extracting CNC from hazelnut shells—an agricultural waste material—demonstrating that the particles had a high crystallinity index of 69.6% and spherical

morphology, and that at concentrations of 2.0 wt% the resulting Pickering emulsions showed no creaming after 28 days of storage <sup>[3]</sup>.

Dong and co-workers prepared spherical CNC (S-CNC, diameter 30–60 nm) by mixed acid hydrolysis of mercerized microcrystalline cellulose with ultrasonic treatment, and used them to stabilize O/W emulsions. The emulsions maintained droplet diameter with no significant increase after 7 days, and displayed ultra-low viscosity even at a high S-CNC concentration of 5 g/L in the aqueous phase. The emulsions were stable across wide ranges of pH, ionic strength, and temperature, demonstrating the versatility of this particle type <sup>[12]</sup>. The Langmuir invited feature article on nanocelluloses further elaborated that the emulsification capability of CNC depends critically on the source material and surface charge, with cotton-, green algae-, and bacterial cellulose-derived CNC all capable of producing highly stable emulsions without chemical modification <sup>[14]</sup>.

Nanochitin (nanochitin crystals, ChNC) represents a complementary polysaccharide-derived particle. Ben Cheikh and co-workers produced ChNC by hydrochloric acid hydrolysis of  $\alpha$ -chitin extracted from crustacean shells, yielding rod-shaped particles with a positive surface charge. These particles were applied to stabilize O/W emulsions of soybean oil, acrylated soybean oil, and epoxidized soybean oil,

demonstrating that the chemical structure of the oil phase significantly modulated emulsion properties. Strong interfacial interaction between ChNC and the functional groups of chemically modified soybean oils enhanced the Pickering stabilization efficiency, yielding emulsions with low droplet size and extended long-term stability [10]. Guo and colleagues took this further by combining negatively charged CNC with positively charged nanochitin to form heteroaggregates through electrostatic attraction. The resulting complexes stabilized O/W Pickering emulsions remarkably effectively under conditions of slight net positive or negative charge; close to charge neutrality (CNC/NCh mass ratio  $\approx 5$ ), large aggregates formed and emulsion stability was lost. At the optimum CNC/NCh ratio under net cationic conditions, interfacial arrest produced non-deformable emulsion droplets with no creaming observed over nine months—a stability record unmatched by either particle alone [5].

Starch nanoparticles (SNPs) provide a cost-effective polysaccharide option. Ko and Kim assessed the influence of environmental conditions on SNP-stabilized Pickering emulsions using waxy maize starch. Their transmission electron microscopy data revealed that decreasing pH (from pH 10 to pH 4) or increasing NaCl concentration (from 0 to 60 mM) induced SNP aggregation, enlarging hydrodynamic diameter and compromising emulsion uniformity. Conversely, an SNP content above 5 wt% was necessary to produce stable emulsions with 10% oil, and stability was highest at pH 3.0, where oiling-off was absent over the storage period. The addition of chitosan at concentrations exceeding 0.4% further suppressed creaming at neutral pH by forming a supplementary solid interfacial layer around oil droplets, as confirmed by confocal laser scanning microscopy [8]. Guo and colleagues demonstrated that reducing the molecular weight of starch through pullulanase hydrolysis enhanced emulsifying performance, because lower-molecular-weight fractions adsorbed more readily at the interface and formed more elastic interfacial films with higher Pickering stabilization efficiency [13].

Cui and colleagues reviewed the broader landscape of polysaccharide-based Pickering emulsions, cataloguing natural polysaccharides, physically or chemically modified variants, and polysaccharide

complexes. They highlighted that while individual natural polysaccharides (cellulose, starch, chitin, pectin, alginate, dextran) offer functional advantages, their emulsification performance is often limited by insufficient amphiphilicity. Physical modification strategies such as high-pressure homogenization, ultrasound treatment, and heat gelatinization, as well as chemical modification including esterification, etherification, and crosslinking, substantially extend the performance envelope. Polysaccharide–protein complexes and polysaccharide–polyphenol conjugates offer additional tunability, enabling control of particle size, surface charge, and contact angle [2].

### **Protein-Based Particles**

Protein particles have attracted considerable interest because they are food-grade, biodegradable, and present inherent amphiphilicity through the spatial arrangement of hydrophilic and hydrophobic amino acid residues.

Chitosan, strictly a polysaccharide but functionally protein-like in its cationic behavior at acidic pH, has been one of the most studied Pickering particle materials. Alehosseini and co-workers prepared chitosan nanoparticles (CSNPs) by ionic gelation of chitosan with sodium tripolyphosphate (STPP) in acetic acid solution and used them to stabilize D-limonene-loaded Pickering emulsions. Three CSNP concentrations (0.07, 0.25, and 0.43% w/v) and three D-limonene-to-emulsion ratios (5, 15, and 25%) were evaluated in a response surface methodology design. Emulsion stability index increased monotonically with CSNP concentration, while viscosity increased with both CSNP concentration and D-limonene ratio. FTIR spectroscopy confirmed the formation of new intermolecular interactions between CSNPs and the oil phase, and differential scanning calorimetry revealed improved thermal stability in the optimized formulations [1]. Ribeiro and colleagues compared two synthesis routes for chitosan nanoparticles—amino deprotonation and tripolyphosphate ionic crosslinking—and found that crosslinked particles (smaller size, narrower zeta potential distribution) produced smaller oil droplets with clearer microscopic evidence of the Pickering stabilization mechanism than deprotonation-derived particles,

which formed a viscous network in the continuous phase rather than a true interfacial film [11].

Niu and colleagues advanced the chitosan nanoparticle system by incorporating chlorogenic acid (CA) into the particle matrix at various CS:CA mass ratios prior to emulsification with cinnamaldehyde essential oil (CEO). Contact angle measurements showed that increasing the CA content in CS-CA particles progressively shifted wettability toward more hydrophobic values, approaching the optimal 90° contact angle and thereby improving interfacial adsorption. The emulsion formulated with a CS:CA ratio of 1:0.75 achieved the minimum creaming index of 26.5 ± 4.6% after 5 days of storage, demonstrating that controlled incorporation of a hydrophobic molecule into the particle matrix is an effective strategy for wettability adjustment [10]. This study also demonstrated, for the first time, the co-encapsulation of both a water-soluble active (CA) and a water-insoluble essential oil (CEO) within the same Pickering emulsion system—a significant step toward multi-functional food-grade delivery vehicles [10].

Sharkawy and colleagues developed Pickering emulsions based on chitosan/collagen peptide nanoparticles for cosmetic skin applications. The nanoparticles had an average size of 32.27 nm and a high zeta potential of +59.7 mV, reflecting strong electrostatic stability. Contact angle measurement of 78.02° ± 2.04° confirmed hydrophilic character consistent with O/W emulsion formation. Confocal laser scanning microscopy (CLSM) confirmed irreversible adsorption of particles at the oil–water interface. The resulting emulsions exhibited shear-thinning viscosity and gel-like texture, with average droplet sizes between 7.63 µm and 15.72 µm. Skin penetration studies showed that the nanoparticles deposited in deep skin layers and that penetration depth correlated positively with particle concentration and exposure time [7].

Whey protein isolate (WPI) provides another protein-based particle option. Heat denaturation of WPI at 90°C and pH 2.0 generates nanofibril structures whose surface hydrophobicity and charge are modifiable by glycation with sugars or crosslinking with Ca<sup>2+</sup> ions. The Molecules review article detailed how Ca<sup>2+</sup>-induced cross-linking produced spherical WPI nanoparticles that efficiently loaded and

stabilized β-carotene-containing high internal phase Pickering emulsions, while glycation with glucose, lactose, or maltodextrin produced WPI nanofibrils that stabilized O/W emulsions through a combined Pickering and electrostatic stabilization mechanism [7]. Zein, extracted from corn endosperm, forms colloidal particles through anti-solvent precipitation from ethanol solution. The addition of xanthan gum or corn fiber gum (CFG) at a zein:CFG ratio of 2:1 shifted the contact angle of zein particles to approximately 90°, yielding emulsions with superior Pickering stabilization compared to pure zein particles alone [7]. Soy protein isolate (SPI) particles formed by Maillard reaction conjugation with okara dietary fiber showed excellent emulsification stability, and emulsions prepared at pH 3.0 exhibited good freeze-thaw stability attributable to the strong electrostatic surface repulsion at low pH [7].

Zhang and colleagues formulated a complex three-component particle system comprising zein, adzuki bean seed coat polyphenol, and sodium alginate (ZAS), assembled by anti-solvent precipitation followed by sequential polyphenol and alginate adsorption. FTIR spectroscopy confirmed hydrophobic interactions and hydrogen bonding between components. Differential scanning calorimetry demonstrated improved thermal stability of the composite relative to pure zein. ZAS-stabilized Pickering emulsions achieved a curcumin loading rate of 81.65 ± 1.56% and bioaccessibility of 27.99 ± 0.26%, substantially outperforming single-component zein emulsions [14].

### **Inorganic Particles**

Inorganic particles such as silica (SiO<sub>2</sub>) and hydroxyapatite (HAp) offer high mechanical rigidity, precise size control, and straightforward surface chemistry modification.

Nano-silica is inherently hydrophilic ( $\theta < 90^\circ$ ) and naturally forms O/W emulsions. Gao and co-workers employed nano-silica particles to investigate the effect of emulsification method on Pickering emulsion characteristics. Their results demonstrated that ultrasound emulsification generated a main droplet distribution peak at substantially smaller droplet diameters than rotor–stator homogenization, and that the combination of both methods produced the finest emulsions, attributed to the synergistic

effects of cavitation-induced droplet disruption and enhanced particle mass transfer toward the interface [4]. Heidari and colleagues addressed the challenge of using silica for W/O Pickering emulsions by modifying SiO<sub>2</sub> nanoparticles with chitosan at various chitosan:SiO<sub>2</sub> ratios and pH values. Chitosan adsorbed electrostatically onto the negatively charged silica surface, increasing zeta potential and shifting contact angle toward more hydrophobic values. EDX-MAP and N<sub>2</sub> adsorption/desorption (BET) analyses confirmed the surface modification. Optimized chitosan-modified silica nanoparticles successfully stabilized W/O Pickering emulsions—a configuration that is challenging to achieve with purely hydrophilic particles—demonstrating the value of surface engineering for expanding the formulation space [16].

Hydroxyapatite (HAp), with the chemical formula Ca<sub>10</sub>(PO<sub>4</sub>)<sub>6</sub>(OH)<sub>2</sub>, is a biocompatible inorganic material with structural similarity to bone and tooth mineral. Unmodified HAp nanoparticles can stabilize O/W Pickering emulsions and have been used to template microspheres composed of biodegradable polymers including PCL, PLLA, and PLGA, which have direct relevance in controlled drug delivery and tissue engineering. Surface-modified HAp nanoparticles, by contrast, stabilize W/O Pickering emulsions and enable the fabrication of porous scaffolds with interconnected porosity suitable for bone regeneration [7].

### **Factors Affecting Emulsion Characteristics:**

#### **Wettability and Contact Angle**

Wettability, quantified by the three-phase contact angle, is the single most influential particle parameter governing Pickering emulsion characteristics. Particles with  $\theta$  near 90° partition most effectively between the two phases, maximizing the adsorption energy and thus producing the most stable emulsions [6,7]. In practice, most biopolymer particles are hydrophilic ( $\theta < 90^\circ$ ), and researchers routinely apply modification strategies to shift contact angle toward this optimum. Niu and colleagues quantitatively demonstrated this relationship by showing that CS-CA particles with increasing CA content exhibited progressively higher contact angles and correspondingly lower creaming indices—direct evidence that wettability tuning translates into improved emulsion stability [10]. Sharkawy and co-

workers reported that their chitosan/collagen peptide nanoparticles with a contact angle of 78.02° produced emulsions with effective O/W configuration and gel-like rheological behavior [7]. Heidari and colleagues showed that chitosan modification of silica nanoparticles raised the contact angle sufficiently to enable the formation of W/O emulsions, a configuration unachievable with unmodified hydrophilic silica [16].

#### **Particle Size and Concentration**

Particle size determines both the scale of coverage achievable at the interface and the diffusion kinetics of particles toward the interface during emulsification. Smaller particles can achieve higher surface coverage per unit mass and are less susceptible to gravitational sedimentation, contributing positively to emulsion stability [7]. The classical relationship dictates that emulsion droplet size scales with particle diameter: larger particles stabilize larger droplets. Silica particle size experiments confirmed this, with nanoparticle radius increasing from 5 to 80 nm causing a corresponding increase in average emulsion droplet diameter from 64  $\mu\text{m}$  to 432  $\mu\text{m}$  [6].

Particle concentration exerts a strong inverse influence on droplet size across all particle types reviewed. Alehosseini and co-workers reported that increasing CSNP concentration from 0.07 to 0.43% w/v progressively decreased the creaming index and improved emulsion stability index, reflecting better interfacial coverage at higher particle loads [1]. Ebrahimi and colleagues observed that increasing CNC concentration from 0.5 to 2.0 wt% decreased droplet diameter approximately 1.8-fold and increased zeta potential in absolute magnitude, both effects contributing to improved stability; at 2.0 wt% CNC, no creaming was observed after 28 days [3]. Ko and Kim found that SNP concentrations above 5 wt% were necessary to produce stable Pickering emulsions with 10% oil content, suggesting a minimum particle loading threshold below which interfacial coverage is insufficient [8]. Dong and co-workers noted that even at high S-CNC concentrations, viscosity remained ultra-low, which is advantageous for applications requiring pourable formulations [12].

## **pH and Ionic Strength**

The surface charge of biopolymer-derived particles is pH-dependent because ionizable functional groups (carboxylic, amino, hydroxyl) are protonated or deprotonated as pH changes. This, in turn, modulates particle aggregation behavior and the electrostatic contributions to inter-droplet repulsion in the emulsion. Ko and Kim systematically demonstrated that both decreasing pH from 10 to 4 and increasing NaCl concentration from 0 to 60 mM caused SNP aggregation as confirmed by dynamic light scattering and TEM, resulting in less uniform emulsions. At acidic pH (3.0), the positive charge on SNPs increased inter-particle repulsion and provided maximum emulsion stability, with no oiling-off observed during storage [8].

Dong and colleagues reported that spherical CNC-stabilized emulsions maintained droplet size stability across pH 3.0–9.0 and NaCl concentrations up to 500 mM, attributing this broad stability to the robust mechanical barrier formed by the dense particle interfacial monolayer in addition to electrostatic stabilization [12]. Ebrahimi and colleagues similarly confirmed that CNC-stabilized Pickering emulsions from hazelnut shells exhibited high stability across a pH range and at elevated salt concentrations, making them suitable for applications in food matrices where ionic strength varies significantly [3]. Guo and co-workers showed that pH indirectly governs the charge ratio of CNC and nanochitin components, and that the stability of CNC/NCh heteroaggregate-stabilized emulsions was maximized under net cationic conditions, while charge neutrality induced particle precipitation and emulsion destabilization [5].

## **Mechanical Emulsification Conditions**

The method and intensity of mechanical energy input during emulsification directly determines the initial droplet size distribution and the rate at which particles adsorb at the newly formed interface. Gao and colleagues conducted the most systematic study of this parameter, comparing rotor–stator homogenization (R-SH) at various speeds, ultrasonic emulsification at various amplitudes, and their sequential combination. Ultrasound produced smaller and more uniformly distributed droplets than R-SH at equivalent energy inputs, because acoustic cavitation simultaneously disrupts the oil phase and generates

intense local convection that transports particles to the interface [4]. The optimal combined process produced the finest and most stable emulsions. Alehosseini and co-workers homogenized samples at 10,000 rpm for 2.5 minutes followed by sonication at 0.2 kW for 3 minutes in an ice bath, demonstrating that combining mechanical and ultrasonic energy is effective for chitosan nanoparticle-stabilized systems [1]. Meirelles and colleagues used both rotor–stator and ultrasound processes for CNC-stabilized emulsions, finding that ultrasound generated smaller droplets that were more effectively covered by CNC particles acting as a mechanical barrier against coalescence [9].

Homogenization speed and duration interact with oil fraction to determine the droplet size distribution. Increasing D-limonene content in CSNP-stabilized emulsions from 5 to 25% substantially increased viscosity, consistent with the increase in internal phase volume fraction [1]. The rheological behavior of most Pickering emulsions reviewed was non-Newtonian shear-thinning (pseudoplastic), meaning that viscosity decreased with increasing shear rate—a behavior modeled by the Power Law equation. Some formulations, particularly those with high particle concentrations, exhibited a yield stress and were better described by the Bingham plastic model, reflecting the gel-like network formed by excess particles in the continuous phase [1,7].

## **Applications Of Pickering Emulsions**

### **Food Science and Active Ingredient Delivery**

The most extensively investigated application domain is food science, where Pickering emulsions serve as delivery vehicles for lipophilic bioactive compounds with poor water solubility and chemical instability. D-limonene, a major component of citrus essential oil with antimicrobial and antioxidant properties, was successfully encapsulated in CSNP-stabilized Pickering emulsions by Alehosseini and co-workers, who demonstrated that the crystalline structure of CSNPs provided an effective physical barrier against volatilization and oxidative degradation during storage [1]. Aw and co-workers encapsulated curcumin—an anti-inflammatory and antioxidant polyphenol with notoriously low water solubility—in CNC-stabilized O/W Pickering emulsions, achieving an encapsulation efficiency exceeding 99%. Under dark storage conditions, the CNC-PE provided a

curcumin half-life of 98.47 days, representing an approximately 20-fold improvement in photostability relative to reference systems. Degradation rate under visible light, UV light, and elevated temperature (50°C) increased in the order: 50°C > UV > visible light > dark, confirming that the dense CNC interfacial layer retards but does not eliminate photo-oxidative pathways [15].

Zhang and colleagues used ZAS composite nanoparticle-stabilized Pickering emulsions to deliver curcumin, achieving loading efficiency of 81.65%, bioaccessibility of 27.99%, and in vitro digestion stability of 55.72%—substantially superior to unmodified zein nanoparticle systems [14]. Niu and co-workers demonstrated co-encapsulation of both a hydrophilic (chlorogenic acid) and a hydrophobic (cinnamaldehyde essential oil) active compound in the same chitosan nanoparticle Pickering emulsion system, opening possibilities for synergistic active packaging applications in fresh produce preservation [10]. The *Molecules* 2020 review catalogued additional food applications including high internal phase emulsions as fat substitutes in reduced-calorie food formulations, where Pickering particles replace both fat and surfactant, and emulsion-based encapsulation of thermolabile vitamins and polyunsaturated fatty acids [7].

### **Food Packaging**

Zhao and colleagues provided a comprehensive review of biopolymer-based Pickering emulsion incorporation into food packaging films. The integration of Pickering emulsions into biopolymer matrices improves film mechanical properties, reduces water vapor permeability, and imparts antimicrobial and antioxidant activity from encapsulated bioactive compounds. Applications included preservation of fruits and vegetables, extension of meat and baked goods shelf life, and colorimetric freshness detection for seafood. The authors noted that biopolymer-particle-stabilized Pickering emulsions allow controlled release of encapsulated actives over the packaging lifetime, which is not achievable with free-surfactant-stabilized emulsions [13].

### **Cosmetics and Skin Applications**

Sharkawy and colleagues demonstrated the potential of chitosan/collagen peptide nanoparticle Pickering emulsions for cosmetic skin delivery. CLSM skin tracking studies showed that the nanoparticles penetrated into deep skin layers including the dermis, and that penetration depth increased with particle concentration and exposure time. This transdermal delivery capability, combined with the biocompatibility of the biopolymer particles, represents a significant advancement over surfactant-based cosmetic emulsions, which are limited by surfactant-induced skin irritation at high concentrations [7]. The shear-thinning and gel-like rheological behavior of these emulsions also provides favorable application characteristics for topical products [7].

### **Pharmaceutical Delivery**

The *Molecules* 2020 review described the use of hydroxyapatite-stabilized Pickering emulsions as templates for fabricating biodegradable polymer microspheres (PCL, PLLA, PLGA) for controlled drug release. The porous scaffold architecture achievable from W/O HAp Pickering emulsions is directly applicable to tissue engineering and orthopedic drug delivery [7]. Curcumin-loaded CNC Pickering emulsions reviewed by Aw and co-workers demonstrated pharmacologically relevant encapsulation efficiencies and storage stability profiles consistent with oral or topical pharmaceutical delivery [15]. The reversible breakdown of thermoresponsive CNC-PNIPAM emulsions upon heating above the lower critical solution temperature, described in the Langmuir review, offers a triggered-release mechanism relevant to stimuli-responsive drug delivery [14].

### **Agriculture and Environmental Applications**

Ben Cheikh and colleagues proposed chitin nanocrystal-stabilized emulsions for coating, ink, and adhesive applications, highlighting the compatibility of these particles with industrial oil-phase chemistries including chemically reactive acrylated and epoxidized soybean oils [10]. The Langmuir invited feature article described the use of CNF-containing Pickering emulsions to produce composite structures and phase change materials for solar energy

applications, illustrating how emulsion processing can yield functional materials beyond food and pharmaceutical domains [14]. Water-in-diesel Pickering emulsions using hydrophobized cellulose nanofibrils were discussed as a strategy for reducing combustion emissions, further expanding the application horizon of Pickering emulsion technology into environmental and energy sectors [14].

## CONCLUSION

This literature review synthesizes findings from twenty-one peer-reviewed studies to establish the central role of stabilizer particle type in determining the characteristics and performance of Pickering emulsions. The following conclusions are drawn:

First, the contact angle of particles at the oil–water interface is the primary determinant of both the type of emulsion formed (O/W vs. W/O) and its stability. Particles with  $\theta$  near  $90^\circ$  generate the highest detachment energies and the most stable emulsions. Engineering particle wettability through composite formation, surface modification, or charge manipulation is the most productive strategy for optimizing Pickering stabilization.

Second, polysaccharide-derived particles—particularly cellulose nanocrystals, nanochitin, and chitosan nanoparticles—dominate current research because they combine functional emulsification performance with biodegradability and food-grade status. Protein-based particles (whey protein, zein, soy protein isolate) provide complementary functionality and nutritional value. Inorganic particles (silica, hydroxyapatite) offer superior mechanical rigidity and chemical stability at the cost of reduced biocompatibility.

Third, hybrid and composite particle systems—including CNC/nanochitin heteroaggregates, chitosan-modified silica, and zein–alginate–polyphenol complexes—consistently outperform single-component systems by combining the advantages of multiple materials. Heteroaggregation between oppositely charged particles can achieve interfacial arrest and extraordinary long-term stability exceeding nine months.

Fourth, particle concentration, pH, ionic strength, and mechanical emulsification method all exert

significant, quantitatively documented effects on emulsion droplet size, zeta potential, viscosity, and stability. These parameters must be co-optimized with particle type rather than treated independently.

Fifth, Pickering emulsions stabilized by food-grade biopolymer particles demonstrate compelling performance in encapsulation, delivery, and protection of bioactive compounds including essential oils, curcumin, vitamins, and antimicrobial agents, with applications spanning food science, pharmaceutical delivery, cosmetics, and active packaging.

Future research should prioritize: (1) scalable production methods that reproduce laboratory-optimized particle characteristics at industrial scale; (2) systematic *in vivo* bioaccessibility and safety studies, particularly for novel hybrid particles; (3) quantitative structure–property relationships linking particle physicochemical parameters to emulsion performance metrics; and (4) life cycle analysis of biopolymer-particle-stabilized emulsions to validate their sustainability advantage over synthetic surfactant systems. The convergence of green chemistry, nanotechnology, and colloid science positions Pickering emulsions as a transformative platform technology across multiple industries.

## REFERENCES

1. Alehosseini E, Jafari SM, Shahiri Tabarestani H. Production of D-limonene-loaded Pickering emulsions stabilized by chitosan nanoparticles. *Food Chemistry*. 2021;354:129591.
2. Cui F, Zhao S, Guan X, McClements DJ, Liu X, Liu F, Ngai T. Polysaccharide-based Pickering emulsions: Formation, stabilization and applications. *Food Hydrocolloids*. 2021;119:106812.
3. Ebrahimi R, Fathi M, Ghoddusi HB. Pickering emulsions stabilized by cellulose nanocrystals extracted from hazelnut shells: Production and stability under different harsh conditions. *International Journal of Biological Macromolecules*. 2024;258:128982.
4. Gao J, Bu X, Zhou S, Wang X, Bilal M, Hassan FU, Hassanzadeh A, Xie G, Chelgani SC. Pickering emulsion prepared by nano-silica particles – A comparative study for exploring the

- effect of various mechanical methods. *Ultrasonics Sonochemistry*. 2022;83:105928.
5. Guo S, Zhu Y, Xu W, Huan S, Li J, Song T, Bai L, Rojas OJ. Heteroaggregation effects on Pickering stabilization using oppositely charged cellulose nanocrystal and nanochitin. *Carbohydrate Polymers*. 2023;299:120154.
  6. Hossain KMZ, Deeming L, Edler KJ. Recent progress in Pickering emulsions stabilised by bioderived particles. *RSC Advances*. 2021;11:39027.
  7. Zhu Q, et al. Food-grade Pickering emulsions stabilized by diverse solid particles: A review on their types, preparation, stability, and applications. *Molecules*. 2020;25:3202.
  8. Ko EB, Kim JY. Application of starch nanoparticles as a stabilizer for Pickering emulsions: Effect of environmental factors and approach for enhancing its storage stability. *Food Hydrocolloids*. 2021;120:106984.
  9. Meirelles AAD, Costa ALR, Cunha RL. Cellulose nanocrystals from ultrasound process stabilizing O/W Pickering emulsion. *International Journal of Biological Macromolecules*. 2020;158:75–84.
  10. Niu B, Chen H, Wu W, Fang X, Mu H, Han Y, Gao H. Co-encapsulation of chlorogenic acid and cinnamaldehyde essential oil in Pickering emulsion stabilized by chitosan nanoparticles. *Food Chemistry: X*. 2022;14:100312.
  11. Ribeiro EF, de Barros-Alexandrino TT, Assis OBG, Cruz Junior A, Quiles A, Hernando I, Nicoletti VR. Chitosan and crosslinked chitosan nanoparticles: Synthesis, characterization and their role as Pickering emulsifiers. *Carbohydrate Polymers*. 2020;250:116878.
  12. Dong H, Ding Q, Jiang Y, Li X, Han W. Pickering emulsions stabilized by spherical cellulose nanocrystals. *Carbohydrate Polymers*. 2021;265:118101.
  13. Zhao Q, Fan L, Li J, Zhong S. Pickering emulsions stabilized by biopolymer-based nanoparticles or hybrid particles for the development of food packaging films: A review. *Food Hydrocolloids*. 2024;146:109185.
  14. Rojas OJ, et al. Emulsions based on nanocelluloses. *Langmuir*. [Invited Feature Article].
  15. Aw YZ, Lim HP, Low LE, Singh CKS, Chan ES, Tey BT. Cellulose nanocrystal (CNC)-stabilized Pickering emulsion for improved curcumin storage stability. *LWT – Food Science and Technology*. 2022;159:113249.
  16. Heidari F, Jafari SM, Ziaifar AM, Anton N. Surface modification of silica nanoparticles by chitosan for stabilization of water-in-oil Pickering emulsions. *Carbohydrate Polymer Technologies and Applications*. 2023;6:100381.
  17. Ben Cheikh F, Ben Mabrouk A, Magnin A, Putaux JL, Boufi S. Chitin nanocrystals as Pickering stabilizer for O/W emulsions: Effect of the oil chemical structure on the emulsion properties. *Colloids and Surfaces B: Biointerfaces*. 2021;200:111604.
  18. Sharkawy A, Barreiro MF, Rodrigues AE. New Pickering emulsions stabilized with chitosan/collagen peptides nanoparticles: Synthesis, characterization and tracking of the nanoparticles after skin application. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 2021;616:126327.
  19. Guo B, Liu C, Grossmann L, Weiss J. Pickering emulsion stabilized by hydrolyzed starch: Effect of the molecular weight. *Journal of Colloid and Interface Science*. 2022;612:525–535.
  20. Zhang X, Sun X, Chen Y, Zheng F, Ban H, Liu J, Cai D, Xiu L. Stability of sodium alginate modified zein/adzuki bean seed coat polyphenol composite nanoparticles and loading of curcumin in emulsion. *LWT – Food Science and Technology*. 2025;226:117978.
  21. Zhao Q, Fan L, Li J, Zhong S. Biopolymer-based Pickering emulsion packaging review. *Food Hydrocolloids*. 2024;146:109185.

**HOW TO CITE:** I Made Fajar Juliantara\*, Ni Made Dwi Angga Yani, Mini Review: The Effect Of Stabilizer Particle Types On The Characteristics Of Pickering Emulsion, *Int. J. Sci. R. Tech.*, 2026, 3 (6), 237-247. <https://doi.org/10.5281/zenodo.20537682>