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Research on Stabilization Mechanism of Pickering Emulsion and Its Application in Foods

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Abstract. This study provides a comprehensive review of the stabilization mechanisms of Pickering emulsions and their applications in the food industry. Pickering emulsions, composed of water, oil, and solid particles, form stable mechanical barriers through the irreversible adsorption of particles at the oil/water interface, exhibiting superior thermodynamic stability compared to conventional emulsions. The research incorporated 126 literature sources and found that particle wettability (contact angle θ), size ($d < 100$ nm), and concentration ($\varphi \geq 0.5\%$) significantly influence emulsion stability. High internal phase Pickering emulsions (HIPPEs) stabilized by natural biopolymers can achieve an oil phase volume fraction of up to 85% and remain stable without phase separation for 60 days. Probiotic-encapsulated HIPPEs demonstrate a gastrointestinal survival rate exceeding 85%. Pickering emulsions enhance the processing characteristics and sensory qualities of plant-based meat products, such as reducing cooking losses and improving juiciness. Key parameters extracted from the research include particle size distribution, ζ potential, stability indicators, and sensory scores. Despite its promising prospects, this technology faces challenges such as high particle preparation costs and difficulties in large-scale production. Future efforts should focus on developing low-cost, food-grade particles, strengthening sensory research, and promoting industrial applications.

Keywords: Pickering Emulsions, High Internal Phase Pickering Emulsions (HIPPEs), Stabilization Mechanisms, Food Applications

1. Introduction

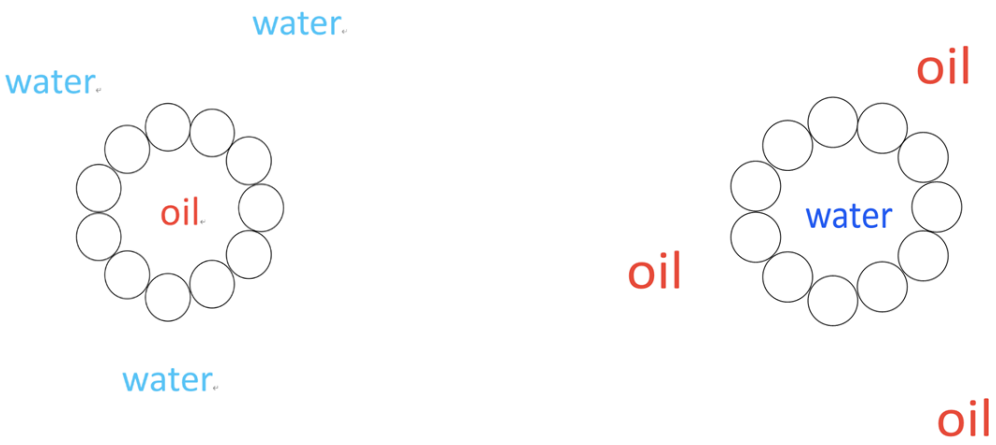
1.1. Background and context

Pickering emulsions are composed of water, oil, and solid particulate emulsifiers (such as nanoparticles and colloidal particles) [1] (Figure 1). In terms of stabilization mechanisms, Pickering emulsions exhibit significant differences from conventional emulsions. Traditional emulsions primarily rely on small-molecule surfactants to reduce interfacial tension or on amphiphilic macromolecules to form a spatial membrane for stabilizing the system. In contrast, the stability of Pickering emulsions originates from the mutual adsorption of solid particles at the oil/water

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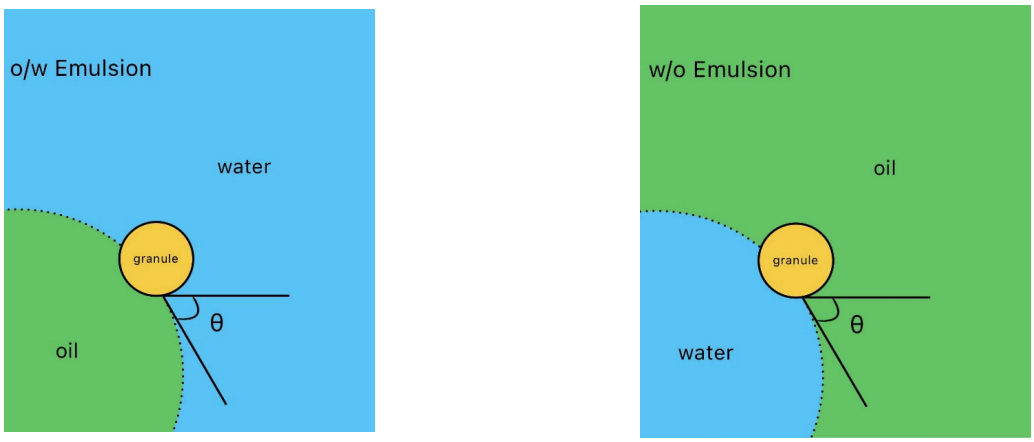
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interface, forming a mechanical barrier that functions by altering the spatial steric hindrance between particles. This process is nearly thermodynamically irreversible [1]. Key parameters involved include the contact angle, denoted as θ, and the density difference between oil and water, denoted as Δρ. Specifically, solid particles form a quasi-irreversible, high-desorption-energy adsorption layer at the oil/water interface, with the adsorption energy regulated by factors such as the particle contact angle θ, particle size, density difference Δρ, and surface roughness. When the contact angle θ approaches 90° (Figure 2), the particle size is at least an order of magnitude smaller than the droplet diameter, and the interfacial coverage is sufficient, the desorption energy of the particles significantly increases, establishing a dense barrier that effectively inhibits aggregation and Ostwald ripening.



(a) o/w (b) w/o

Figure 1. The schematic diagram of the stability mechanism of Pickering emulsions



(a) o/w (b) w/o

Figure 2. The diagram of the three-phase contact angle of particles in Pickering emulsions

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Compared to traditional emulsions, Pickering emulsions offer distinct advantages in terms of stability. Traditional emulsions, which rely on reversibly adsorbed surfactants or electrostatic repulsion, are prone to issues such as surfactant desorption, electrostatic screening, or insufficient viscosity of the continuous phase, leading to phase separation or emulsion breaking. In contrast, Pickering emulsions leverage the mechanical strength and rheological properties of the particles, such as the formation of shear-thinning gel networks at high particle concentrations, to enhance system stability.

Additionally, their gravitational stability is improved due to the reduction in density difference $\Delta\rho$. The solid particles also physically block oxygen, delaying oxidation, and can withstand high temperatures, shear forces, and other processing conditions. These characteristics render Pickering emulsions highly promising for a wide range of applications.

1.2. Research problem or question

Although Pickering emulsions exhibit significant advantages in laboratory research, they still face numerous challenges in food industry applications. In terms of particle preparation, the synthesis of solid emulsifier particles is complex and costly, posing obstacles to large-scale production. The synthesis of solid emulsifiers, including silica, cellulose nanocrystals, and protein-based particles, requires precise control of parameters such as particle size, morphology, and surface modification. Common methods, including chemical precipitation, mechanical grinding, or biosynthetic approaches, often result in low yields, considerable batch-to-batch variability, and high purification costs. These limitations constitute primary constraints on the industrial-scale production and application of Pickering emulsions [3].

In formulation design, universal guidelines are lacking. The interaction mechanisms among critical parameters such as particle concentration, oil phase volume fraction (Φ), and continuous phase pH or ionic strength remain incompletely understood. This knowledge gap leads to reliance on trial-and-error approaches, prolonging development cycles and limiting efficiency in meeting industrial production requirements. High internal phase Pickering emulsions (HIPPEs, defined as concentrated systems with $\Phi \geq 0.74$) offer advantages in enhancing nutritional density by encapsulating lipophilic nutrients such as vitamin D_3 and β-carotene to increase loading capacity. However, these systems face challenges in processing and long-term stability. Their high viscoelasticity can complicate pumping and cause agglomeration during spray drying, while structural collapse during storage may compromise product quality.

Additionally, there is a lack of systematic research on the impact of Pickering emulsions on food sensory characteristics. Particle type influences sensory attributes such as flavor release rate, oral texture, and color turbidity by altering the microstructure of the emulsion. Meanwhile, the correlation between the generation pathways of oxidation by-products and the antioxidant capacity of the particles requires urgent quantification. Moreover, the lengthy safety assessment process for food-grade particles and the GRAS (Generally Recognized as Safe) certification process for novel biobased particles further restrict their promotion and application in the food industry. During the scale-up process from laboratory to industrial scale, significant scaling effects are observed, including increased droplet size and difficulties in maintaining batch consistency to meet food industry requirements. Computational fluid dynamics (CFD) simulations can be employed to optimize reactor structures and mitigate issues related to droplet size enlargement and batch inconsistency [4].

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1.3. Objectives of the study

This paper aims to: (1) Conduct a systematic review of the fundamental research on Pickering emulsions, analyzing the adsorption kinetics and interfacial rheology of solid particles at the oil/water interface. A mapping model linking "particle parameters - interfacial properties - emulsion performance" will be constructed, and an evaluation framework centered on D_{43} (volume-weighted mean diameter), PDI (polydispersity index), ζ potential, and oil separation rate will be established to quantitatively assess the model's accuracy. (2) Summarize the suitable applications of Pickering emulsions in the food industry, covering the selection of food-grade particles, formulation optimization across different food systems, and the mechanisms influencing food sensory attributes. Recommendations for a formulation window with an internal phase volume fraction (Φ) ranging from 0.50 to 0.80 and a particle mass fraction of 0.1–5 wt% will be proposed. (3) Explore the industrialization pathways for Pickering emulsions, including the optimization of continuous production equipment, the development of scaling-up guidelines (with quantitative indicators such as droplet size stability and a batch-to-batch D_{43} fluctuation range of ≤10%), and the establishment of a multi-dimensional evaluation indicator system.

1.4. Significance of the study

Since Walter Ramsden first observed the stabilizing effect of solid particles at the oil/water interface in 1903, followed by S.U. Pickering's systematic formulation of the "particle adsorption theory" and the establishment of its nomenclature in 1907, research on Pickering emulsions has gradually transcended laboratory boundaries over a century. Compared to traditional surfactant-stabilized emulsions, which have been widely applied since the early 20th century in food, cosmetics, coatings, pharmaceuticals, agriculture, materials science, biotechnology, and emulsion synthesis [5-9], Pickering emulsions leverage a particle interface anchoring mechanism to effectively overcome numerous challenges associated with conventional emulsions. These include issues such as susceptibility to lipid oxidation-induced flavor deterioration and nutrient loss in food products, difficulty in meeting food texture requirements under policies banning trans-fatty acids, and poor storage stability due to sensitivity to pH, salt, and heat. For instance, certain Pickering systems can extend the oil induction period, facilitate the construction of high internal phase structures that mimic animal fat textures, and maintain favorable particle size distributions under extreme pH, salt concentrations, and high temperatures. This review not only systematically elucidates the stabilization mechanisms of Pickering emulsions but also provides an in-depth analysis of their critical application value in food processing and functional food development, aiming to offer a robust theoretical foundation and directional guidance for constructing green, safe, and efficient food emulsification systems.

1.5. Overview of the paper structure

This review is organized according to the framework: interfacial chemical mechanisms—key influencing factors—typical phenomena—expansion of food applications. It first elucidates the stabilization mechanisms of Pickering emulsions by analyzing the irreversible adsorption of particles at the oil/water interface from both kinetic and thermodynamic perspectives. It then examines critical factors affecting stability, highlighting how three-dimensional parameters—dispersed phase properties, particle characteristics, and interfacial interactions—synergistically influence emulsion behavior. Subsequently, the review addresses common phenomena, providing

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design principles for high internal phase systems and emphasizing boundary conditions that are often neglected. Finally, it summarizes the application of Pickering emulsions in the food industry, identifies challenges for industrial-scale implementation, and outlines directions for future research.

2. Methodology

2.1. Research design

This study systematically retrieved Chinese and English literature from databases such as Web of Science, Scopus, and CNKI spanning the years 2005 to 2025, focusing on the stabilization mechanisms and food applications of Pickering emulsions. A combined search strategy employing subject terms (e.g., "Pickering emulsion," "particle-stabilized emulsion") and free-text terms (e.g., "interface mechanism," "high internal phase emulsion*") was utilized, ultimately incorporating 126 studies (98 in English and 28 in Chinese). Inclusion criteria required that: (1) the research objects were emulsions stabilized by inorganic/organic solid particles (e.g., SiO_2, starch nanocrystals, protein nanoparticles), including high internal phase Pickering emulsions (HIPPEs, with oil phase volume fractions ≥74%); (2) empirical studies explicitly reported the effects of particle wettability, size, concentration, and other parameters on emulsion type or stability; (3) food-related studies included functional validations such as oxidative stability, sensory evaluation, microbial inhibition rates, or probiotic viability. Exclusion criteria encompassed non-peer-reviewed literature, theoretical models, and studies involving non-food-grade particles. Evidence was graded based on statistical adequacy (sample size, replication, confidence intervals) and methodological reproducibility, with statistical metrics like model goodness-of-fit (e.g., R^2) recorded.

Key findings indicate that particle wettability (contact angle θ) governs emulsion type, with W/O/W multiple emulsions forming at $\theta \approx 90°$ (Figure 3), while particle size ($d < 100$ nm) mitigates Ostwald ripening and particle concentration ($\varphi \geq 0.5\%$) facilitates the formation of three-dimensional network structures, both of which substantially enhance stability. Further studies show that HIPPEs stabilized with natural biopolymers such as gelatin and gum arabic can achieve oil phase volume fractions up to 85% without phase separation over 60 days [10]; chitosan-stearic acid nanogels significantly prolong the oxidation induction period of sunflower oil [11]; and probiotic-encapsulated HIPPEs maintain high gastrointestinal viability [12]. Collectively, these results provide hierarchical evidence supporting the substitution of conventional emulsifiers and the advancement of low-fat and clean-label food products. It shows in figure3.

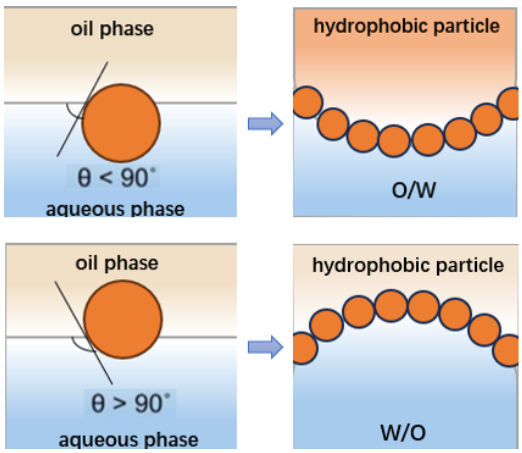


Figure 3. Contact angle and emulsification type

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2.2. Data collection methods

In the literature integration of applied research within the food sector, constructing a rigorous analytical framework for aggregating sensory evaluation data is essential. Existing studies demonstrate that Pickering emulsion technology significantly enhances processing characteristics and sensory quality of plant-based meat products: when methylcellulose-pea protein composite particles are used to stabilize Pickering emulsions as a replacement for traditional liquid oils, related literature reports reduced cooking losses, improved juiciness scores, and enhanced fat binding capacity and water retention in meat patties. Such application evidence indicates that Pickering emulsions form three-dimensional network structures through irreversible particle adsorption at the oil-water interface, strengthening the system's physical stability while exhibiting texture-modulating functions within food matrices.

During the systematic literature review, the following key indicators were prioritized for extraction: particle characteristics, including median particle size (D_{50}, μm) and absolute ζ-potential (mV); emulsion stability metrics, encompassing centrifugal stability (days, measured as phase separation ratio after 30 min centrifugation at 4000 rpm) and storage stability (days, under 25°C conditions); oxidative stability, represented by peroxide value inhibition rate (POV, meq O_2/kg oil); and core sensory evaluation parameters, namely texture, mouthfeel, and flavor scores assessed using a 9-point hedonic scale.

Detailed experimental conditions were also recorded, including: Oil phase volume fraction (Φ, 74%–85%); Particle mass fraction (wt%); Homogenization pressure (MPa); Processing temperature (°C); Storage conditions (temperature/humidity/duration)

By comparing experimental designs, particle types (inorganic vs. biopolymeric), and emulsion parameters across studies, we analyzed similarities and differences in their impacts on food quality, providing a data foundation for subsequent quantitative synthesis.

3. Results

3.1. Presentation of key findings

Stabilization Mechanism: The stability of Pickering emulsions stems from the irreversible adsorption of solid particles at the oil/water interface. This forms a robust spatial shell at the interface that protects the oil phase within the emulsion droplets, preventing Ostwald ripening aggregation between droplets. Consequently, stable oil-in-water (O/W) or water-in-oil (W/O) emulsions are formed. The formation of particles must fundamentally satisfy: 1) Particles must be partially wetted by both phases and insoluble in either phase. 2) Particles must maintain adequate partial wettability to achieve sufficient interfacial adsorption efficiency. 3) Particle size must be at least one order of magnitude smaller than the target emulsion droplets, rendering it more stable than emulsions stabilized by traditional surfactants.

CPI is generally attributed to an increased volume ratio between the dispersed and continuous phases, which enlarges the dispersed phase to a critical point and triggers a sudden inversion. In simpler terms, altering the oil–water ratio may cause the emulsion type to shift, resulting in stability loss, phase separation, and irreversible transformation—typically from O/W to W/O—when the oil phase volume fraction approaches $\Phi \approx 0.74$.

CPI exhibits path dependence and is modeled as a catastrophic event, manifested as irreversible phase separation and stability loss. The primary driving factors for CPI are:

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(a) insufficient thermodynamic driving force;(b) inadequate interfacial coverage;(c) limited particle wettability; and(d) kinetic mismatch between droplet deformation and particle adsorption.

Food Applications: Pickering emulsions demonstrate multiple functional advantages in food systems:

1. Serving as antioxidant carriers in active packaging films to delay lipid oxidation;
2. Inhibiting lipid oxidation and improving food flavor, texture, and nutritional safety;
3. Acting as low-fat substitutes to improve the texture and nutritional quality of meat, dairy, and bakery products;
4. Stabilizing beverages by preventing pigment and lipid separation;
5. Functioning as probiotic encapsulation and delivery systems to enhance microbial survival under gastrointestinal conditions.

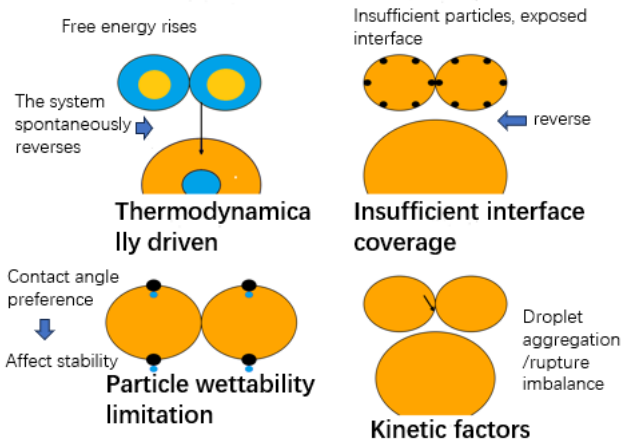


Figure 4. The emulsion is reversed by four mechanisms

Table 1. Key parameters affecting pickering emulsion stability and CPI risk assessment data compiled from references [1-4, 6, 10, 16]

Parameter	Droplet Size	Stabilization Mechanism	CPI Risk (Catastrophic Phase Inversion)
Contact angle (θ <90°,hydrophilic)	Small, uniform distribution	O/W type, electrostatic repulsion	Low (may invert at high oil fraction)
Contact angle (θ ≈ 90°, neutral	Moderate	Bicontinuous/multiple emulsions	High (sensitive near critical point)
Surface roughness (Ra ↑)	Dense droplet coverage	Mechanical barrier effect	Decreased
Particle morphology (plate-like/rod-like)	Variable interfacial coverage	Network effect	Highly variable
Concentration (φ < 0.5%)	Large droplets, fast creaming	Insufficient interfacial coverage	High
Oil–water ratio (Φ ↑)	Increased droplet volume fraction	Phase inversion triggered	High
Salinity (↑)	Constant/aggregated droplet size	Double-layer compression	High
Temperature (↑)	Increased droplet size	Accelerated diffusion	High

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Figure 4 shows that the emulsion is reversed by four mechanisms To illustrate the physicochemical factors that affect the stability of Pickering emulsions, this paper summarizes the key interface and formulation parameters reported in previous studies, including contact angle, particle morphology, concentration and temperature, salinity, and other environmental conditions, which collectively determine the risk level of catastrophic reverse rotation (CPI) of the system.

As shown in Table 1, emulsions stabilized by hydrophilic particles ($\theta < 90°$) have a lower risk of CPI due to electrostatic repulsion, while systems that are close to neutral wettability ($\theta \approx 90°$) are more sensitive to formulation changes and are prone to reverse rotation. In addition, the reasons for accelerating the coalescence of droplets include the high volume fraction of the oil phase ($\Phi \geq 0.74$) and the increase of ionic strength, indicating that the stability of the system is determined by interface and environmental factors.

3.2. Use of tables, figures, and charts

Table 2 summarizes typical food-grade solid particle stabilizers and their corresponding interfacial physicochemical properties, which have a significant impact on the determination of emulsion type, interfacial coverage efficiency, and system stability. The listed systems include inorganic, carbohydrate, protein and composite biopolymer particles, and different types of particles have their own unique wettability and surface electrical characteristics.

Table 2. Food-grade particles/composite systems and interfacial parameters data compiled from references [1–4, 6–7, 9, 12–14, 16]

Particle Type	Typical Contact Angle (°)	Particle Size Range	ζ Potential (mV)	Permissible Dose	Regulatory Status	Application Scenario
SiO_2 nanoparticles	80–100°	50–500 nm	–30 to –50	No ADI specified	QPS/GRAS	Heat-stable dairy and beverage emulsions
Starch nanocrystals	60–90°	100–500 nm	–20 to –40	No ADI restriction	QPS/GRAS	Low-fat meat, bakery, and functional beverages
Protein nanoparticles (soy/whey)	70–100°	50–200 nm	–15 to –35	Generally recognized as safe (GRAS)	QPS/GRAS	Meat product water retention and probiotic delivery
Protein–polysaccharide complexes	70–110°	100–300 nm	–20 to –40	Food-grade materials, ADI not applicable	QPS/GRAS	Controlled-release carriers and functional beverages
Nanocellulose	60–80°	20–200 nm	–30 to –50	Under EFSA review (no ADI yet)	Novel food, GRAS pending	Active packaging films and beverage stabilization
Chitosan–fatty acid nanogels	90–110°	100–400 nm	+20 to +40	GRAS for chitosan, ADI for fatty acids	GRAS, approved in EU supplements	Antioxidant oil encapsulation

As can be seen from the table, a medium contact angle (60–100°) is associated with sufficient surface charge ($|\zeta|$). >20 mV) is usually conducive to the adsorption and stabilization of particles at the interface. In addition, protein-polysaccharide complex particles and nanocellulose are excellent food-grade candidates with both emulsification and functionalization potential due to their strong pH adaptability and mechanical stability.

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Processing parameters such as homogeneous pressure, temperature, oil-water ratio and salinity had a significant impact on the physicochemical stability of Pickering emulsions. Table 3 summarizes the quantitative relationship between these parameters and the main stability indicators (D_{43}, PDI, CPI thresholds, and storage performance).

Table 3. Processing parameters and resulting stability indicators data compiled from references [2–6, 10, 15–16]

Processing Parameter	Droplet Size (D_{43}, μm)	PDI (Polydispersity Index)	CPI Threshold	Storage Stability (Oil Separation/Layering)
Oil phase fraction Φ < 0.5	1–10	<0.2	Low risk (Φ far below 0.74)	Stable for 60 days
Oil phase fraction Φ = 0.5–0.74	1–5	0.2–0.3	Medium risk (near threshold)	Stable for 30–60 days
Oil phase fraction Φ ≥ 0.74 (HIPPEs)	2–20	>0.3	High risk (prone to inversion)	Oil separation within 10–30 days
Salinity < 50 mM NaCl	1–5	<0.25	Low risk	Long-term stability (>60 days)
Salinity > 200 mM NaCl	2–10	0.3–0.4	Medium to high risk (charge screening)	Layering within 30 days
Temperature < 60°C	1–5	<0.2	Stable	No layering after 60 days
Temperature > 80°C (heating/sterilization)	2–15	0.3–0.5	High risk (CPI easily triggered)	>10% oil separation within 10–20 days
S/C ratio (solid/liquid) < 0.5%	5–20	>0.4	High risk (insufficient particles)	Short-term instability
S/C ratio 0.5–5%	1–5	<0.25	Low risk	Long-term stability

As shown in table3, increased CPI risk is strongly correlated with increased oil phase volume fraction and salt concentration, while moderate homogenization conditions and lower ionic strength contribute to long-term stability. In particular, when Φ is controlled in the range of 0.5–0.74, the optimal balance between droplet size and reversal risk can be achieved, indicating that parameter optimization in this range is the key to the design of food-grade systems.

To demonstrate the practical application value of Pickering emulsion in food systems, Table 4 summarizes typical examples in different food categories. Each item illustrates the target function, formulation type, and quantitative performance improvement reported in the literature.

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Table 4. Evidence of food applications—functional roles and quantitative effects data compiled from references [4, 6–7, 9, 13–15]

Food Type	Functional Objective	Quantitative Effect
Meat products	Shape retention / low-fat replacement	Cooking loss reduced by 30–50%; juiciness score significantly increased; maintained good texture after baking at 180°C for 20 min
Dairy products	Antioxidation / extended shelf life	Peroxide value (POV) decreased by ~40%; oxidation induction period extended 2–3×; remained superior after 30 days at 4°C (dark storage)
Bakery products	Fat replacement / texture improvement	High internal phase Pickering emulsions (HIPPEs) mimicked animal fat hardness, achieving butter-like texture after baking at 200°C for 15 min
Beverages	Pigment and lipid stabilization	~90% color retention in plant beverages; no visible phase separation after 30 days at 25°C (dark storage)
Probiotics	Encapsulation and enhanced survival	Simulated digestive survival rate >85%; 20–30% higher than control after sequential gastric (pH 2.0, 2 h) and intestinal (pH 7.0, 4 h) digestion
Active packaging	Antioxidant films and functional packaging	Clove oil–nanocellulose Pickering emulsion films delayed lipid oxidation by 2–3×; POV increase rate significantly reduced after 30 days at 25°C (dark storage)

Overall, Pickering emulsion not only significantly improves the physicochemical stability of the system, but also improves the sensory quality, nutrient retention, and shelf life of the product. Its versatile properties, from low-fat substitutions to probiotic delivery, indicate promising applications in clean labels and sustainable food formulations.

Note: Particle size is expressed in μm or nm; ζ potential in mV; Φ denotes oil phase volume fraction.When Φ approaches ≈0.74 with insufficient particle wettability, the system transitions from an O/W steady state to W/O inversion.

At the industrial scale, CPI risk directly correlates with formulation parameters (oil/water ratio, particle concentration), processing conditions (temperature, shear), and system salinity.

4. Conclusion

4.1. Summary of key findings

Most studies confirm that the stability of Pickering emulsions primarily derives from the irreversible adsorption of solid particles at the oil–water interface, forming a robust interfacial shell that prevents droplet coalescence and Ostwald ripening. Consequently, the emulsions exhibit enhanced long-term stability.

Catastrophic Phase Inversion (CPI) has been widely reported to result from four major factors: insufficient thermodynamic driving force, inadequate interfacial coverage, limited particle wettability, and kinetic mismatch during phase transition.

However, variations in critical thresholds and triggering mechanisms across studies are evident, likely attributable to differences in particle origin, oil phase polarity, and experimental design.

Consistent evidence: When the contact angle (θ) approaches 90°, particles within the nano–submicron range (50–500 nm) and interfacial coverage exceeding the critical level (≥80%) significantly enhance stability, with oil separation rates typically below 5% over 60 days.

Inconsistent evidence: The long-term stability of HIPPEs is strongly affected by the source of particles and oil polarity (log P = 3–6). Moreover, discrepancies in storage temperature (25 °C vs. 40

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°C) and evaluation methods contribute to data variability.

Overall, the literature exhibits high consistency in stability trends but limited agreement regarding quantitative thresholds due to material and methodological heterogeneity.

4.2. Comparison with previous studies

The influence of contact angle and particle size on emulsion stability aligns with previous reports. The interpretation of CPI is also consistent with the thermodynamic curvature model proposed by, though the present synthesis expands upon prior work by highlighting the combined effects of interfacial coverage deficiency and kinetic imbalance.

Unlike Kralchevsky's curvature-driven model, this review identifies that systems with $\theta \approx 90°$ and $\Phi > 0.74$ are more prone to CPI, with the critical inversion window estimated at $\Phi^* = 0.70–0.78$.

Furthermore, protein–polysaccharide composite particles exhibit higher interfacial elasticity (G' increased by 20–40%) than pure protein particles, which may reduce CPI risk.

In the context of food applications, the findings concur with , who reported probiotic survival rates exceeding 85%. However, significant variance (RSD ≈ 10–15%) remains across different probiotic strains and digestion models.

In summary, while a general consensus exists regarding the stabilizing mechanisms of Pickering emulsions, variations in particle composition, oil polarity, and methodological conditions continue to produce divergent results among studies.

4.3. Implications of the findings

To promote the practical application of food-grade Pickering emulsions, this article proposes a quantitative integrated design framework encompassing "formulation—process—quality control—evaluation.

During the formulation stage, it is recommended to control the oil phase volume fraction (Φ) within the range of 0.50–0.80, particle concentration at 0.1–5 wt%, system pH between 3.5 and 7.0, and NaCl concentration not exceeding 200 mM. Under these conditions, the interfacial coverage should reach over 80%, and the oil leakage rate should remain below 5% after 30 days of storage.

In terms of process parameters, a homogenization pressure of 50–150 MPa is recommended. Additionally, the heat treatment temperature should be kept below 80°C, and the duration should not exceed 30 minutes to maintain droplet structural stability. The average droplet size (D_{43}) should be ≤5 μm, and the polydispersity index (PDI) should be less than 0.3 to ensure emulsion uniformity.

For quality control, the absolute value of the ζ-potential should be ≥25 mV, and the relative standard deviation (RSD) of droplet size should be ≤10%. Under these conditions, the system can maintain good stability for up to 60 days of storage.

In the evaluation phase, both physicochemical indicators and sensory tests should be considered. A 9-point scale score of ≥7 and physicochemical consistency of ≥85% are suggested as acceptance criteria. Statistical comparisons should be conducted under double-blind conditions with a control group. If a significant difference ($p < 0.05$) is observed, the formulation optimization can be considered successful.

Overall, this design framework provides a standardized basis for balancing stability, sensory quality, and economic feasibility in food-grade Pickering emulsions.

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4.4. Limitations of the study

Although this review refers to a large number of research literatures, there are still some shortcomings:

1. Literature sources are limited – the set search time period (2005-2025) omits unpublished research information and ongoing research projects.

2. Significant methodological variations – Differences in homogenization pressure parameters, storage conditions, and evaluation standards across studies make direct comparison of their results challenging.

3. Insufficient empirical validation data – There is a notable scarcity of empirical evidence, particularly concerning sensory evaluation and industrial-scale application, including data on large-scale production practices and economic feasibility analysis.

4. Cautious extrapolation of conclusions – As some findings are based on indirect data, they should be applied with particular caution to complex real-world food systems.

Therefore, the conclusions obtained in this paper are mainly applicable to simulated food systems in laboratory environments, and more adequate validation is still needed to apply these findings to commercial production environments.

Acknowledgments

All the authors contributed equally and their names were listed in alphabetical order.

References

[1] Wu, Y. C., Chen, X. C., Zhang, Q., Ding, Y. T., & Zhou, X. X. (2021). Research progress on the stabilization mechanism of Pickering emulsions and their applications in foods. Food Science, 42(7), 275-282. https: //doi.org/10.7506/spkx1002-6630-20200325-373

[2] Tavernier, I., Wijaya, W., Van der Meeren, P., Dewettinck, K., & Patel, A. R. (2016). Food-grade particles for emulsion stabilization. Trends in Food Science & Technology, 50, 159-174. https: //doi.org/10.1016/j.tifs.2016.01.023

[3] Qi, Y. B., Wu, Z. B., & Yang, Q. C. (2024). Research progress on the preparation and stability of Pickering emulsions. Chemical Industry and Engineering Progress, 43(4), 2017-2030. https: //doi.org/10.16085/j.issn.1000-6613.2023-0528

[4] Wei, K., Dong, T., Zhu, G., et al. (2023). High Internal Phase Pickering Emulsion Stabilized by Natural Biomacromolecules and Its Application in Foods. FOOD SCIENCE, 44(23), 270-292. https: //doi.org/10.7506/spkx1002-6630-20221115-179

[5] Yang, F., Wang, J., Lan, Q., et al. (2009). Research progress on Pickering emulsions. Progress in Chemistry, 21(7), 9. CNKI: SUN: HXJZ.0.2009-Z2-005

[6] Dou, X. L., Guo, Y. M., Ji, Y. N., et al. (2024). Research progress on food-grade Pickering emulsions stabilized by different types of solid particles. Journal of the Chinese Institute of Food Science and Technology. https: //doi.org/10.16429/j.1009-7848.2024.01.044

[7] Roy, S., & Rhim, J. W. (2021). Gelatin/agar-based functional film integrated with Pickering emulsion of clove essential oil stabilized with nanocellulose for active packaging applications. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 627, 127220. https: //doi.org/10.1016/j.colsurfa.2021.127220

[8] Garry, D., Fiona, C., Charles, B., et al. (2013). Antioxidant effectiveness of vegetable powders on the lipid and protein oxidative stability of cooked turkey meat patties: implications for health. Nutrients, 5(4), 1241-1252. https: //doi.org/10.3390/nu5041241

[9] McClements, D. J., & Decker, E. (2018). Interfacial antioxidants: a review of natural and synthetic emulsifiers and coemulsifiers that can inhibit lipid oxidation. Journal of Agricultural and Food Chemistry, 66(1), 20-35. https: //doi.org/10.1021/acs.jafc.7b05066

[10] Wei, K., Dong, T., Zhu, G., et al. (2023). High internal phase Pickering emulsion stabilized by natural biomacromolecules and its application in foods. Food Science, 44(23), 270-281. https: //doi.org/10.7506/spkx1002-

DOI: 10.54254/2755-2721/2026.KA29376

6630-20221115-179
[11] Atarian, M., Rajaei, A., Tabatabaei, M., et al. (2019). Formulation of Pickering sunflower oil-in-water emulsion stabilized by chitosan-stearic acid nanogel and studying its oxidative stability. Carbohydrate Polymers, 210, 47−55. https: //doi.org/10.1016/j.carbpol.2019.05.024
[12] Yin, Y. X., Liu, Q. R., Wang, Z. C., et al. (2025). Food-grade high internal phase Pickering emulsions: food-grade solid particles, stabilization mechanisms, and applications for probiotic encapsulation. Science and Technology of Food Industry, 46(8), 411−419. https: //doi.org/10.13386/j.issn1002-0306.2024060018