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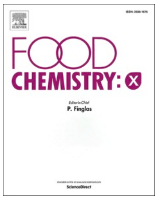

Research progress on plant-based protein Pickering particles: Stabilization mechanisms, preparation methods, and application prospects in the food industry

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ABSTRACT

At present, there have been many research articles reporting that plant-based protein Pickering particles from different sources are used to stabilize Pickering emulsions, but the reports of corresponding review articles are still far from sufficient. This study focuses on the research hotspots and related progress on plant-based protein Pickering particles in the past five years. First, the article describes the mechanism by which Pickering emulsions are stabilized by different types of plant-based protein Pickering particles. Then, the extraction, preparation, and modification methods of various plant-based protein Pickering particles are highlighted to provide a reference for the development of greener and more efficient plant-based protein Pickering particles. The article also introduces some of the most promising applications of Pickering emulsions stabilized by plant-based protein Pickering particles in the food field. Finally, the paper also discusses the potential applications and challenges of plant-based protein Pickering particles in the food industry.

1. Introduction

An emulsion is a composite system comprising two or more immiscible liquids (Wang et al., 2022). Typically, stabilizers, continuous phases, and dispersed phases are integral components of this system (Yan et al., 2020). The stability of traditional emulsions is improved by incorporating surfactants with small molecular structures (Tian et al., 2022). By reducing the interfacial tension between the oil and water, these surfactants guarantee the long-lasting stability of the emulsion (Song et al., 2020; Wei et al., 2020). This helps to maintain the desired consistency while preventing the phases from separating (Keramat et al., 2022). However, the utilization of surfactants in emulsion foods is hindered by their cytotoxicity and environmental pollution upon discharge into natural ecosystems (Shi et al., 2020). Consequently, the application of surfactants in emulsion foods has been significantly restricted. Consumer preferences for healthier and more environmentally sustainable emulsions require reevaluating conventional emulsions and identifying emulsifiers that are more efficient, healthier, and environmentally friendly. At the beginning of the 20th century, Ramsden and Pickering achieved a revolutionary breakthrough by demonstrating that colloidal particles exhibit interfacial behavior and have the ability to efficiently stabilize emulsions (Pickering, 1907; Ramsden, 1904). In order to honor the notable achievements of these trailblazers in the respective discipline, the emulsion that is stabilized through the adsorption of colloidal particles at the interface of oil and water has been named Pickering emulsion. In contrast to emulsions stabilized by surfactants, Pickering emulsions exhibit remarkable resistance to coalescence and Ostwald ripening (Sarkar & Dickinson, 2020). Consequently, they have found utility in various domains, including the food and pharmaceutical industries, where long-term stability is of paramount importance (Albert et al., 2019; Chen et al., 2020; de Carvalho-Guimarães et al., 2022; Xia et al., 2021). As a result, the popularity of Pickering emulsions has significantly increased in these industries.

Pickering particles that can stabilize Pickering emulsions include inorganic and organic particles. Recent research has demonstrated that inorganic particles, such as clay, ferric oxide, calcium carbonate, and silicon dioxide, have the capability to form stable Pickering emulsions (Huang et al., 2019; Sun et al., 2020; Yu et al., 2021a; Zhang et al.,

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2022). Due to their excellent stability, moisture retention and ability to carry active ingredients, Pickering emulsions prepared by these inorganic particles have been widely used in the chemical, pharmaceutical and cosmetic industries. However, the biodegradability, biocompatibility, bioaccessibility, and consumption safety of inorganic particles are all low, which has greatly limited the application of inorganic particles in the food field (Wang et al., 2022). Therefore, the food industry is committed to finding greener and safer food-grade Pickering particles. Presently, a paramount objective is the advancement and implementation of organic particles, particularly those derived from biomass, as emulsion stabilizers. Indeed, many organic particles composed of natural biomass have a Pickering-stabilizing effect. Notably, polysaccharide particles (e.g., starch granules, cellulose, chitosan), protein particles (e.g., soy protein, zein, wheat prolamin, pea protein, peanut protein, β-lactoglobulin), and fat particles (e.g., lipoprotein, diacylglycerol crystals) are among the effective materials in this regard (Fan et al., 2022; G. Li et al., 2021b; Z. Li et al., 2023c; Y. Liu et al., 2023; Ning et al., 2020; Su et al., 2020; Tang et al., 2023; B. Yu et al., 2023; Y. Zhang et al., 2022; Z. Zhao et al., 2020; Zhong et al., 2023). Among them, proteins are regarded as ideal Pickering emulsion stabilizers (Yan et al., 2020). Protein particles possess remarkable benefits including surface behavior, low toxicity, compatibility with living organisms, ability to break down naturally, easy extraction from natural sources, nutritional worth, and approval in the food sector (Yan et al., 2020). Moreover, the distinctive functional attributes of protein particles enable the manipulation of Pickering emulsion properties. For instance, by altering factors such as pH value, ultrasonic intensity, temperature, and others, the structure and properties of proteins can be adjusted, thereby facilitating the manipulation of protein-stabilized Pickering emulsions (Qin et al., 2018; Ren et al., 2021; X. Zhang et al., 2020). This is especially beneficial for food products, as it allows for the creation of a stable product with the desired texture and flavor profile. Additionally, the use of Pickering emulsions also reduces the need for added preservatives and other additives.

To acquire desirable emulsifying properties, natural proteins frequently necessitate processing and modification to transform them into Pickering particles. Following straightforward processing or modification, proteins derived from both animal and plant sources can exhibit exceptional Pickering particle characteristics. However, it is important to mention that plant-based protein is significantly more environmentally friendly than animal-based protein and meets the requirements for a clean label (Sarkar et al., 2020). Plant-based proteins are also an efficient source of nutrition, with high levels of essential amino acids, vitamins, minerals, and dietary fiber (Sha & Xiong, 2020). In addition, plant-based protein is more widely available and cheaper than animal protein (Raja et al., 2022). Furthermore, plant-based protein comes from a wide range of sources and is an effective source of nutrients. Furthermore, employing plant-derived proteins to create Pickering particles for the purpose of stabilizing Pickering emulsions presents a cost-effective and ecologically sound strategy (Ribeiro et al., 2021). Moreover, plant-based protein Pickering emulsions are widely used in the food industry, including as an active substance carrier, inhibiting lipid oxidation, replacing hydrogenated vegetable oil, and as a biomimetic interfacial catalytic reactor (Ge et al., 2022; Ni et al., 2022; Shen et al., 2021; C. Wang et al., 2023a). Consequently, current scholarly investigations primarily concentrate on the development of preparation techniques and stabilization mechanisms for plant-based protein Pickering particles, as well as the application of stable Pickering emulsions in the food industry (Sarkar et al., 2020). The intricate stabilization mechanism of plant-based protein Pickering particles was initially elucidated through prior endeavors. Additionally, current research focuses on exploring environmentally friendly, cost-effective processing and modification techniques for the preparation of plant-based protein Pickering particles, as well as the high-value application of plant-based protein Pickering emulsions within the food industry.

Extensive research has been carried out on the techniques and applications of Pickering particles derived from plants, including soy, peanut, corn, pea, quinoa, wheat, and others. However, a thorough assessment of Pickering emulsions that are stabilized by plant-derived protein Pickering particles is lacking in the existing body of literature. Hence, this article aims to offer a thorough exploration of the stabilization mechanism, techniques for preparation, and various applications of Pickering particles derived from plant-based proteins. Initially, various stabilization mechanisms of plant-based protein Pickering particles were scrutinized. Subsequently, a comprehensive overview of essential methods for acquiring and modifying Pickering particles derived from plant-based proteins is provided. Finally, the significant application of plant-based protein Pickering emulsions in the food industry is summarized. In summary, this review offers readers a comprehensive comprehension of the stabilization mechanism and research advancements pertaining to plant-based protein Pickering emulsions. Furthermore, it provides a theoretical direction for the exploration and development of environmentally friendly, secure, and sustainable plant-based protein emulsions.

2. Stabilization mechanism of plant-based protein Pickering particles

The primary means by which plant-derived protein Pickering particles stabilize is through the adsorption of particles at the interface between oil and water, the creation of network structures within the continuous phase, and depletion stabilization (Yan et al., 2020). Pickering emulsions are complicated systems. In a stable Pickering emulsion system, the Pickering particle-stabilized emulsion is often completed through a variety of different stabilization mechanisms. Therefore, this section will introduce three different stabilization mechanisms separately.

2.1. Adsorption of particles at the interface between oil and water

The primary obstacle to the creation of an emulsion is the interfacial tension occurring at the interface between oil and water. When the immiscible oil phase and water phase are dispersed together to form an emulsion under the action of amphiphilic Pickering particles, not only will the interface be created, but the interfacial tension will also change (Wang et al., 2022). When liquid molecules at the oil-water interface are replaced by amphiphilic Pickering particles, the interfacial tension and the energy needed to create the new interface are reduced. Pickering particles adsorbed at the oil-water interface can form a spatial or electrostatic barrier layer that prevents emulsion droplet coalescence (Rayner et al., 2012). The stability of Pickering emulsions relies on the amount of free energy (ΔG_S) possessed by Pickering particles that have been absorbed at the interface between oil and water. For a single isotropic sphere particle with a radius of r, the ΔG_S value can be expressed by Formula (1):

$$\Delta G_s = -\Delta E = \pi r^2 \gamma_{ow} (1 \pm Cos\theta)^2 \tag{1}$$

ΔE represents the energy needed for spherical Pickering particles to detach from the oil-water interface in the formula. The radius of the spherical Pickering particles is denoted as r, while γ_{ow} represents the tension between oil and water at the interface. Additionally, θ represents the three-phase contact angle of the Pickering particles. Formula (1) shows that the radius r has a significant influence on the stability of the emulsion. The value of ΔG_S is proportional to r^2. Surfactant molecules are generally smaller than spherical Pickering particles. This is the main reason why Pickering emulsions are much more stable than traditional emulsions formed with surfactants. The study by Binks et al. (Binks, 2002) found that when Pickering particles are reduced to less than 0.5 nm, which is equivalent to surfactant molecules, they will be easily desorbed from the oil-water interface. In addition, from Equation (1), it is not difficult to find that the ΔG_S value is also closely related to the size of the three-phase contact angle θ. θ is an important parameter to quantify the wettability of spherical Pickering particles to the oil and water phases, and can be provided by Formula (2):

$$Cos\theta = \gamma_{po} - \gamma_{pw}/\gamma_{ow} \tag{2}$$

The formula includes γ_{po}, which represents the interfacial tension between Pickering particles and oil, and γ_{pw}, which represents the interfacial tension between Pickering particles and water. Considering that the two phases of the oil-water interface are wetted by the Pickering particles, the wettability of the Pickering particles is another key factor determining the stability of the Pickering emulsion. Formula (2) reveals that particles are predominantly wetted by water when θ is less than 90°. At this time, Pickering particles at the oil-water interface tend to bend toward the oil phase to create oil-in-water (O/W) Pickering emulsions. When θ is greater than 90°, the particles are preferentially wetted by the oil phase. Pickering particles at the oil-water interface tend to bend toward the water phase, forming water-in-oil (W/O) Pickering emulsions. When $\theta = 90^\circ$, the ΔG value of Pickering particles is the largest, and the formed Pickering emulsion has the highest stability. Fig. 1 is a schematic diagram of the type of Pickering emulsion when the three-phase contact angle of Pickering particles is <90° and >90°. In addition, it is important to point out that these conclusions are based on the assumption that Pickering particles are rigid uniform spheres (Wang et al., 2022). The stabilization mechanism of Pickering emulsions cannot be accurately described by the appeal formula when a plant-derived protein soft micelle possessing surface charges and deformability is employed as Pickering particles (Shi et al., 2020). However, to comprehend the Pickering stabilization mechanism of plant-based protein particles, it is crucial to grasp the Pickering stabilization mechanism of classical rigid spherical particles. Therefore, it is necessary to develop a new model to explain the Pickering stabilization mechanism of plant-based protein particles. In this way, a better understanding of the Pickering stabilization mechanism and more efficient Pickering emulsions can be achieved.

When creating Pickering emulsions using homogenization or high-speed shearing, the particles derived from plants will display characteristics of soft particles and undergo deformation upon adsorption at the oil-water interface during the formation of Pickering emulsions (D. Wang et al., 2020a). In this case, plant-based protein particles cover a larger oil-water interface area than traditional rigid spherical Pickering particles. It should be noted that Equation (1) is no longer applicable at this time. To calculate the interfacial desorption energy of deformable plant-based protein particles, Equation (3) can be used. As shown in Fig. 2, the radius of the plant-based protein when it is not deformed is R, and a is the radius of the plant-based protein after deformation due to adsorption at the oil-water interface. In the formula, A_W and A_O are the particle-water and particle-oil interface areas, respectively.

$$\Delta E = 4\pi r R^2\gamma_{pw} + \pi a^2\gamma_{ow} - A_W\gamma_{pw} - A_O\gamma_{po} \tag{3}$$

In this scenario, due to the increased contact radius of the deformed particles, the desorption energy needed to break away from the oil-water interface is higher than that of rigid particles of the same volume. In addition, calculated from Eqs. (1) and (2), the interfacial free energy of the emulsion system also decreases as the interface area decreases. In theory, deformable plant-based protein particles are promising and efficient stabilizers for Pickering emulsions. Some plant proteins (such as soy protein, pea protein, peanut protein, corn protein, etc.) have been used to prepare deformable particles to stabilize Pickering emulsions (Ning et al., 2020; Tan et al., 2021; Tang et al., 2023; D. Wang et al., 2020a). It is worth noting that considering the complexity of the structure and properties of plant-based proteins, these mechanisms and related methods may only be applicable or suitable for some specific proteins and should not be considered universal rules. Therefore, it is important to consider the characteristics of different plant proteins when designing and preparing Pickering emulsions. Different proteins may require different techniques and methods for successful emulsion stabilization. Additionally, the effectiveness of the stabilization process may vary with different proteins.

2.2. *Form a three-dimensional network structure*

Undoubtedly, the existence of protein particles in Pickering emulsion systems boosts the emulsion stability through particles adsorbing at the interface between oil and water. Additionally, certain particles contribute to the emulsion's stability by creating a three-dimensional network structure within the continuous phase (Berton-Carabin et al., 2021). By preventing the merging of oil droplets, this network arrangement enhances the stability of the emulsion. Pickering emulsions also have three-dimensional network structures when plant-based proteins are present in excess. A schematic diagram of the three-dimensional network structure formed by the excess plant-based protein Pickering particles in the Pickering emulsion is shown in Fig. 3. According to Dickinson et al. (Dickinson, 2010), this three-dimensional network structure can reduce the movement of droplets within Pickering emulsion systems. Additionally, it can inhibit the descent of water particles and the buoyancy of oil particles, thereby improving the emulsion's stability. By enhancing the emulsion stability, it becomes possible to store it for an extended duration without experiencing any alterations in its characteristics. Furthermore, this arrangement has the potential to alter the characteristics of the Pickering emulsion, including its consistency, interfacial tension, and droplet size. Zhang et al. (X. Zhang et al., 2020) used different concentrations (1 % – 3 %, w/v) of soy protein isolate-carboxymethylcellulose composite particles to emulsify 74.05 % of the oil phase to form a high internal phase Pickering emulsion. With an increase in the concentration of composite particles, the droplet size of the high internal phase emulsion decreases, leading to an increase in stability. The utilization of scanning electron microscopy enabled the observation of the three-dimensional network structure formed by

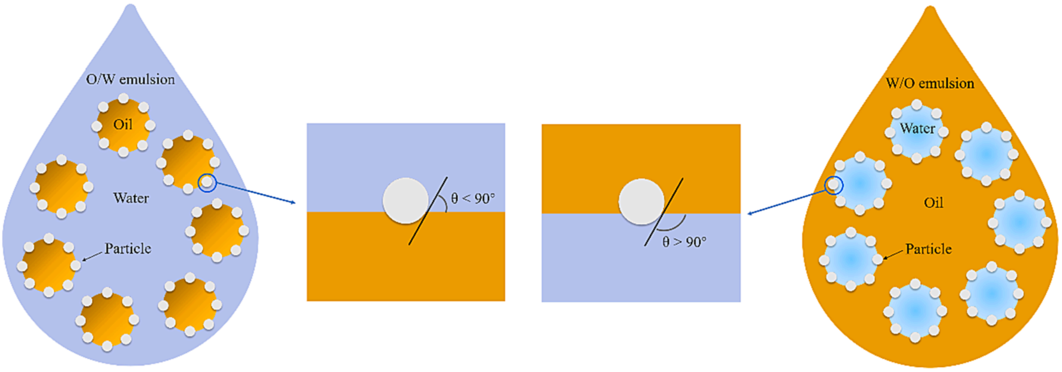

Fig. 1. Schematic diagram of Pickering emulsion types when the three-phase contact angle of Pickering particles is <90° and >90°.

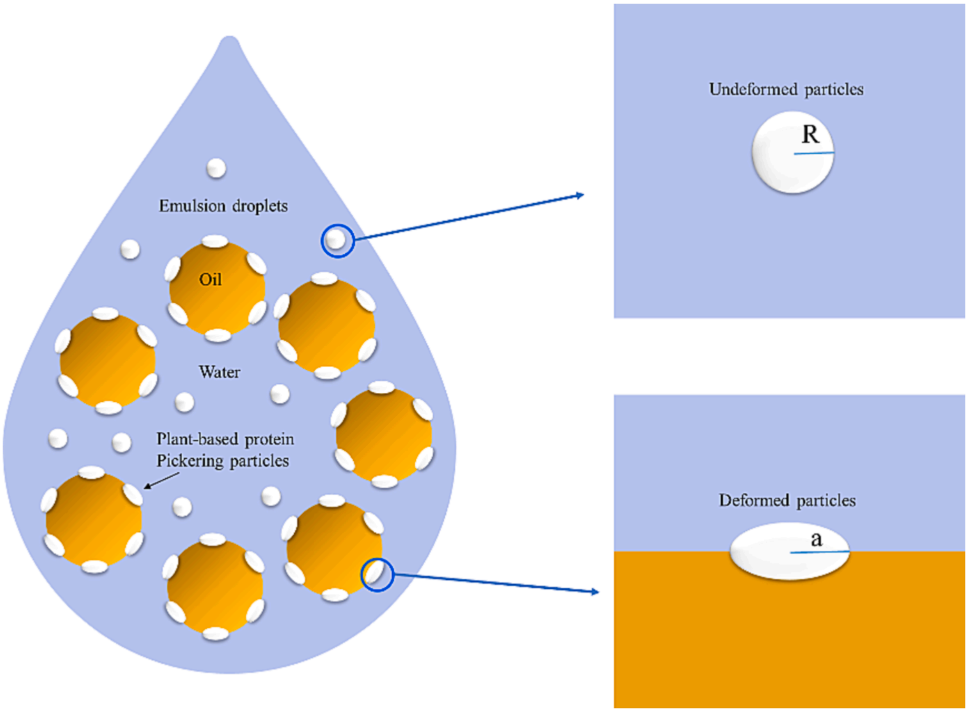

Fig. 2. Schematic diagram of adsorption and deformation of plant-based protein Pickering particles at the oil-water interface.

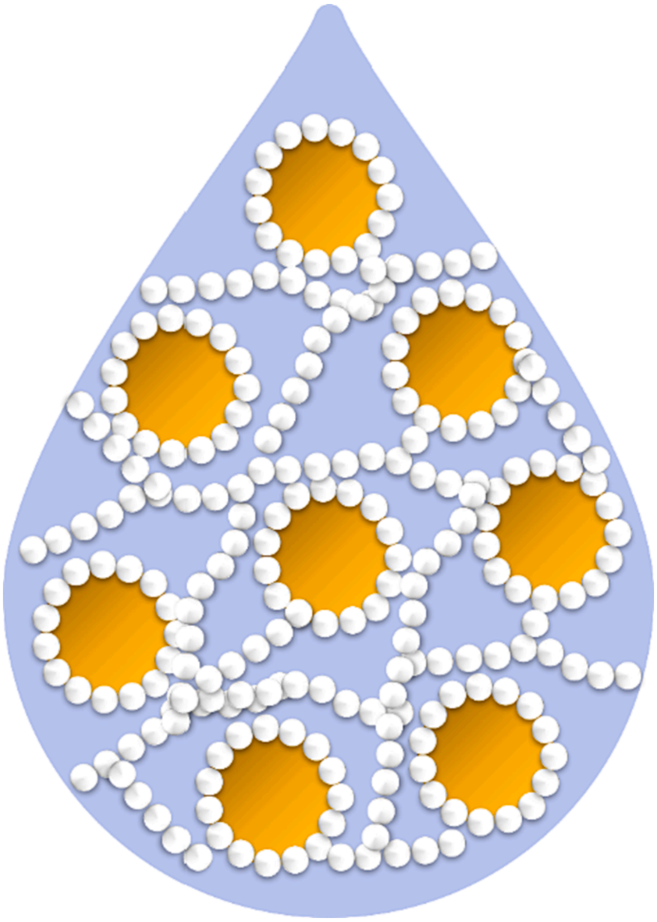

Fig. 3. Schematic diagram of the three-dimensional network structure formed by excess plant-based protein Pickering particles in Pickering emulsion.

composite particles, which was found to be a crucial determinant in augmenting the stability of the emulsion. The viscosity is also influenced by the arrangement of the network since a greater number of particles results in increased viscosity. The stability and viscosity of the emulsion improved by controlling the particle concentration.

Another report used peanut protein isolate microgel to emulsify more than 85 % of the oil phase to prepare Pickering emulsions (Jiao et al., 2018). Through scanning electron microscopy and optical microscopy observations, they found that the protein layer formed on the surface of the oil droplets and that the three-dimensional network structure formed by the protein microgel in the water phase jointly stabilized the Pickering emulsion. The protein layer increases the hardness of the emulsion, and the three-dimensional network structure inhibits oil droplet movement. This report also shows that changing the pH value of the aqueous phase can adjust the structure and rigidity of the three-dimensional network. The change in pH value of the aqueous phase can also affect the oil droplet size, which in turn can influence the viscosity of the emulsion. This can lead to different textures in the final product. Yan et al. (Yan et al., 2020) found that the initial concentration of protein particles in the continuous phase is one of the key factors that determine the formation of the three-dimensional network structure in Pickering emulsions. If the concentration of protein particles is too low, it will not be possible to form a three-dimensional network structure in the continuous phase. If the concentration of protein particles is too high, the emulsion will become difficult to homogenize. Therefore, protein particles of appropriate concentration should be screened to prepare stable Pickering emulsions. The concentration of protein particles should be carefully adjusted according to the desired properties of the emulsion and the application.

2.3. Depletion stabilization mechanism

The mechanism of depletion stabilization involves the consumption of protein particles in the Pickering emulsion system that are not absorbed at the interface between oil and water to stabilize Pickering emulsions. Different types of plant-based proteins vary greatly in structure and properties. When excess protein exists in the continuous phase of the emulsion, some types of protein do not form a network structure. Instead, they exist in the form of nonabsorptive polymers. When there are sufficiently high concentrations of nonabsorbable polymer molecules in the emulsion system, they promote the flocculation of emulsion droplets and colloidal particles in Pickering emulsions by generating osmotic stress (Bai et al., 2018). According to research, the enhancement of emulsion stability in oil-in-water emulsions can be achieved by incorporating protein fibers, which leads to an increase in the depletion attraction force among particles within the system (Peng et al., 2016). Fig. 4 is a schematic diagram of the depletion stabilization mechanism of protein fibrils in Pickering emulsions. Currently, there is a limited amount of research on the stability of Pickering emulsions that are improved by plant-derived proteins using the depletion mechanism. However, in certain exceptional scenarios, the significance of this mechanism cannot be disregarded. Therefore, more attention should be given to the depletion stabilization mechanism of plant-based proteins in future research. Such research could ultimately offer a more sustainable and eco-friendly approach to emulsion stabilization. This could provide products with better performance and properties while reducing the environmental impact of their production.

3. Preparation method of plant-based protein Pickering particles

Plant-based proteins often need to be modified to make plant-based protein Pickering emulsions meet food industry requirements. This section introduces the preparation methods and related applications in several plant-based protein Pickering particles, including the heat-induced aggregation method, mechanical treatment method, pH-cycling method, antisolvent precipitation method, chemical cross-linking method, and enzyme treatment (Table 1). These methods can change the structure of plant-based proteins, improving their emulsifying ability. As a result, these modified plant-based proteins can be used to create sustainable alternatives to animal-based products.

3.1. Heat-induced aggregation method

The preparation of Pickering particles can be achieved through a straightforward, environmentally friendly, and effective heat treatment method. It has been widely studied and applied to improve plant-based protein amphiphilicity. The amphiphilic characteristics of proteins can be modified to varying degrees, and this modification can be regulated through parameters related to heat treatment. Improving the emulsifying and foaming properties of the protein, which are crucial functionalities, can also be achieved through heat treatment. Heat-induced aggregation of proteins refers to changing the molecular conformation of unaggregated proteins through heat treatment, thereby changing the function of the protein. The heat treatment process modifies the quantity of protein hydrophobic groups that are exposed, thereby preparing Pickering particles. This is because heat treatment can change the structure of plant-based proteins, causing protein parts to unfold, fold, or aggregate. Thermal treatment technology has been proven suitable for plant-based proteins such as soy protein (B. Cui et al., 2022a), *Phaseolus vulgaris L.* protein (C. Li et al., 2023a), corn protein (T. Song et al., 2021) and peanut protein (Ning et al., 2020). In a study conducted by C. Li and colleagues in 2023 (C. Li et al., 2023a), it was shown that heat treatment can expose *Phaseolus vulgaris L.* protein hydrophobic groups. Furthermore, heat-treated *Phaseolus vulgaris L.* protein exhibits better emulsification ability than raw materials without heat treatment. They show better stabilizing ability for oil-in-water Pickering emulsions. In addition, there are studies demonstrating the development of Pickering nanoparticles through dual induction of selenium-rich peanut protein by heat treatment and different concentrations of sodium chloride ions (Ning et al., 2020). Peanut protein nanoparticles have a high surface charge and excellent oil-water two-phase wettability, and an O/W Pickering emulsion with a more uniform droplet distribution and smaller size can be prepared by increasing the nanoparticle concentration. Pickering particles prepared by heat treatment are simple to operate, low cost, suitable for industrial scale and have other significant advantages (J.-X. Liu et al., 2021). Therefore, it has significant application potential in the preparation of plant-based protein nanoparticles and Pickering emulsion stabilization. The potential of Pickering particles is significant in various fields, including delivering drugs, preserving food, and treating wastewater (Kouhi et al., 2020). Moreover, they have the potential to generate inventive substances possessing a diverse array of characteristics.

3.2. Mechanical treatment method

The principle of mechanical preparation of plant-based protein Pickering particles is to prepare large-sized proteins into small-sized particles through external mechanical force and energy. The droplet size of Pickering emulsions is mostly micron-scale, and it is generally believed that the size of Pickering particles must be an order of magnitude smaller than the size of emulsion droplets. To prepare Pickering particles, large proteins must be broken down into smaller ones. Currently, commonly used mechanical methods include micro fluidization, high-pressure homogenization, high-intensity ultrasound, and high hydrostatic pressure.

According to Qin et al. (Qin et al., 2018), subjecting quinoa protein to ultrasonic treatment for a duration of 20 min at a power level of 100 W led to an augmentation in the hydrophobic characteristics and emulsifying capacity of the quinoa protein. Furthermore, the research conducted by the authors also revealed a positive correlation between the salt concentration and the freeze–thaw stability of the quinoa protein Pickering emulsion. This was attributed to the salting-out effect that inhibited the formation of ice crystals. The high hydrostatic pressure method processes proteins by providing constant, uniform pressure. High hydrostatic pressure enhances proteins' functional and nutritional characteristics, including their ability to emulsify, dissolve, digest in vitro, and reduce allergenicity (Sui et al., 2021). Furthermore, employing high hydrostatic pressure can effectively decrease the

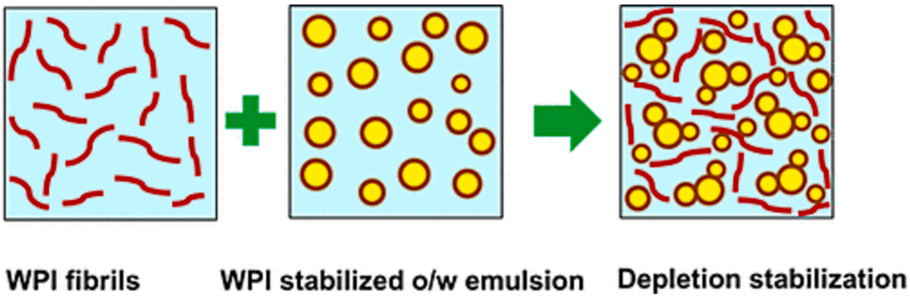

Fig. 4. Mechanisms of depletion stabilization of protein fibrils. Reprinted (adapted) with permission from (J. Peng et al., 2016). Copyright ©2016, American Chemical Society.

Table 1
Comparison of preparation methods for plant-based protein Pickering particles.

Methods	Protein type	Effects	References
Heat-induced aggregation	*Phaseolus vulgaris L.* protein	Increased surface hydrophobicity and emulsifying ability	(C. Li et al., 2023a)
	Peanut protein	Increased surface hydrophobicity and amphiphilicity	(Ning et al., 2020)
	Soy protein isolate	Enhanced emulsifying ability	(B. Cui et al., 2022a)
Ultrasonic treatment	Quinoa protein	Enhanced protein Increased and emulsifying ability	(Qin et al., 2018)
High hydrostatic pressure	Soy protein isolate	Reduced size, increased emulsifying ability	(Tan et al., 2021)
Micro fluidization	Soy protein isolate	Increased adsorption capacity and amphiphilicity	(N. Wang et al., 2023b)
pH-cycling	Ginkgo seed protein	Significant increase in solubility, hydrophobicity, and emulsifying ability	(W. Zhang et al., 2021b)
	Wheat gluten protein	Enhanced solubility and emulsifying ability	(Xiong et al., 2023)
Anti-solvent precipitation	Hemp protein	The number of random coils and β-sheets increases, and the emulsifying ability is enhanced	(Y. Sun et al., 2023)
	Zein	Enhanced emulsifying ability under alkaline and neutral conditions	(D. Wang et al., 2020a)
Chemical cross-linking	Soy protein isolate	Enhanced emulsifying ability after cross-linking with Genipin	(Xiao et al., 2023)
	Hemp seed protein	Total sulfhydryl groups and surface hydrophobicity decreased after cross-linking with Genipin	(Q. Wang et al., 2019)
	Ginkgo seed protein	Solubility, surface hydrophobicity and fluorescence intensity are reduced after cross-linking with Genipin	(He et al., 2023)
Polyphenol modification	Soy protein isolate	Enhanced emulsification through hydrophobic interactions and hydrogen bonding to form non-covalent bonds	(G. Chen et al., 2019)
	Black soybean protein isolate	Enhanced emulsifying ability	(X. Cui et al., 2022b)
Glycosylation modification	Soy protein isolate	Reduced particle aggregation, enhanced solubility, and emulsifying properties	(Y. Wang et al., 2020b)
Enzyme treatment	Soy protein isolate	Enhanced emulsifying properties	(Luo et al., 2019)
	Hemp seed protein	Enhanced emulsification and water-holding capacity	(Zhou et al., 2022)
	Pea protein	Enhanced emulsifying, gelling, and water-holding capacity	(Yi et al., 2024)

quantity of microorganisms in the item, consequently enhancing the preservation of the functionality and nutritional value of food components in processed goods and enhancing the parameters of food quality. Tan et al. (Tan et al., 2021) treated soybean protein isolate with high hydrostatic pressure combined with a pH shift. Through the analysis of various data, including the circular dichroism spectrum, far-ultraviolet spectrum, and surface hydrophobicity, they observed that the structure of soybean protein isolate underwent partial unfolding and dissociation. This resulted in a significant increase in surface charge and solubility and a decrease in particle size. In addition, it was also found that increased pressure enhances the pH shift effect. The synergistic effect of high hydrostatic pressure and pH shift can significantly unfold the protein structure, further improving SPI emulsification activity and stability. This leads to improved product quality and shelf life. The encapsulation efficiency of the emulsions is also enhanced. Overall, this approach is an effective method of improving emulsification. Microfluidization is an advanced technology that effectively harnesses the synergistic impact of various factors, including high pressure, instantaneous pressure drops, strong shear, and cavitation (Sui et al., 2021). According to a study conducted by N. Wang et al. in 2023 (N. Wang et al., 2023b), it was discovered that the stability of Pickering emulsions can be greatly improved by combining soy protein isolate and tannic acid through noncovalent complexation, along with the application of micro fluidization treatment. Furthermore, the protein concentration absorbed at the emulsion oil–water interface, emulsion viscosity, and oxidative stability were significantly enhanced after micro fluidization treatment. This suggests that micro fluidization is a successful approach to enhancing emulsion characteristics. Microfluidization is also easy to control and cost-effective compared to other methods.

3.3. *pH-cycling method*

A variety of plant-based proteins have large differences in structure and properties, so they often have diverse isoelectric points (McClements & Grossmann, 2021). Under different pH values, the protein structure, solubility, and hydrophobicity will change to varying degrees. This will lead to changes in its emulsifying ability, foaming, gelling, and other functional properties. The pH-cycling technique proves to be a highly effective approach in the production of hydrophobic Pickering particles derived from plant-based proteins (Rahman & Lamsal, 2021). To partially expand or unfold the protein structure, the pH-cycling technique initially exposes the protein to highly acidic or alkaline conditions (Xiong et al., 2023). Next, they modify the pH to achieve a neutral state, which leads to the folding of protein molecules and the creation of novel structures that impact their functional characteristics. Ginkgo seed protein properties can be significantly improved by pH cycling (W. Zhang et al., 2021b). Its solubility is increased by 141 %, the hydrophobicity is more than doubled, and the emulsification ability is also greatly improved. In addition, a recent investigation conducted by Xiong et al. (Xiong et al., 2023) revealed that when subjected to a combination of pH cycling and heat treatment, wheat gluten solubility exhibited an almost tenfold increase under conditions where the temperature did not exceed 80 °C. The study also found that the emulsifying ability of processed wheat gluten was significantly improved. The pH-cycling method offers clear benefits, such as its straightforward operational procedure, affordability, and applicability in industrial settings. Hence, the pH-cycling technique exhibits promising potential in the synthesis of nanoparticles derived from plant-based proteins and the stabilization of Pickering emulsions. Furthermore, this method can be used to produce food ingredients and other functional food materials.

3.4. *Antisolvent precipitation method*

The antisolvent precipitation method can be used to prepare plant-based protein Pickering particles of various sizes, shapes, and surface properties, and the interactions between particles can be controlled

(Truong-Dinh Tran et al., 2016). In the antisolvent precipitation process of plant-based protein Pickering particles, the protein must first be completely dissolved in a solvent phase (such as alcohol or alcohol solution) (F. Li et al., 2021a). Then, under different mixing conditions, the anti-solvent (such as an aqueous solution) is injected into the solvent at a pH far away from the isoelectric point, inducing solute supersaturation to provide the driving force for precipitation. Finally, the solvent phase in the dispersion solution is removed by a certain method. The mutual solubility of the solvent phase and antisolvent is a prerequisite for Pickering particles prepared by this method. The formation principles of Pickering particles include hydrogen bonding, electrostatic interactions, and hydrophobic interactions(Wang et al., 2022). Pickering emulsions can be effectively stabilized by utilizing plant-based protein nanoparticles produced through the antisolvent precipitation technique.

The performance of Pickering emulsions stabilized with hemp protein nanoparticles was optimized by tuning the emulsion properties through the utilization of an antisolvent precipitation method in a study (Y. Sun et al., 2023). Compared to nanoparticles prepared by high and low saturation, nanoparticles prepared by medium supersaturation have a smaller particle size and a higher surface charge and are more wettable and emulsifiable. According to the study conducted by Wang et al. in 2020 (D. Wang et al., 2020a), it was discovered that the pH level of the zein binary aqueous solution (80 % ethanol) could be used to modify the dimensions and hydrophobic properties of spherical zein nanoparticles produced through antisolvent precipitation. Under alkaline conditions, Zein particles exhibit a reduced particle size and possess a hydrophilic surface, enhancing their affinity for water. Zein nanoparticles, once obtained, have the potential to function as Pickering stabilizers in neutral environments, facilitating the formation of enduring Pickering emulsions. The obtained zein nanoparticles can be used as Pickering stabilizers under neutral conditions to form stable Pickering emulsions. Li et al.(D. Li et al., 2023b) successfully fabricated buckwheat protein/soybean polysaccharide composite particles and buckwheat protein/soybean polysaccharide/pterostilbene ternary nanoparticles by an antisolvent precipitation method. Based on the study results, the nanocomplexes were found to have a high level of physical stability and foaming ability. Pterostilbene has a much higher antioxidant capacity in ternary nanoparticles than in the free form. Antisolvent precipitation is a promising method for preparing plant-based protein Pickering particles due to its simple operation, low cost, and applicability to a variety of food ingredients. Furthermore, the process is amenable to scale-up and can be used to tailor the size of the particles, with potential applications in food engineering and delivery systems.

3.5. Protein cross-linking method

The protein cross-linking method can change the structure and properties of plant-based proteins and give them better emulsification capabilities. Protein crosslinking methods mainly include self-crosslinking between protein molecules and composite crosslinking induced by other substances. Protein intermolecular cross-linking is mainly achieved through chemical cross-linking, and composite cross-linking mainly includes induction by polyphenol modification, glycosylation, and induction by chemical cross-linking agents (Nooshkam et al., 2023; Qi et al., 2023; Sui et al., 2021).

3.5.1. Chemical cross-linking method

Chemical cross-linking is an effective method to improve and adjust plant-based protein particle solubility, wettability, and emulsifying ability (T. Zhang et al., 2021a). Plant-based proteins treated with chemical cross-linking can form new ionic and covalent bonds. Glutaraldehyde, phthalic acid, and genipin are the primary chemical cross-linking agents frequently employed (Gao et al., 2022; Y. Yu et al., 2021b). Plant-based proteins treated with chemical cross-linking agents can improve their amphiphilicity and emulsifying ability. Glutaraldehyde and phthalic acid-crosslinked proteins are limited in the food industry due to their low biocompatibility and high oral toxicity. Hence, this article exclusively presents the introduction of plant proteins that are cross-linked using genipin, which is a natural cross-linking agent characterized by its low toxicity and high biocompatibility. Some scholars have prepared a stable O/W Pickering emulsion by coating linseed oil with genipin cross-linked soy protein isolate nanoparticles (Xiao et al., 2023). Next, the Pickering emulsion was introduced into a self-healing hydrogel made from polyacrylic acid and guar gum. The inclusion of Pickering emulsion enhanced the hydrogel's remarkable self-repair capacity (achieving a self-healing efficiency of 6.10 % within 91 h) and mechanical characteristics (with a tensile strength of 0.89 MPa and a strain of 853.2 %). In another study, it was found that the use of different concentrations of genipin to modify hemp seed protein isolate led to a decrease in the total sulfhydryl content and free amino content of the protein, and the surface hydrophobicity decreased by approximately 30 % (Q. Wang et al., 2019). Pickering emulsions and hydrogels were prepared using genipin cross-linked proteins, and it was observed that when the emulsions were incorporated into the gels, the gelling ability was significantly enhanced. The modification of Ginkgo seed protein isolate (GSPI) was carried out by He et al. (He et al., 2023) utilizing genipin. The modified Ginkgo seed protein exhibited decreased solubility, surface hydrophobicity, and fluorescence intensity. This study also compared gel properties prepared with modified and unmodified GSPI. The study discovered a substantial increase in the firmness of the gel and its ability to retain water after modifying GSPI. Researchers are increasingly favoring genipin, as it serves as a natural agent for cross-linking proteins, effectively enhancing the emulsifying capability of plant-based proteins. Further investigation is necessary in the future regarding Pickering emulsions formed by genipin-crosslinked plant-based proteins.

3.5.2. Polyphenol modification method

The interaction between phenolic compounds and plant-based proteins can improve plant-based proteins' physicochemical properties, including oxidation stability, thermal stability, emulsification, etc. (X. Cui et al., 2022b). Research has found that tea polyphenols and soybean protein can enhance soybean protein emulsification by forming non-covalent bonds through hydrophobic interactions and hydrogen bonds (G. Chen et al., 2019). Other noncovalent interactions, such as ionic bonds, are minor in the interaction of polyphenols with proteins, but they can still be used to modify the functional properties of proteins. In another study, black soybean isolate protein/cyanidin-3-O-glucoside complex particles were prepared by using cyanidin-3-O-glucoside to induce black soybean protein isolate (X. Cui et al., 2022b). The high internal phase Pickering emulsions obtained with different concentrations of composite particles all have high storage and oxidation stability. As the concentration of composite particles increases, the droplet size of Pickering emulsions decreases, and the droplet distribution becomes more uniform. Chen et al. (H.-H. Chen et al., 2022) prepared pea protein isolate-maltodextrin-epigallocatechin-3-gallate (PPI-MD-EGCG) ternary conjugates through glycosylation and covalent reactions under alkaline conditions. They prepared curcumin-loaded Pickering emulsions using PPI-MD-EGCG. The study concluded that PPI-MD-EGCG was an effective delivery system for curcumin due to its high stability and loading efficiency. According to the research, the combination of protein, sugar, and polyphenols resulted in the disruption of the secondary formation of pea protein isolate. Consequently, there was a reduction in the hydrophobicity of the surface, along with a boost in the ability to form emulsions and scavenge DPPH free radicals. Additionally, it has the potential to be utilized in the creation of innovative food items that exhibit enhanced stability and shelf life. The potential applications of this delivery system in the food industry could be significant.

3.5.3. Glycosylation method

Glycosylation reactions, also known as Maillard reactions, are a complex series of nonenzymatic reactions between sugars and proteins

(Rabbani et al., 2020). Most proteins have shortcomings such as low solubility and poor hydrophilicity. Through the glycosylation reaction between proteins and polysaccharides, the surface activity of proteins and the hydrophilicity of sugars can be preserved simultaneously (Kutzli et al., 2021). Numerous studies have indicated that plant proteins undergoing the Maillard reaction exhibit enhanced emulsifying, solubility, antibacterial and antioxidant effects (Sui et al., 2021). Wang et al. (Y. Wang et al., 2020b) found that the functional properties of soy protein isolate can be significantly improved through the glycosylation reaction between maltose and soy protein isolate. The modified soy protein isolate particles are looser and uniform in size, molecular aggregation is significantly reduced, and solubility and emulsification properties are improved. In addition, the freeze–thaw stability of Pickering emulsions prepared from glycosylated soybean separated eggs was stronger. Some studies have also found that Pickering emulsions prepared from pea protein concentrate modified by gum arabic and the Maillard reaction can still exhibit excellent physical stability after treatment at 72 °C and high ionic strength (500 mM) (Zha et al., 2019). This study also found that the foul flavor of the emulsion (beany smell, etc.) was effectively improved after the Maillard reaction. This shows that the Maillard reaction can enhance plant-based protein emulsification properties and flavor. In the middle and late stages of the Maillard reaction, some harmful intermediates and byproducts (such as melanoidins, acrylamide, etc.) will be formed, which may pose hidden dangers to food nutritional value and safety (Sui et al., 2021). Therefore, future research will focus on controlling the production of Maillard reaction byproducts to ensure food safety while forming excellent plant-based protein Pickering particles. To do so, strategies should be developed to reduce the formation of byproducts by controlling reaction conditions such as temperature, pH, and the presence of catalysts. Additionally, new methods should be explored to further improve the stability and safety of plant-based Pickering particles.

3.6. *Enzyme treatment*

The advantages of enzymes in plant-based proteins are their specificity, low pollution levels and toxicity. Currently, commonly used enzymes for modifying plant-based proteins mainly include laccase, transfer glutaminase (TGase), tyrosinase, etc. (Nasrabadi et al., 2021). TGase and laccase are the main enzymes that improve protein stability and functionality. The impact of TGase on the gelling behavior of soybean protein isolated emulsions induced by salt was examined by Luo et al. in 2019 (Luo et al., 2019). It was found that precrosslinking soy protein isolate emulsion with TGase before gelling increases gel resistance to deformation and water-holding capacity. Zhou et al. (Zhou et al., 2022) found that TGase can catalyze the cross-linking of casein and hemp seed protein to form a complex. The cross-linked complex has better emulsifying activity and water capacity. In addition, pea protein function can be improved through chlorogenic acid-mediated laccase catalysis (Yi et al., 2024). The emulsifying activity, emulsifying ability, gel strength, and water-holding capacity of pea protein can be greatly enhanced through cross-linking with chlorogenic acid using laccase. The food industry is increasingly favoring enzyme treatment techniques for enhancing plant-based proteins due to their high efficiency, minimal pollution, and beneficial effects.

4. Application of plant-based protein Pickering emulsions in the food field

Plant-based protein particles are safe, nontoxic, degradable, and highly bioaccessible, and their stable Pickering emulsions have enormous application potential in the food field. As an active substance carrier, inhibiting lipid oxidation, replacing hydrogenated vegetable oil, and being used as a biomimetic interfacial catalytic reactor (Table 2) are the most scientific, economic, and social application directions of plant-based protein Pickering emulsions (Chang et al., 2023; Kan et al., 2023; Xi et al., 2021). Therefore, this section will introduce developments in the application of plant-based protein Pickering emulsions in these directions.

Table 2
Application of plant-based protein Pickering emulsion in the food field.

Application type	Stabilizer type	Advantages	References
Active substance carrier	Bacterial cellulose nanofibers/Soy protein isolate	Significantly improved retention and bioavailability of curcumin	(Shen et al., 2021)
	Hydrolyzed rice glutelin nanoparticles	Improved bioavailability and conversion rate of curcumin	(Z. Yang et al., 2023b)
	Soy protein hydrolysate microgel particles	Improved encapsulation efficiency and sustained release of quercetin	(J. Yang et al., 2023a)
	Pea protein and high methoxyl pectin colloidal particles	Improved β-carotene availability	(Yi et al., 2021)
Inhibit lipid oxidation	Gliadin/chitosan hybrid particles	Decreased primary oxidation products of lipid	(Zeng et al., 2017)
	Gliadin–chitosan nanoparticles	Enhanced antioxidant capacity	(Li et al., 2019)
	Zein-adzuki bean seed coat polyphenol covalent crosslinking nanoparticle	Enhanced lipid oxidation stability	(Ge et al., 2022)
Alternatives to Hydrogenated Vegetable Oil	Soy protein isolate	Replaces vegetable butter with a delicate taste	(C. Wang et al., 2023a)
Biomimetic interface catalytic reactor	Phosphorylated zein nanoparticles	Catalytic yield increased by more than twice	(Xi et al., 2021)
	Sodium caseinate	Higher reaction efficiency, rapid product separation and recovery, and recycling enzyme to maintain catalytic activity	(Xi et al., 2022)
3D printing	Rice proteins and carboxymethyl cellulose	Optimal printing resolution, hardness, adhesion and chewiness	(Wan et al., 2021)
	Pea protein-pectin-EGCG complexes	Emulsion-based inks provide strong support and smooth extrusion characteristics	(Feng et al., 2022)
	Tea residue protein/xanthan gum particles	Ideal for smooth extrusion and excellent self-supporting ability	(An et al., 2023)

4.1. *Active substance carrier*

Plant-based Pickering emulsions provide excellent carriers for active ingredients that are sensitive to environmental conditions. Studies have shown that high internal phase Pickering emulsions prepared using bacterial cellulose nanofiber/soy protein isolate composite particles can be used as encapsulation carriers for curcumin (Shen et al., 2021). The retention rate of curcumin in high internal phase emulsions is as high as 94.18 ± 2.97 %, and its bioavailability is also increased significantly.

Yang et al. (Z. Yang et al., 2023b) prepared curcumin-loaded Pickering emulsions by hydrolyzing rice glutenin with various concentrations of ethanol (25 %-100 %). It was found that the curcumin bioavailability and conversion rate were the highest in the ethanol-hydrolyzed rice glutenin nanoparticle Pickering emulsion at a concentration of 50 %, which may be due to its thicker oil–water interface film. In another study using a soybean protein-hydrolyzed microgel particle Pickering emulsion to carry quercetin, it was found that when the pH value was 9, the encapsulation efficiency of quercetin was the highest (89.45 %), and quercetin could be released continuously (J. Yang et al., 2023a). In vitro simulated digestion experiments showed that the fatty acid release rate in the emulsion was low (61 %) and the bioavailability of quercetin was high (65 %). In a study using pea protein Pickering emulsion to carry β-carotene, it was found that adjusting the oil phase fraction of the emulsion could regulate the intestinal release and stability of β-carotene in the emulsion (Yi et al., 2021). Overall, Pickering emulsions are proven carriers for delivering active substances. It has been shown to increase the bioavailability of compounds and enhance emulsion stability. These properties make it a promising tool for improving active substance delivery.

4.2. *Inhibit lipid oxidation*

Oxidation of lipids in food can produce potentially toxic components, leading to a decrease in the sensory and nutritional quality of fatty foods (Kaderides et al., 2021). The main cause of lipid oxidation in emulsion liquid-based foods is the interaction between lipid peroxides and transition metal ions near the droplet surface(Villeneuve et al., 2023). The oil-water interface layer of plant-based protein Pickering emulsions is much thicker than that of surfactant emulsions. It can better prevent lipid peroxides in oil droplets from contacting transition metal ions in the water phase to delay oxidation. In addition, some studies have found that many plant-based proteins also have antioxidant capabilities. For example, the presence of amino acids in gliadin side chains with antioxidant capacity can reduce the oxidation of lipids in emulsions by scavenging free radicals(Zeng et al., 2017). In addition, studies have shown that the rate of lipid oxidation in emulsions is also affected by the surface charge of the droplets. Li et al.(Li et al., 2019) found that the oxidative stability of fat in Pickering emulsions stabilized by gliadin/chitosan nanoparticles can be adjusted by adjusting the pH value of the emulsion. The Pickering emulsion prepared below gliadin's isoelectric point ($PI = 6.8$) has excellent oxidative stability. This is due to the strong positive charge of the adsorbed gliadin particles under this condition. This repels transition metal ions from the surface of oil droplets. In Pickering emulsions, lipid oxidation can also be inhibited by using polysaccharides or polyphenols to change the properties of adsorbed protein particles. For example, the resistance of Pickering emulsions to lipid oxidation can be improved by the interaction of soy protein isolate stabilizers with anthocyanins as well as zein and adzuki bean seed coat polyphenols(Ge et al., 2022; Ju et al., 2020). These studies demonstrate that plant-based proteins as Pickering emulsion stabilizers can significantly improve lipid oxidative stability. This, in turn, can increase the shelf life of food products and make them more appealing to consumers. Moreover, the use of plant-based proteins for stabilizing Pickering emulsions is an environmentally friendly and sustainable solution.

4.3. *Alternatives to hydrogenated vegetable oil*

In the food industry, animal fats and vegetable hydrogenated oils have a delicate and dense taste. They are loved by consumers and widely used in foods such as cream, ice cream, and butter. Animal fats are expensive and have a high carbon footprint. The trans fatty acids formed during the hydrogenation process of vegetable hydrogenated oils have negative effects on the cardiovascular system when ingested by the human body. Developing Pickering emulsions using plant-based proteins and vegetable oils is therefore a potential development path. Wang et al.(C. Wang et al., 2023a) prepared a high internal phase Pickering emulsion from soybean protein isolate and found that the high internal phase emulsion could replace hydrogenated vegetable oil. In addition, gliadin-stabilized high internal phase Pickering emulsions can also be used as a substitute for hydrogenated vegetable oils(Hu et al., 2016). By adjusting the pH value, the properties of gliadin-stabilized high internal phase Pickering emulsions can be changed. Klojdová et al.(Klojdová & Stathopoulos, 2022) reviewed the application prospects of water-in-oil-in-water (W/O/W) Pickering emulsions in functional ice cream. The application of W/O/W Pickering emulsions in ice cream can not only reduce the fat content and retain the creaminess of the product but also provide ice cream functionality by encapsulating probiotics and active substances. In addition to encapsulating flavors, colors, and other ingredients, Pickering emulsions can also increase the stability of ice cream. Additionally, the Pickering emulsion can provide a longer shelf life for the ice cream, allowing it to stay fresh for a longer period. The high internal phase Pickering emulsion can convert the liquid oil into a solid with a certain viscoelasticity to replace the solid fat. This has the advantages of being environmentally friendly, healthy, and inexpensive. Based on this, the replacement of hydrogenated vegetable oil by plant-based protein-stabilized Pickering emulsions is the focus of future research.

4.4. *Biomimetic interface catalytic reactor*

Pickering emulsion droplets have a large specific surface area, and applying them to biomimetic interface catalytic reactors can greatly improve catalytic efficiency (Ni et al., 2022). In addition, Pickering emulsions usually consist of an oil phase, a water phase, and Pickering particles adsorbed at the oil-water interface (H. Zhao et al., 2022). The Pickering emulsion can be demulsified by adjusting the pH value, heating, and repeated freezing and thawing, thereby achieving separation of the oil phase and the water phase. Therefore, applying Pickering emulsion to a biomimetic interfacial catalytic reactor can also achieve rapid separation of catalytic substrates and catalytic products (Ni et al., 2022). The study found that Pickering emulsions prepared by phosphorylated zein particles immobilized in gold nanoparticles can be used as catalysts for oil-water interface cascade reactions (Xi et al., 2021). In addition to excellent catalytic activity and recovery ability in various oil phases, this catalytic method also has high catalytic activity. In particular, the use of metal catalysts and biocatalysts at the oil-water interface can achieve cascade reactions, and the catalytic efficiency is more than 2 times higher than that of single metals. In addition, another study found that a CO2/N2 responsive oil-in-water Pickering emulsion stabilized only by sodium caseinate could serve as an efficient and sustainable biocatalytic system (Xi et al., 2022). The system can easily separate and recover sodium caseinate, enzymes and catalytic products. The recovered enzyme can still maintain high catalytic activity. However, there are few studies on the use of Pickering emulsions as biomimetic interfacial catalytic reactors in the current food field. However, Pickering emulsions have irreplaceable advantages in the field of biomimetic interface catalytic reactors. Therefore, it has bright application prospects in food catalysis.

4.5. *3D printing*

3D printing technology is an emerging food manufacturing process that has multiple advantages, such as low waste, time savings, high precision, and high efficiency. 3D printing follows the additive principle of layer-by-layer deposition based on a digital 3D model to build customized finished products that meet consumer needs in terms of shape, taste, texture, color, and nutrition. Wan et al. (Wan et al., 2021) used high internal phase Pickering emulsions prepared from rice protein and carboxymethylcellulose as inks for food-grade 3D printing. By changing the degree of substitution of carboxymethylcellulose, the hydrophobic/hydrophilic properties of rice proteins can be changed. This allows it to achieve controllable injectability and printability during 3D printing. In addition, Feng et al. (Feng et al., 2022) used a Pickering emulsion prepared by a protein-pectin-EGCG complex for 3D printing. They found that the loss rate of cinnamaldehyde as the flavor component decreased within 10.02±0.01 % and 11.29±0.01 %, respectively, during 3DP processing. An et al. (An et al., 2023) found that Pickering emulsion gel stabilized by tea residue protein/xanthan gum particles can also be used in 3D printing. They found that Pickering emulsion gel with xanthan gum over 1.5 % showed desirable smooth extrusion and excellent self-supporting capability to maintain the designed shape and structure. With the popularization and promotion of 3D printing technology in the food field, consumer preferences for 3D printed food should be fully considered to improve its acceptability. Safety is also an important aspect that must be considered.

5. Summary and outlook

Plant-based protein Pickering particles offer good application prospects in Pickering emulsions due to their advantages in green safety, emulsification, and modification. This article reviews the stabilization mechanism and preparation methods of plant-based protein Pickering particles and introduces the latest research progress in the application of stabilized Pickering emulsions in the food field. In view of the unique advantages of plant-based protein Pickering particles, we believe that more scholars will conduct in-depth research. In the future, in-depth research can be considered in the following aspects: (1) Exploring the stabilization mechanism of different types of plant-based proteins in Pickering particles; (2) Developing more plant-based proteins that can be used to stabilize Pickering emulsions; (3) Developing greener, safer and lower-cost preparation and modification methods for plant-based protein Pickering particles; (4) Exploring more valuable application fields of plant-based protein Pickering emulsions and improving plant-based protein Pickering particle added value; (5) Evaluating the compatibility of plant-based protein Pickering particles with other food ingredients and additives; and (6) Investigating the influences of various parameters on plant-based protein Pickering particle stability.

CRediT authorship contribution statement

Yachao Tian: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Fuwei Sun:** Formal analysis, Methodology, Software. **Zhuying Wang:** Conceptualization, Software, Validation, Visualization. **Chao Yuan:** Investigation, Supervision, Validation. **Zhongjiang Wang:** Project administration, Resources, Funding acquisition. **Zengwang Guo:** Funding acquisition, Project administration, Supervision. **Linyi Zhou:** Funding acquisition, Methodology, Project administration, Supervision, Validation, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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