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Animal-derived proteins as stabilizers of Pickering emulsions: applications and challenges

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Abstract

Emulsions are precursors for formulating stable food products with high demand worldwide and efficient cosmetics that can provide the capability of delivering bioavailable active ingredients. The development of Pickering emulsions is crucial because they can eliminate the more prolonged need for chemical stabilizers, increasing the sustainability and stability of the formulation. Conventional emulsion formulations employ chemical surfactants to stabilize. Nevertheless, incorporating proteins as emulsion stabilizers improves stability and attractiveness. Therefore, a systematic reference review is essential to give theoretical knowledge of Pickering emulsions and their structures and properties to review critical aspects, the mechanisms, and the vital applications to promote their stability. The subject of this review article is research focused on developing new protein modification technologies, improving their properties, and extending their applications. The applications of casein, whey protein, and egg albumin as emulsion stabilizers primarily focus on widely published literature. The present study focuses on evaluating the food industrial applications of casein, whey protein, egg albumin, lactoferrin, and myofibrils. The bioavailability of casein, whey protein, and egg albumin is essential for applying in Pickering emulsion, and it can be a limiting factor. We are opening new opportunities and options for utilizing alternative proteins, such as emulsion stabilizers.

Keywords: Pickering emulsions; lactoferrin; protein of animal origin; casein; albumin.

Practical Application: Animal proteins boost Pickering emulsions for better stability and sustainability.

1 INTRODUCTION

Emulsions are thermodynamically unstable systems constituted of a continuous and dispersed phase in the shape of tiny droplets. To ascertain the stability of these droplets, a surfactant or emulsifying agent is employed in the formulation, reducing the surface tension between the phases (Wang, Wang, et al., 2023). The stability of emulsions is a critical factor for their application, and it is conditional on the development phases and the proportion between the phases, size, and distribution of the droplets, concentration, type of emulsifier, free energy of the system, and the environmental factors (pH and temperature) (Luo & Wei, 2023). Therefore, alternative stabilization mechanisms exist, such as using solid particles that present advantages over traditional emulsions, offering more excellent stability, flocculation, and coalescence (Carvalho-Guimarães et al., 2022).

Pickering emulsions (PE) demonstrate greater biosafety and biocompatibility compared to traditional emulsions (stabilized by increasing viscosity) (PE) demonstrate greater biosafety and biocompatibility (Du et al., 2024). The particles adsorb at the interface between the immiscible liquid phases, forming a stratum around the droplets and the stabilized dispersed phase. A dense three-dimensional obstacle prevents the coalescence and Ostwald ripening phenomenon, increasing the product's shelf life (Jiang et al., 2020). The combination of good stability, reduced use of emulsifiers, and tunable rheological properties makes these systems relevant for several contexts, including food applications, the pharmaceutical industry, cosmetics, and the petrochemical industry (Ran et al., 2023).

Since PE has recently received attention, PEs have been employed in different formulations, always following the intended primary purpose. Pharmaceutical and cosmetic industries can benefit from PE, as it allows stable formulations of encapsulated and nonencapsulated products (Chu et al., 2021) and enrichment and modification of raw materials utilized in different formulations (Du et al., 2024). and enrichment and modification of raw materials used in different formulations (Chen et al., 2020; Huang et al., 2022; Ran et al., 2023) in bakery formulations (Su et al., 2023) as in other applications. PE can be used to improve waste treatment and sanitation technologies in environmental applications (Hadi et al., 2024) across many industrial sectors.

PEs stabilized with animal proteins offer notable advantages over those stabilized with plant-based particles, particularly in structure, functionality, and nutritional benefits. Proteins such as casein and whey, in addition to facilitating adsorption at the

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oil-water interface, form stable and flexible layers that resist coalescence and Ostwald ripening, increasing emulsion stability. Proteins used as PE stabilizers exhibit high stability over a wide range of pH and temperature conditions, making them ideal for applications involving thermal processing or variable pH environments. In addition, emulsions stabilized with animal protein particles provide excellent nutritional value and are more easily digestible and absorbable by the human body (Wen et al., 2023).

This study aimed to develop a systematic literature review on using animal proteins as stabilizers in PEs. The review aims to provide a theoretical basis from the available data on the PE concept, properties, and structure knowledge, as well as review the mechanisms and applications necessary to promote stability.

1.1 Relevance of the work

This study holds significant relevance as it explores the potential of animal-derived proteins as stabilizers in Pickering emulsions, presenting a sustainable alternative to conventional chemical surfactants. By enhancing the stability, functionality, and bioavailability of these emulsions, the research responds to the increasing demand for environmentally friendly and effective solutions in food and cosmetic formulations. Furthermore, it delves into innovative protein modification techniques that could streamline the incorporation of alternative proteins into product designs. This work not only advances the understanding of Pickering emulsions but also promotes sustainability, paving the way for safer and more efficient formulations across various industries.

2 METHODS

This study was initially based on a strict methodology to identify, select, and integrate the evidence available in scientific literature. Initially, the search was carried out on academic platforms, including ScienceDirect, Wiley, PubMed, and Google Scholar, using relevant search phrases ("Pickering emulsions," "Pickering," "protein of animal origin," "casein," and "albumin") to identify relevant studies on PE. After the initial selection, the inclusion and exclusion criteria were predefined and applied to identify those that met the review's objectives. The selected articles were assessed based on methodological excellence and scientific relevance, prioritizing publications from the last 5 years. Repeated articles were excluded to ensure a diverse range of sources. Research with significant innovations in the field was emphasized.

In some cases, older bibliographic references were included due to their high relevance and the limited availability of recent articles on specific topics. Relevant information, including the main results and conclusions of the included studies, was rigorously extracted and systematically synthesized (Figure 1).

Initially, 2,383 articles were selected and refined based on methodological quality. After evaluating the selected articles according to their scientific significance, an additional 2,184 research articles were discarded, resulting in 150 articles. Filters for scientific relevance were used, and publications from the last 5 years were selected; 96 studies remained for this review. In some cases, older articles were included in the text due to the study's relevance. The articles were critically examined and interpreted to identify trends, gaps in knowledge, and directions for new and innovative research that will use lactoferrin (LF) and myofibrillar proteins as stabilizers in emulsions. To increase the validity and consistency of the research results. Transparency and replicability were crucial at all stages of the systematic review to improve the reliability and validity of the findings presented.

3 GENERAL ASPECTS OF PICKERING EMULSIONS

PEs are regarded as substitutes for traditional surfactant stabilizers of emulsions (Sarkar & Dickinson, 2020), being attractive because of their higher stability and biodegradability (Gonzalez Ortiz et al., 2020). Compared to conventional emulsions, PE presents promising advantages, such as higher stability contrary to coalescence and phase separation, and superior resistance to pH and temperature variations (Mukherjee, 2020). The overall stabilization mechanism, based on the adsorption of solid particles at the interface of immiscible phases, is schematically illustrated in Figure 2. The decreased use of chemical surfactants, which can result in discomfort or allergic reactions, enlarges the potential application of PEs in multiple sectors like

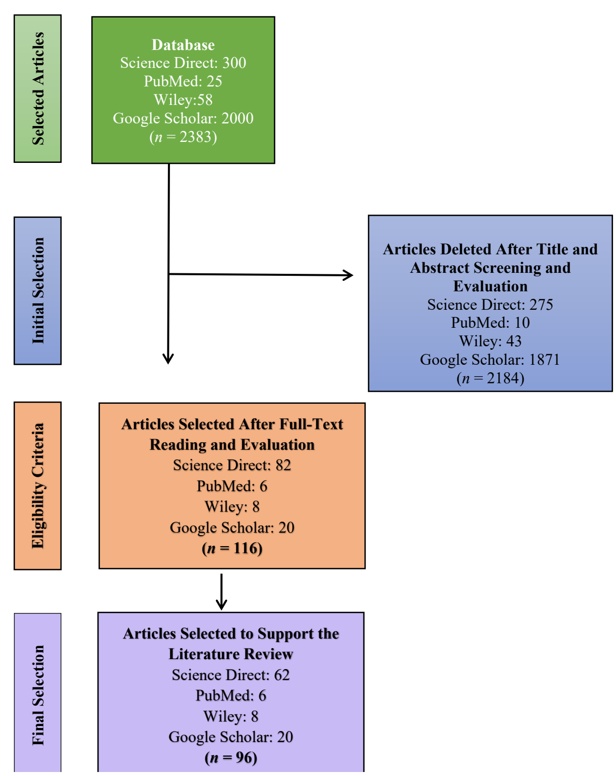

Figure 1. Diagram of the article determination system for review.

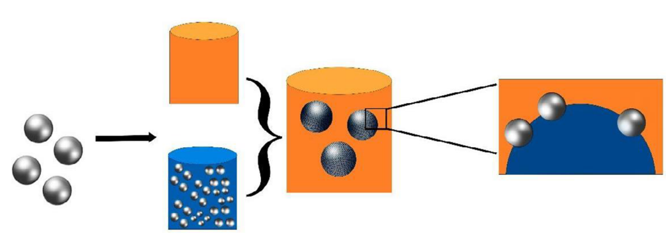

Figure 2. The mechanism of stabilization in Pickering emulsion highlights the use of solid particles.

the production of chemicals, food, cosmetics, and pharmaceuticals (Carvalho-Guimarães et al., 2022). The area of PE is consistently developing, primarily attributable to the research and investigation of new types of stabilizing particles, methods of formulation, and specific formulations. These stabilization processes increase the resistance of emulsions to changes in light, pH, and temperature variations, which enhances their application in the food industry (Doost et al., 2019). According to Li, Li, et al. (2023), PE presents higher stability, multifunctionality in applications, diversity, and stabilization using solid particles. The preference for the PE type is increased by the reduction and/or elimination of chemical surfactants (Carvalho-Guimarães et al., 2022), primarily attributable to the growing environmental interest.

A noteworthy aspect of using PE is the competence to control physical properties (stability and rheology), adapting to the nature and characteristics of the solid particles used. Furthermore, it can potentially enhance food's nutritional value and gastric protection (Xu et al., 2020). The excellent stability attributes become a potential system for advancing controlled properties and optimized performance (Du et al., 2024). Based on Du et al. (2024), using nanocrystals made using starch permitted the development of curcumin-encapsulated emulsions with higher stability, not just in the emulsion but also in the stability of the active ingredient, permitting this controlled compound release.

Specific strategies can be used by applying PE as models to structure liquid with low viscosity using vegetable oils into soft solids and oil gels (Li et al., 2022). Regarding their structure, emulsions are known as one of the most appropriate systems for delivering bioactive ingredients (Fanfan et al., 2005). When selecting a Pickering system, it is necessary to consider factors including emulsion stability, application content, enhanced performance, particle size, and shape (Doost et al., 2019). Moreover, the preference for organic and natural compounds is increasing, principally based on the absence of allergenic, inorganic, and environmental compounds (Li et al., 2019).

3.1 Stabilization methodologies

PEs arise through many intermolecular mechanisms that allow their formation (Wang, Jiang, & Shi, 2024b), including Van der Waals interactions, polymer adsorption, electrostatic forces, particle surface modifications, and many others (Elbers et al., 2016). The Van der Waals interactions play a vital role in stabilizing Pes. Due to their weak intermolecular forces that originate from the random fluctuation of electric charges, they directly influence the structure of the oil–water interface, inhibiting the coalescence of dispersed particles (Elbers et al., 2016). The interaction depends on crucial factors, including material, particle size and shape, and dispersed medium properties. The type of particle material is directly responsible for the influence of polarizability and the capacity to induce dipoles in another molecule (Wu et al., 2025). In contrast, more petite and irregular shapes of particles frequently show more significant interaction with dispersed phase droplets as a result of the larger surface area. Furthermore, the dispersed medium's polarity, viscosity, and temperature affect how the particles and droplets interact.

According to Ding et al. (2020), the same electrical charge can repel particles from each other, inhibiting the dispersed phase's droplets from approaching and, as a result, coalescence. The repulsion becomes more effective when the particles contain high charges and a reduced distance between them. Additionally, ions carrying the same charge as the particles adsorb on the surface of the dispersed phase droplets, forming a repulsive double layer that prevents the particles from approaching and contributes to the stability of the emulsion (Atkins, 2024). In this context, it is essential to know the factors such as size, shape, particle surface charge, pH, and ion concentration of the medium influence electrostatic stability (Chen, Chen, et al., 2022), and as a result, the stability reduction of the emulsion and the strength of the double layer of electricity.

Surface modification might change the affinity of particles with the dispersed or continuous phase, impacting the distribution of particles at the interface and the stability of the emulsion (Li et al., 2022). Various techniques are usable to modify the surface of particles in PE, such as chemical functional modification, impregnation, covering the surface, and morphology modification. The surface modification enlarges the possibility of applications for emulsions in critical areas (Chen, Chen, et al., 2022; Huang et al., 2018). Regardless of the numerous advantages, modification steps still, in effect, have some challenges, for example, precise control of the modification, scalability steps (enhance technical and economic viability), and awareness of the mechanisms of interaction between modified particles, including others.

3.2 Pickering emulsions and industrial applications

In the present field, in light of the increasing research and discoveries in the production of PE, a significant impact has been observed in the large-scale production and associated benefits. According to Koroleva and Yurtov (2020), using silica and metal particles to stabilize emulsions improves the production of micro- and nanocapsules and colloidosomes. The experimental investigation demonstrated that emulsions formulated with silica/magnetite nanoparticles at pH 8 are stable to cream due to the appearance of a gel-like structure in the aqueous phase of the emulsions. In contrast, silica/gold nanoparticles were unstable. The study concluded that hetero-aggregates of silica and gold nanoparticle chains were unstable, gradually transforming into spherical aggregates. The oil phase fraction increased in the residual emulsion due to the partial separation from the aqueous phase. Nevertheless, it demonstrated a smaller and less dense packing, which can influence the quality of the particle.

Examining to explore alternatives to encapsulate and enhance the availability of the antioxidant, bioactive, antibacterial, and anti-inflammatory properties of curcumin, Wang, Jiang, and Shi (2024b) created a PE formulated using casein as a stabilizer, incorporating curcumin. Aiming to overcome this compound's reduced stability and low bioaccessibility, the authors used the glycation method with transglutaminase (TGase), analyzing beneficial effects, especially during *in vitro* digestion. Casein glycated via TGase type was demonstrated to be favorable for preserving hydrophobic compounds in PE, showing excellent stability under different environmental stresses and enhancing the application of these nutrients in commercial products. Moreover, the emulsion stabilized with casein glycated with TGase type enhances a positive environment for the distribution of bioactive substances and curcumin's bioaccessibility.

Concerning the application in the food industry, Tao et al. (2024) stated that using particles in the emulsion's stabilization can replace allergenic ingredients. The researchers evaluated different emulsion formulations, focusing on improving the color parameters and texture and decreasing water evaporation, while avoiding any alterations to the baked product quality. It was observed that the supplementation of bilayer emulsions was responsible for lower "hardness," better appearance, greater color, and specific volume in the sponge cake formulations. About 60% of bilayer emulsions presented the best quality.

Another factor that significantly affects the study and application of different PE formulations is the development of novel food packaging with functional potential. Furthermore, PE can also be applied in the manufacture of packaging. Bu et al. (2022) examine the necessity of substituting standard packaging with packaging made from natural polymers, mechanical resistance, food protection, developed shelf life, light barrier, and water resistance, among other things. Ran et al. (2023) developed collagen films modified by PE formulations using cinnamon essential oil and chitosan colloidal particles to conserve pork. The movie containing PE presented excellent thermal stability, ultraviolet-blocking properties, water resistance, and good antioxidant and antimicrobial activity levels.

Despite the enormous potential of different engineering methodologies, compared to the necessary demand, few studies exist about the effectiveness of these methodologies in formulating emulsions. Li et al. (2022) analyzed how various engineering methods affected the properties of oil/water emulsions fortified with nutraceuticals. The authors stated that LF, in place of other milk proteins, is attributable to the higher isoelectric point, which allows the formation of complexes with anionic polysaccharides under neutral conditions. This represents a promising alternative to the issue raised by Tao et al. (2024) in the bakery industry. Therefore, the covalent interactions of the polysaccharide to the protein modified the interfacial properties, thus being noticeable that the formulations containing LF and hyaluronic acid demonstrated better physical and chemical stability, with the conjugates supplying a more significant improvement.

An additional significant consideration is the improvement of methods and technologies intended to treat environmental waste. In this regard, the process reverses, and a comprehensive understanding is required, or more importantly (Baig et al., 2022). Emulsification technology is beneficial in several environmental processes. However, it is also responsible for generating significant amounts of emulsified oily wastewater (Wen et al., 2024), so it is essential to understand how to reverse it. Comprehending the subject being studied so that, if necessary, when it becomes waste, it can be managed and directed correctly (Ye et al., 2025), preventing the generation of environmentally contaminating waste.

4 ANIMAL PROTEIN PARTICLES AND NANOPARTICLES

The interest in animal protein particles and nanoparticles has attracted industrial involvement primarily because of their functional properties and ability to encapsulate, protect, and release bioactive substances. These nanoparticles may carry vitamins, minerals, and bioactive compounds (Dala-Paula et al., 2021). They present a wide range of sizes, with some nanoparticles exhibiting diameters less than 100 nm. Particular properties, for example, high surface charge and adsorption capacity at interfaces, make them superior emulsifiers, stabilizers, and nutrient carriers. For PE application, two specific types of solid particles may be utilized: inorganic and organic (Wu et al., 2025).

Since PEs were developed as substitutes for traditional emulsions, a key challenge for researchers within the field is the investigation of quality polymers, given that most of the polymers used are not biodegradable in the natural environment, except for proteins and polysaccharides (Ding et al., 2020). Therefore, different classes of proteins and polysaccharides (especially animal proteins) were given priority when selecting particles for their use in the emulsions. Applying protein complexes with polyphenols is an efficient way to obtain improved protein structural properties (Pourmohammadi & Abedi, 2021).

The low solubility of plant proteins in aqueous or food phase is considered an essential functional characteristic for researchers working with PEs (Sarkar & Dickinson, 2020). Authors such as Huang et al. (2018) emphasize the relevance of emulsion research, mainly owing to their increasing application in the encapsulation of fatty acids, for example, omega-3. They also analyze the limitations of traditional emulsions, which are susceptible to breakdown by gastric fluids and result in insufficient bioavailability. Solid particles can improve the properties of incorporated materials (Ding et al., 2024); however, such factors are essential points that can influence the research for more effective particles to enrich emulsions, particularly particles of animal protein sources.

4.1 Bovine casein and whey protein: Definition and stabilization mechanisms in Pickering emulsions

Casein is a phosphoprotein (comprising phosphoserine residues) from the heteroprotein class, existing in milk and its derivatives. It consists of multiple types of polypeptide chains (each with a distinctive function), divided into α-casein (most prevalent—50% of total casein), β-casein (second most pervasive—30% of total casein), κ-casein (necessary for the micelles stability and the coagulation stage by rennet—10% of total casein), and γ-casein (less prevalent fraction and soluble in water—8% of total casein). It is responsible for delivering, in adequate proportions, essential amino acids required by the human body. At pH 6.6, it is insoluble in water. However, it can be solubilized by acids or bases. Additionally, the solubility can be affected by salts or other solutes (Sadiq et al., 2021).

Casein is effectively digested by proteolytic enzymes in the human digestive tract by the chymotrypsin in the small intestine, responsible for hydrolyzing casein into smaller peptides that can be absorbed. Casein is prominent for being a rich source of essential amino acids (histidine, isoleucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine) and a great source of calcium and phosphorus, however, making it a preferable ingredient in crucial food formulations (Wang, Jiang, & Shi, 2024a). Moreover, in the food industry, casein is notable in different applications (Cosmetics industry—creams, lotions; Pharmaceutical industry—medicines and dietary supplements). The functional performance of casein is commonly improved, predominantly through creating physical complexes with oppositely charged polysaccharides (Hu et al., 2024).

The amphipathic structure serves as the key factor responsible for the emulsifying properties and, as a result, makes casein one of the most commonly used natural polymers in the preparation of PE (Wang, Jiang, & Shi, 2024a). However, knowing about the low solubility in the aqueous phase and its sensitivity to the variations of pH increases the difficulty of controlling the size and stability of emulsions with elevated polyphenol load (Kuang et al., 2023). To address this issue, relevant authors, including Wu et al. (2025), Wang, Jiang, and Shi (2024a), and others, suggest the use of the protein modification technique by glycation with TGase. The use of the TGase method permits the increase of the antioxidant and antibacterial activities of proteins (Wang, Jiang, & Shi, 2024a) and improves functional properties, including water solubility, emulsification, and foaming capacity (He et al., 2021).

Bovine casein is the principal and relevant protein in cow's milk (constituting 80%), presented in micelles (aggregates of molecules that disintegrate gradually in water). The bovine casein is broken down gradually by the stomach, synthesizing a gel capable of retaining water and nutrients, promoting satiety, and the gradual absorption of amino acids over several hours (Wen et al., 2024). Whey protein, or whey proteins, is the soluble fraction preserved after the extraction of casein and is notable for its high solubility over a wide pH range and for being rapidly digested and absorbed by the body (Kilara & Vaghela, 2018).

Whey protein presents good emulsification and foaming properties; however, it is less heat resistant than casein. Casein, however, is more stable at high temperatures and exhibits a greater capacity for binding with water and forming gels (Nayik et al., 2024). Whey protein isolate (WPI), although a co-product widely used in crucial industrial applications, is unstable in aqueous solutions. Biopolymeric particle compilation techniques have been proposed (Damodaran & Parkin, 2017) to enhance stability without compromising structure. The instability can be addressed by using cross-linked aldehydes acting as Pickering stabilizers (Kaseem & Ko, 2021) as a result of applying WPI in PEs as a viable option (Li, Zhao, Han, et al., 2024).

Zhu, Qiu, et al. (2024) found that PE stabilized with whey protein isolate fibrils (WPIFs), and using sodium alginate complexes, they were developed for encapsulation and carrying lycopene. PE showed enhanced physicochemical properties, including a reduction in droplet size and a good increase in viscoelasticity, due to the formation of a dense protective layer and a compact structure around the oil droplets. These emulsions provided good protection against lycopene's thermal and photochemical degradation, making them a promising system for delivering bioactive compounds with excellent stability during *in vitro* digestion.

Table 1 presents various studies performed using different PE particle categories, their properties, and the primary characteristics observed. It also presents the objective of each study. Evaluating the principal objective of each study executed, the breadth of the application of PE can be observed, intending to enhance the efficiency of the capacity of encapsulation of the nanoparticles applied in the emulsion, producing a new formulation to replace macronutrients responsible for inducing negative effects on health, among other things.

4.1.1. Mechanisms of stabilization of casein and whey protein in Pickering emulsions production

Caseins are great PE stabilizers due to their singular adsorption and interaction properties with the oil–water interface. Specifically, caseins are capable of stabilizing emulsions by a combination of electrostatic repulsion and steric hindrance. Casein is an amphiphilic particle, permitting it to be quickly adsorbed at the oil-water interface and creating a protective layer around the oil droplets (Guo et al., 2021). Furthermore, the modified casein particles can interact with one another and other particles in the aqueous solution, formulating a system capable of providing enhanced mechanical stability to emulsions. The casein solution's surface properties and particle size can be modified by adjusting the pH, which enhances emulsion stability. As an example, it has been demonstrated that high internal phase PEs stabilized using casein adjusted to different pHs demonstrate excellent viscoelasticity and thermal stability; in contrast, they are sensitive to freeze-thaw treatment (Guo et al., 2021). PEs stabilized by casein are founded on a multidimensional approach that includes rapid adsorption at the interface, formation of a protective layer through electrostatic repulsion and steric barrier, and the modification of particle properties to improve the emulsion stability under different environmental conditions (Zhang et al., 2023).

In particular, WPI stabilizes emulsions effectively through different mechanisms. The adsorption of proteins to the oil–water interface creates a protective barrier around the oil droplets and is one of the principal stabilization methods. The protein layer produces a physical barrier inhibiting coalescence (droplet fusion) and flocculation (droplet agglomeration), increasing emulsion stability. WPI is composed of soluble proteins, for example, β-lactoglobulin, which can exhibit good affinity to the oil–water interface, providing mechanical stability to shear stresses (Zhao et al., 2023). Furthermore, WPI can form nanoparticles capable of acting as emulsifiers in Pickering systems, creating a rigid physical barrier around the oil droplets. The principal idea of the stabilization mechanism conferred by these particles is to prevent direct contact between droplets, reducing coalescence phenomena (Chen & Zhang, 2019).

Another relevant mechanism of stabilization is the modification of WPI proteins and the combination with polysaccharides or phenolic compounds, which can further enhance the stability of emulsions under various pH, temperature, and ionic strength conditions (Shi et al., 2019). Therefore, WPI provides stability to the emulsions by physical mechanisms and promotes the continuity and protection of bioactive compounds, such as antioxidants and vitamins, in crucial industrial applications.

Table 1. Properties and characteristics of Pickering emulsions stabilized with casein microparticles and nanoparticles.

Products developed	Technology applied	Principal characteristics of the emulsion	Principal particle properties	Objective	References
Pickering emulsion formulated with casein and oligochitosan by glycation using transglutaminase (TGase)	Glycation using transglutaminase	Higher encapsulation efficiency of curcumin (92.93%)	Stability under different environmental stresses; Delayed release and enhanced bioaccessibility of curcumin	Optimizing the accessibility and bioaccessibility of curcumin in PE for commercial use	(Wang, Jiang, & Shi, 2024b)
Oil-in-water PE of algae using casein-mannose conjugates developed by ultrasound-assisted Maillard reaction	Ultrasound-assisted Maillard reaction	Superior stability	Enhanced lutein retention, reduced droplet size, improved stability	Enhance bioaccessibility of lutein and relieve retinal thinning in mice with AMD	(Liu et al., 2024)
Pickering emulsion stabilized by the whey protein isolate nanoparticles and vanillin	WPI-vanillin nanoparticles	Bacteriostatic effect opposed to *Escherichia coli* and *Staphylococcus aureus*; Enhanced vitamin E stability	Vitamin E retention is 43% superior to control after 21 days of storage at 4°C	Formulating a bacteriostatic Pickering emulsion and enhancing the bioaccessibility of vitamin E	(Zhao et al., 2023)
Stabilized Pickering emulsion with whey protein isolate and nicotinamide	Complexation with nicotinamide	Enhanced thermal stability and strength to the oxidative processes	Particles with an average size of 120 nm and enhanced stability against coalescence	Prolong the stability of bioactive compounds and potentially apply them in functional foods	(Li, Zhao, Hu, et al., 2024)
Pickering emulsion stabilized by WP and sucrose esters	Use of WP combinates with sucrose esters	Enhanced stability and better emulsification	Smaller particles and enhanced heat resistance	Improving the stability of food systems rich in lipids	(Ye et al., 2025)
Pickering emulsion with WP and anthocyanins	Stabilization by anthocyanins	Superior antioxidant protection and stability against pH variations	High preservation capacity of phenolic compounds and stability of color	Utilization in colored foods and beverages	(Wang, Zhang, & Zhang, 2022)

AMD: age-related macular degeneration; PE: Pickering emulsion; WP: whey protein; WPI: whey protein isolate.

The combination of WPI with different compounds, such as vanillin, can also provide antibacterial properties to the emulsions, making them ideal for products required for microbiological degradation (Zhao et al., 2023).

4.2 Egg albumin

Albumins are globular proteins soluble in water, identified in various organisms, and have biological and immunological defense functions. They are categorized into four general classes, with egg albumin being one of them (Dala-Paula et al., 2021). Egg albumin is classified as a glycoprotein, containing a phosphate group in the phosphoprotein class, abundant in the egg white of birds, representing approximately 54% of the protein content (Damodaran & Parkin, 2017). The structure enables it to easily bind with water, which can form gels and facilitate the transfer of nutrients during embryo development (Kaseem & Ko, 2021). Furthermore, egg albumin presents antimicrobial and emulsifying properties, enzymatic, nutritional functions, and allergenic properties (making its use difficult in some cases). Therefore, comprehension is indispensable when seeking to incorporate it into new products.

Egg albumin effectively stabilizes PEs, particularly in high internal phase emulsions (HIPEs). Xu et al. (2018) highlighted that egg albumin is an outstanding Pickering nanostabilizer, providing a robust protective layer around the oil droplets and preventing coalescence. This is facilitated by creating a stable three-dimensional network at the interface, conferring more excellent structural stability to the emulsion. Moreover, the association of egg albumin with another compound, for example, tannic acid (TA), can improve emulsions' emulsification properties and stability. The complexation of ovalbumin (OVA)-TA was researched, demonstrating that these combinations can structure a robust interfacial layer that enhances the emulsion stability under various pH conditions and during the storage and freeze-thaw processes.

When the egg albumin is denatured, the structure becomes insoluble, which is recommended when applying emulsions, especially the Pickering type (Shimoni et al., 2013), facilitating favorable rheological properties. The insolubility promotes a high adsorption capacity at the oil–water interface, contributing directly to enhanced stabilization and, as a result, stability improvement over time (Tsai & Lin, 2022). Egg albumin can also create a protective layer around the oil droplet emulsion (Damodaran & Parkin, 2017), preventing coalescence and separation. This phenomenon occurs due to the egg albumin proteins adsorbed at the interface between oil and water, forming a physical barrier that prevents the fusion of oil droplets (Kaseem & Ko, 2021); as a result, it represents a promising alternative for application in PE. The emulsifying properties of egg albumin can be adjusted by processing modifications (different pH variations, protein concentration, heat treatments, and other variables), consequently enabling control of rheological properties and emulsion stability. Egg albumin provides the advantage of being a natural polymer and safe for human consumption, consequently being a promising choice as a stabilizing particle in a range of food and industrial applications (Dala-Paula et al., 2021; Hosseini et al., 2021).

As a result of its excellent emulsifying properties, egg albumin has become a viable alternative for incorporation in PEs. During the formulation of different types of HIPPEs stabilized with egg albumin and pectin, Wang, Zhang, Li, et al. (2022) and Badar et al., 2024 evidenced a significant improvement in viscoelasticity and water binding capacity and consequently enhanced the rigidity of the gels present in the structure of their emulsions. As stated by the authors, these characteristics permit greater applicability in different food products, providing another specific type of viable and interesting technology.

Table 2 provides results derived from the research of different types of particles used in PEs, emphasizing each study's principal properties, characteristics, and objectives. Evaluating the research objectives, it was reported that PE was applied in the development of biodegradable and edible films to enhance the preservation and protection of fruit and vegetables, in the development of 3D inks for the food industry, and in improving the quality of bakery products, with a focus on substituting ingredients that can cause allergies or present potential health risks. Furthermore, PE was used to increase the availability of bio-compounds in food and for other benefits.

4.3 Lactoferrin

In case the proteins are used in emulsifying systems, the functional characteristics of protein-polysaccharide complexes may differ according to the concentrations of proteins and polysaccharides used for the formulation; this influences the quality of the emulsion obtained (Cheng et al., 2021). LF is a glycoprotein from the transferrin family widely found in human and bovine milk. The principal characteristic of this protein is the ability to bind iron and its antimicrobial, antioxidant, anti-inflammatory, and immunomodulatory properties. These

Table 2. Properties and characteristics of Pickering emulsions stabilized with egg albumin microparticles and nanoparticles.

Products and technology used	The principal characteristic of the emulsion	Principal particle properties	Objectives	References
Pickering emulsion of essential oil of neem stabilized with pectin/persimmon ovalbumin	Addition to the gelatin/sodium alginate-based mixture matrix	Significantly enhanced flexibility (45.23%), excellent oxygen barrier (32.32%), and oxygen barrier water (37.02%)	Develop biodegradable films with improved mechanical, water barrier, and antimicrobial properties for cherry tomato preservation	(Yang et al., 2024)
Gelation is induced in the continuous phase with Ca^{2+} particles of complete-electrostatic stabilized with ovalbumin and low-content pectin of methoxyl	Enhance viscoelasticity, binding capacity to water, and rigidity of HIPPE gel	Stable interface; Sophisticated network structure; Compact oil droplet size; Higher stability	Capable of developing new HIPPE gels for different food applications	(Wang, Liu, Bi, et al., 2023)
High-phase Pickering emulsion internal stabilized by electrostatic protein-polysaccharides complexes	Direct three-dimensional printing capacity of food	Higher viscoelasticity and rigidity; Good wettability of the complex	Develop 3D inks for the food industry capable of printing a complex food geometry	(Li, Li, et al., 2023)
Pickering emulsion of seed oil perilla stabilized by electrostatic complex ovalbumin and gum arabic	Addition of gelatin to enhance spray drying performance	Decrease of particle size; Reduction in secondary emulsion viscosity; Great fluidity and water dispersibility of PSO powder	Enhance the economics of producing powders with ultra-high oil contents through spray drying of PE stabilized by the ovalbumin-GA complex	(Li, Yu, et al., 2023)
Pickering emulsion of ovalbumin-acid ferulic-carrageenan	Butter substitute	Specific volume of PE bread is higher than that of bread with butter (showing an enhancement of 21.96%); Continuous and complete gluten network; Good gelatinized starch incorporated into the gluten network	Enhance the quality of white bread, reducing the adverse effects on health caused by butter	(Su et al., 2023)
Curcumin nanocrystalline self-stabilizing Pickering emulsion	Prepared by high-pressure homogenization	Mean particle size: 163.66 ± 6.78 nm; Mean drug content: 2.78 ± 0.01 mg/mL; Spherical core-shell structure	Improve the oral bioavailability of curcumin and the therapeutic effect on airway inflammation	(Wang, Liao, et al., 2023)
HIPPEs prepared by coacervates of ovalbumin and pectin	Improved wettability and ability to reduce the surface tension of coacervates	Oil droplet size: 21.3 ± 2.3 µm; More efficient and compact droplet packing; Stronger gel network structures	Formulate biopolymer particles as effective Pickering stabilizers in the food industry	(Wang, Liao, et al., 2023)

3DP: direct three-dimensional printing; Cur-NSSPE: curcumin nanocrystalline self-stabilizing Pickering emulsion; GA: gum Arabic; GS: sodium alginate; HIPPE: High-phase Pickering emulsion internal; LMP: low content pectin of methoxyl; PE: pectin; PN: pectin; OVA: ovalbumin; PSO: Pickering emulsion of seed oil perilla; OLECP: pickering emulsion of seed oil perilla.

characteristics make LF a relevant component in functional nutrition, especially in improving intestinal health and treating iron deficiencies; this establishes it as a versatile and valuable ingredient (McCarthy & O'Callaghan, 2024). Concerning the techno-functional properties of LF, it can offer stable nanoparticles, making it effective in the formulation of food and pharmaceutical products. The stability of LF can vary according to the form (apo or holo), with the holo form presenting more excellent resistance to thermal denaturation and proteolysis (McCarthy & O'Callaghan, 2024).

When applied to PEs, LF is effective as a stabilizer owing to the ability to produce nanoparticles that can adsorb at the oil–water interface, creating a physical barrier preventing the coalescence of oil droplets. This enhances the stability of the emulsion, especially under adverse and various conditions, such as pH and temperature variations. These emulsions mainly protect bioactive compounds during digestion, making them promising delivery systems for functional foods and bioactive compounds (Shimoni et al., 2013). Furthermore, the combination of LF with polysaccharides, like alginate and carrageenan, provides resistance to proteolysis and more excellent stability of the emulsions under gastric conditions, which qualifies them for application in controlled release systems (David-Birman et al., 2013).

LF's stabilization mechanisms in PEs include the interfacial adsorption of nanoparticles on the surface of oil droplets, forming a protective layer that prevents coalescence. Furthermore, when combined with polysaccharides, LF enhances the emulsion's resistance to enzymatic degradation during digestion, securing greater efficacy in gastrointestinal systems (Shimoni et al., 2013). These techniques make LF a good stabilizer of PEs, particularly promising for developing functional food products and nutrient delivery systems, such as iron in enriched foods (McCarthy & O'Callaghan, 2024).

Table 3 shows some information from research using LF applied in PE, as well as the properties and principal characteristics corresponding to each work's objective.

4.4 Myofibrils

Myofibrillar proteins (myofibrils) are the principal components of muscle proteins and perform a fundamental role in muscle contraction, composed predominantly of actin and myosin (Lin et al., 2019). Myofibrils produce thick and thin filaments that interact to generate force and facilitate muscle movement. Myofibril is an amphiphilic protein with both hydrophilic and hydrophobic regions, enabling it to act in emulsification processes. Furthermore, proteins of the myofibrillar structure, for example, myosin, have an excellent emulsification and fat stabilization capacity, making them functional for forming gels and stabilizing emulsions (Xiong, 2018).

Considering the technological characteristics, like physical stability, biocompatibility, film-forming capacity, and emulsifying properties, myofibrillar proteins have been widely applied in the food industry to create edible and stable products. Myofibrils have a relevant water-binding capacity, offering beneficial properties in preserving the texture and hydration in processed products and facilitating the stabilization of emulsions with a high internal phase content (Wang, Cui, et al., 2023).

Furthermore, PEs resist environmental changes because solid particles are subjected to irreversible adsorption at the droplet interface (Nhouchi et al., 2022). PEs associated with myofibrils

Table 3. Properties and characteristics of Pickering emulsions stabilized with lactoferrin.

Developed products	Technology applied	The main characteristic of the emulsion	Main particle properties	Objectives	References
Lactoferrin-stabilized Pickering emulsion	Lactoferrin nanoparticles	Substantial reduction in creaming rate	Nanoparticles formed with carrageenan and alginate; increased stability	Improve the stability of emulsions under digestion conditions	(Shimoni et al., 2013).
Pickering emulsion stabilized using lactoferrin and polysaccharides	A complexation with alginate and carrageenan	Resistance to proteolysis and more excellent stability during digestion	Average particle size: 100–200 nm; enhanced stability under gastric conditions	Develop delivery systems for bioactives during digestion	(David-Birman et al., 2013)
Lactoferrin-stabilized emulsion for better iron delivery	Lactoferrin nanoparticles	High iron binding capacity and stability at acidic pH	Antimicrobial properties and improved iron absorption	Improving iron bioavailability in functional foods	(McCarthy & O'Callaghan, 2024)
Emulsion stabilized by lactoferrin and EGCG conjugates	Ultrasound-assisted conjugation	Protection against oxidation and aggregation	Generation of nanoemulsions with high stability	Improving the oxidative stability of algae oil	(Zhang et al., 2022)
Oil–water emulsion with lactoferrin and pectin	Emulsification with protein and polysaccharide complexes	Increased thermal stability and resistance to flocculation	Protein and polysaccharide complexes; increased viscosity	Increase the stability of emulsions under adverse conditions	(Yuliarti et al., 2019)
Emulsion stabilized by lactoferrin and anionic polysaccharides	Preparation of orange oil emulsions with lactoferrin and pectin	More excellent resistance to flocculation and coalescence	Nanostructures with good particle distribution	Application in beverages and food products with emulsions	(Zhao et al., 2015)

EGCG: epigallocatechin-3-gallate.

are highly appealing to applications, especially in the food and pharmaceutical industries (Zhu, Thian, et al., 2024). Moreover, more excellent physical stability with lower toxicity is associated with the good results attained by protein and polysaccharide emulsifying agents (Badar et al., 2024) and the ability of myofibrillar proteins to form a protective layer around oil droplets.

Engaged in new PE formulations, Zhang et al. (2024) formulated edible emulsions stabilized by grass carp myofibrillar protein particles. These particles conferred reduced oil droplet size, enhanced water retention capacity, and optimized rheological stability. Wang, Cui, et al. (2023) investigated the modification of sturgeon myofibrillar proteins to form stable PEs. The results indicated that the surface hydrophobicity of the proteins was enhanced, altering the secondary structure of the protein particles and, consequently, upgrading the stability of the emulsions.

Table 4 presents the principal characteristics of emulsion formulations containing myofibril microparticles and nanoparticles. The use of myofibrillar proteins (and their modification) presents

Table 4. Properties and characteristics of Pickering emulsions stabilized with myofibril microparticles and nanoparticles.

Products and technology used	The principal characteristic of the emulsion	Principal particle properties	Objective	References
High internal phase Pickering emulsions based on linseed-derived diglycerides at different levels (0, 10, 20, 30, 40, and 50%)	Influence on myofibrillar protein gels by increasing whiteness and decreasing water retention capacity	Increased whiteness with increasing HIPPE levels; Decreased water retention capacity; Greater amount of ionic bonds at 10% HIPPE; Greater amount of hydrogen bonds at 40 and 50% HIPPE; Reduced T2 relaxation time with increasing HIPPE levels; G′ values significantly higher than G″ over time; More compact microstructure with low HIPPE levels	Use as fat substitutes in meat products; Improve the nutritional quality of meat products; Influence the rheological and physicochemical properties of MP gels	(Badar et al., 2024)
Pickering emulsion based on sodium starch octenyl succinate	Improvement of the physicochemical properties of hairtail myofibrillar protein gels subjected to freeze-thaw cycles	Increased water retention capacity and storage modulus (G′); Improved texture and whiteness; Promoted secondary structure transformation; Increased hydrogen bonding and hydrophobic interactions; Change in disulfide bond conformation	Improve the properties of myofibrillar protein gels; Reduce quality degradation after FT cycles; Act as a potential fat substitute; Increase the stability of gels after FT cycles	(Wang, Zhang, et al., 2024)
Preparation of edible Pickering emulsions stabilized with GMP particles using low-value grass carp myofibrillar protein	Stable Pickering emulsion with improved water retention, storage stability, and rheological stability	Irregular polyhedral structure; Amphiphilic nanoparticles	Stabilize PE; Serve as a potential vehicle for the delivery of food-grade active substances; Improve emulsion stability	(Zhang et al., 2024)
Stabilization of Pickering emulsions with myofibrillar protein microgel particles using different oil phases	The oil phase affects the stability and droplet size of the Pickering emulsion	Smaller droplet size (−26.17 µm) and high stability with sunflower oil; Larger droplet size (−77.00 µm) and low stability with peanut oil; Sunflower oil with low content of saturated fatty acids (15.68%) and super long-chain fatty acids (0); Peanut oil with high content of saturated fatty acids (23.67%) and super long-chain fatty acids (9.02%); Low viscosity favors the dispersion of oil droplets, improving the stability of the emulsion	Identify suitable oils for the preparation of Pickering emulsions with myofibrillar proteins; Improve the stability of Pickering emulsions for food applications; Reduce the floating and aggregation of droplets in the emulsion	(Feng et al., 2023)
Modification of sturgeon myofibrillar protein by the combination of malondialdehyde and ultrasonic induction	Formation of a stable high internal phase Pickering emulsion with an internal phase of up to 75%	Reduction of fluorescence intensity; Increased surface hydrophobicity; Alteration of secondary structure; Smooth surface	Improve emulsion stability; Improve quercetin encapsulation efficiency; Increase lipid digestion rate; Increase quercetin bioavailability; reduce quercetin degradation	(Wang, Cui, et al., 2023)
Stabilization of Pickering emulsions with myofibrillar hairtail proteins using different metal ions (Na+, K+, Mg2+, and Ca2+)	Stability and gel-like behavior in the presence of monovalent ions (Na+ and K+)	High absolute values of Zeta potential in Na+ and K+; Small particle size and uniform droplet distribution in Na+ and K+; High thermal stability in Na+ and K+; Lower stability in divalent ions (Mg2+ and Ca2+)	Utilization of high-value fish proteins; Construction of stable emulsion systems; Development of emulsions with improved thermal stability and uniform droplet distribution	(Wang, Cui, et al., 2023)
Microfluidics to prepare myofibrillar microgel particles	Stable Pickering emulsion with smaller droplets and lower degree of flocculation	Average diameter of 150–250 nm; Improved amphipathic property; Three-phase contact angle of about 88.5°	Improve emulsifying ability; Improve emulsion stability; Provide a theoretical basis for scientific preparation and screening of microgel Pickering emulsifiers	(Sun et al., 2021)

FT: freeze-thaw; GMP: grass carp myofibrillar protein; HIPPE: High internal phase Pickering emulsions; MP: myofibrillar protein. PE: pickering emulsion.

an increasing trend attributed to the attractive structural characteristics. Therefore, myofibrillar proteins are favorable for various biological applications, primarily due to their excellent transport capacity for the controlled discharge of bioactive transport.

5 CONCLUSIONS

The increasing interest in PEs for application in food science and other chemical industries is primarily due to excellent stability properties and potential benefits. The exceptional stability combined with the reduction and/or exclusion of the surfactants, the controlled discharge of actives, and the versatility of materials (some materials can be used as stabilizing particles in PE (proteins and polysaccharides) are highly appealing factors for the use. As is known, the stability of an emulsion can be affected by the following factors: the size of droplets and particles, shape, surface charge, pH, and ion concentration of the medium phase influence, and it can result in instability. However, modifying the particle surface is sufficient to enhance stability with the dispersed phase.

Casein has an amphipathic structure responsible for its most excellent stabilizing characteristic, and its performance as an emulsion stabilizer can be improved when associated with polysaccharides due to forming opposite charges. Egg albumin is notable as an emulsion nano stabilizer, and it can create a rigid layer around the dispersed phase, tuning it to make it resistant to phase separation. LF and myofibril are suitable for stabilizing and applying emulsions for the food industry. However, there is a gap in obtaining and availability of these materials, which is a factor that should be enhanced, as well as an investigation of their application.

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