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The Types, Preparation, Applications and Prospects of High Internal Phase Emulsions

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Abstract. The characteristic of High Internal Phase Emulsions(HIPEs) is that the volume fraction of the dispersed phase exceeds 74.05%. They possess features such as high viscosity elasticity and stability. In recent years, the research focus has shifted from traditional small molecule surfactants to natural macromolecules and bio-derived solid particles as stabilizers, as they possess biocompatibility and environmental safety. This review summarizes the latest progress in the preparation methods, emulsifier systems, and food-related applications of high internal phase emulsions stabilized by biological macromolecules. It highlights the mechanisms by which these natural stabilizers enhance the stability of the emulsions. It also discusses typical food applications, such as delivering functional components and serving as fat substitutes. Finally, it outlines the current challenges and future development directions, with a focus on improving the long-term stability of water-in-oil type high internal phase emulsions and developing new bio-based emulsifiers. This study provides theoretical guidance and technical support for the sustainable design and application of HIPEs in the food industry.

Keywords: Highly homogeneous emulsion, application, preparation

1. Introduction

High internal phase emulsions (HIPEs) are emulsions in which the dispersed phase occupies more than 74.05% of the total volume, giving rise to semi-solid characteristics and exceptional rheological stability. Depending on the nature of the dispersion medium, HIPEs can be classified as oil-in-water (O/W), water-in-oil (W/O), or gas-in-liquid systems such as CO_2-in-water. Since Cameron and co-workers introduced the concept of emulsion templating in the late twentieth century, HIPEs have received wide attention because of their distinctive internal structure, controllable pore size, and versatile physicochemical behavior. The densely packed droplets generate a continuous interfacial film, which contributes to mechanical rigidity and allows the encapsulation, protection, and controlled release of various functional components [1-5].

In food science, HIPEs have been explored as promising formulations for developing low-fat or fat-reduced products that retain desirable texture and mouthfeel. Common examples, including milk, mayonnaise, and cream, can be viewed as natural emulsions stabilized by proteins, phospholipids, or polysaccharides. In recent years, the use of natural macromolecules and bio-derived particles as

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stabilizers has gained importance, replacing conventional surfactants to improve biocompatibility, safety, and environmental sustainability. These bio-based stabilizers can form strong viscoelastic interfacial networks, significantly enhancing the physical stability of the emulsions. Furthermore, HIPEs have shown great potential as carriers for lipophilic nutrients and bioactive compounds such as carotenoids, vitamins, and polyphenols, improving their dispersibility, oxidative stability, and bioavailability. With ongoing research into formulation design and interfacial engineering, HIPEs are expected to contribute substantially to the development of functional foods, nutritional delivery systems, and bio-inspired soft materials in the near future [6-8].

2. The definition of high-phase-inclusion emulsion

HIPEs (High Internal Phase Emulsions) are also known as super-concentrated emulsions. They refer to emulsions where the volume fraction of the dispersed phase is over 74.05% [2]. They mainly include three types: water-in-oil (O/W), oil-in-water (W/O), and supercritical CO2 (C/W). The research on HIPEs originated from the shortcomings of traditional materials in terms of pore structure control and functional integration. Since the Cameron team first proposed the emulsion templating method in the late 20th century, this technology has been widely applied in various fields, especially in the food industry. Some foods composed of two immiscible liquid phases or pseudo-liquid phases can be regarded as emulsions, such as milk, milk beverages, salad dressings, mayonnaise, ice cream, and chocolate, which can be considered O/W emulsions [1]; butter, margarine, and cream can be regarded as W/O emulsions.

3. Stable high internal phase emulsion stabilized by surfactants

3.1. Small molecule surfactants

Stable high internal phase emulsions (HIPEs) can be stabilized by either small-molecule surfactants or biological macromolecular surfactants. However, when small-molecule surfactants are employed, their intrinsic kinetic instability often limits long-term emulsion stability. In addition, concerns regarding potential toxicity and limited biocompatibility further restrict their application in food and biomedical systems. Consequently, research in recent years has increasingly focused on replacing conventional surfactants with amphiphilic biopolymers and bio-derived solid or organic particles, which offer improved environmental compatibility, structural stability, and functional versatility in emulsion systems.

3.2. Macromolecular surfactants

Biological macromolecules can be used as surfactants into two categories: proteins and polysaccharides. The use of the amphiphilicity of proteins and the thickening property of polysaccharides can stabilize HIPEs. The molecular structure of proteins has hydrophilic and hydrophobic groups at both ends, which are dispersed on the oil-water interface of the emulsion and play the role of emulsifier. The commonly used protein as an emulsifier is plant protein. Compared with animal protein, plant protein is widely studied as an emulsifier due to its good biocompatibility and environmental sustainability. Some amphiphilic polysaccharides or modified polysaccharides can also be used as emulsifiers or thickening agents, reducing the surface tension of the oil-water interface or increasing the viscosity of the aqueous phase, thereby improving the stability of the emulsion. In a recent study, using pea protein as the emulsifier and eight polysaccharides as stabilizers, sunflower seed oil as the oil phase, O/W HIPEs (φ = 80%) were prepared. The

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synergistic effect of plant protein and different polysaccharides in stabilizing the emulsion was studied. Through analysis of storage stability, rheology and particle size, it was concluded that the HIPEs stabilized by pea protein and carrageenan, xanthan gum, and tara gum were the most stable, and they have the application prospect as fat substitutes in food formulations. An increasing number of studies have investigated the stabilization mechanisms and functional performance of HIPEs formulated with various biopolymeric emulsifiers. Representative examples of HIPEs stabilized by biological macromolecules, including their composition, internal phase volume fraction, and observed stability characteristics, are summarized in Table 1.

Table 1. HIPEs stabilized by biological macromolecules

Emulsion type	Emulsion composition	Internal phase volume fraction	conclusion	references
W/O	Oil phase: Rapeseed oil, Beeswax, Mono-glyceride; Aqueous phase: Carrageenan	0.8	This system can transport two types of substances: β-carotene and anthocyanins, which are both hydrophobic and hydrophilic.	[7]
O/W	Oil phase: Sunflower seed oil; Aqueous phase: Pea protein, 8 types of polysaccharides	0.8	The HIPEs stabilized by pea protein and carrageenan, xanthan gum and taragel can be used as fat substitutes.	[3]
O/W	Oil phase: Medium-chain triglycerides (containing polymethoxyflavones); Aqueous phase: Whey protein isolate and low methoxyl pectin	0.82	Compared with the polymethoxyflavones in medium-chain triglycerides, the bioavailability of limonin and hesperetin in HIPEs increased by 5 times and 2 times respectively.	[8]

4. Stable high internal phase emulsion of solid particles

Solid particles can be classified into two types: inorganic particles and organic particles. Due to the poor biocompatibility of inorganic particles, their application in the fields of food and medicine has been limited. Therefore, the research focus has gradually shifted to bio-derived particles, such as polysaccharides, proteins, and their complexes.

4.1. Polysaccharide granules

Most polysaccharides are inherently hydrophilic biopolymers, and thus require appropriate hydrophobic modification to acquire interfacial activity and effectively stabilize lipid-based Pickering high internal phase emulsions (HIPEs) [9-13].

4.2. Protein particles

Protein-based particles have attracted considerable attention as efficient stabilizers for Pickering high internal phase emulsions (HIPEs) because of their natural abundance, amphiphilic nature, and nutritional benefits. Proteins can readily adsorb onto the oil–water interface, reducing interfacial tension and forming a cohesive viscoelastic layer that prevents droplet aggregation. The ability of protein particles to stabilize emulsions is influenced by factors such as particle size, surface hydrophobicity, charge distribution, and structural conformation [14-18].

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Thermal or enzymatic treatments can alter the molecular structure of proteins, enhancing their interfacial behavior and film-forming capacity. Denatured or partially unfolded proteins often display increased hydrophobic exposure, which promotes strong interactions at the interface and improves emulsion stability. For instance, wheat gluten protein has been shown to form robust water-in-oil HIPEs with no signs of demulsification even after long-term storage, indicating its potential as a natural food-grade stabilizer.

In addition, proteins can form composite particles with other biopolymers such as polysaccharides, thereby improving the rheological and mechanical properties of the emulsions. These hybrid systems show greater resistance to pH fluctuations, temperature variations, and ionic strength, making them suitable for practical food applications. Protein-stabilized HIPEs also provide a promising platform for encapsulating bioactive components such as carotenoids, polyphenols, and vitamins, enhancing their stability and bioavailability. Table 2 summarizes representative examples of Pickering HIPEs stabilized by protein and composite particles, including their composition, oil phase volume fraction, and stability characteristics.

Table 2. Stable Pickering HIPEs composed of particles

Particle type	Particle composition	Volume fraction of the oil phase	conclusion	references
Polysaccharide	Cellulose nanocrystals	Soybean oil (0.8)	Significantly enhance hydrophobicity. Stable Pickering HIPEs can be prepared when the particle mass fraction is 0.1%.	[19]
Protein	Wheat gluten protein	Corn oil (0.8)	When the mass concentration of wheat gluten protein particles is 20 g/L, stable Pickering HIPEs can be prepared. After being stored for 2 months, there is no demulsification phenomenon.	[10]
Composite particle	Maize prolamin - Arabic gum	Corn oil (0.85)	The composite particle-stabilized HIPEs have higher apparent viscosity and storage modulus, and are relatively stable in response to changes in pH value, temperature and ionic strength.	[11]

4.3. Composite particles

Compared with the use of polysaccharides or proteins alone, polysaccharide–protein composite particles integrate the functional advantages of both components, exhibiting superior interfacial adsorption capacity, enhanced emulsifying efficiency, and improved structural stability against environmental perturbations.

5. Preparation method of high-intensity emulsion

The preparation methods of high internal phase emulsions mainly include one-step emulsification method and two-step emulsification method, among which the one-step emulsification method for preparing HIPEs is simple and easy to operate, and is the most commonly used preparation method.

5.1. One-step emulsification method

The one-step emulsification approach for preparing high internal phase emulsions (HIPEs) typically involves techniques such as high-speed shear homogenization, ultrasonication, and vortex mixing. Among these, high-speed shear homogenization is the most widely applied method [12]. In this process, the dispersed phase is introduced directly into the continuous phase, followed by homogenization under controlled shear rate and duration to obtain stable HIPEs. Tripathi et al. [13]

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examined the effect of shear time on the rheological properties and stability of HIPEs, demonstrating that increasing the shear rate and extending the homogenization time reduced droplet size and enhanced droplet dispersion, leading to higher storage modulus and viscosity, thereby improving emulsion stability.

5.2. Two-step emulsification method

High-energy and low-energy input processes are the characteristics of the two-step emulsification method. Through this two-step emulsification process, the emulsification efficiency can be improved, and at the same time, the size of the emulsion droplets becomes smaller, and the emulsion becomes more stable [4]. To regulate the stability and particle size of the emulsion, a method of precisely controlling the pre-emulsification process of the oil phase and water phase can be adopted. This method is suitable for preparing emulsions with a higher volume fraction of the dispersed phase, especially for products that require higher emulsification quality and stability [5]. The one-step emulsification method, due to its simple operation, has become the most commonly used method, but the stability of the emulsion is relatively low; in contrast, the two-step emulsification method can enhance the gel network structure of HIPEs and improve the freeze-thaw stability [14,15].

6. The application of high internal phase emulsions in the food industry

6.1. Delivery function components

One of the major applications of high internal phase emulsions (HIPEs) in the food industry is the encapsulation and delivery of functional bioactive compounds. Many bioactive substances exhibit poor water solubility and limited stability, resulting in low bioavailability. Encapsulation within HIPEs can effectively address these limitations. Due to their high internal phase volume, HIPEs offer enhanced loading capacity for active compounds, along with improved storage stability and extended shelf life.

For instance, β-carotene, a lipid-soluble compound with notable antioxidant and anticancer properties, suffers from low water solubility. Its natural form contains unsaturated conjugated double bonds that are highly susceptible to oxidative degradation under light, heat, or oxygen exposure, leading to reduced bioavailability and restricting its utilization in food formulations. Previous studies have demonstrated that lipid-based delivery systems, such as liposomes, cyclodextrins, and microcapsules, can effectively improve the solubility, stability, and bioavailability of β-carotene [16].

The loading amount of β-carotene was significantly increased through the use of gelatin cross-linked chitosan microgels stabilized by Li et al. [9] in HIPEs. The loading amount of the microgel emulsifier reached 2wt% even at a concentration of only 0.1wt%. In emulsion systems with an emulsifier dosage much lower than the conventional dosage (approximately 10wt%), the loading amount of β-carotene was more than 10 times higher than that reported in the literature. At the same time, the stability of β-carotene after encapsulation was significantly improved against ultraviolet light irradiation, heat treatment, iron ions, and hydrogen peroxide. Moreover, if the in vivo bioavailability can be simulated by constructing an in vitro digestion model. A recent study aimed to improve the stability and bioavailability of β-carotene by using a method of stabilizing O/W HIPEs with preheated whey protein isolate and glucose lactone. After adding glucose lactone, the retention rate and bioavailability of β-carotene were significantly improved (88.34% ± 0.77%). At the same

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time, the gel network structure of HIPEs also delayed the degradation of β-carotene in the gastrointestinal tract [6].

6.2. Fat substitute

Furthermore, the high internal phase emulsion (HIPE) is a semi-solid material that can be used to replicate the texture characteristics of saturated fatty acids and is suitable for the production of low-fat foods. The common mayonnaise in daily life is prepared using vegetable oil as the oil phase and egg yolks, vinegar, and some seasonings as the water phase, which can be regarded as a typical O/W HIPEs. The egg yolks in mayonnaise play a crucial role in the stability and sensory properties of the emulsion [17]. However, the higher levels of cholesterol and saturated fat in egg yolks increase the risk of obesity and are not suitable for people with high cholesterol levels. In addition, the supply of animal protein is difficult to keep up with the growing world population, and intensive livestock farming can damage the environment. Using plant protein instead of animal protein in the diet can address these issues and promote the sustainable development of food [18].

A recent study reported the successful preparation of stable oil-in-water (O/W) high internal phase emulsions (HIPEs, φ = 75%) using wheat gluten protein as the stabilizer. The resulting emulsions exhibited rheological and tribological properties comparable to those of commercial mayonnaise, while demonstrating superior freeze–thaw stability. Similarly, O/W HIPEs stabilized by heat-aggregated soy protein isolate particles can serve as a full substitute for egg yolk in mayonnaise formulations. The resulting product maintains freeze–thaw stability and achieves a significant reduction in cholesterol content compared with conventional mayonnaise.

In addition to using plant protein-based stabilizers, the incorporation of dietary fibers into plant protein matrices has also proven effective for HIPE stabilization. For instance, HIPEs (φ = 75%) formulated with citrus fiber and corn peptide have been developed as plant-based mayonnaise alternatives. These emulsions not only enhance the dietary fiber content in food systems but also exhibit exceptionally low friction coefficients, contributing to a creamier and smoother texture than traditional egg-based mayonnaise.

7. Conclusion

High internal phase emulsions (HIPEs), characterized by their high internal phase volume and unique rheological behavior, have found broad applications in materials science, food technology, chemical engineering, life sciences, and the petroleum industry. In recent years, HIPEs stabilized by biologically derived macromolecules or solid particles have shown remarkable potential in the food sector. Specifically, oil-in-water (O/W) HIPEs stabilized by polysaccharides and proteins typically possess internal phase volume fractions exceeding 85%, demonstrating favorable physical and storage stability. When used as delivery systems for liposoluble bioactive compounds such as β-carotene and phenolic substances, these systems effectively enhance the stability and bioavailability of encapsulated actives.

In contrast, the development of water-in-oil (W/O) HIPEs stabilized by biopolymers or bio-based solid particles remains at an early stage. The low viscosity of both the aqueous phase and the oil phase, combined with the limited availability of efficient and biocompatible emulsifiers, restricts the achievable volume of the inner phase and often leads to phase transitions, thereby destabilizing the emulsion. These constraints pose significant challenges to the practical application of W/O HIPEs in food systems.

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Future research should prioritize improving the formulation stability of W/O HIPEs, identifying and designing novel bioparticle-based emulsifiers, and optimizing the encapsulation efficiency and bioavailability of functional components. Furthermore, a systematic investigation of their gastrointestinal digestion behavior and in vivo functional mechanisms is essential to establish a theoretical basis for the development and application of bio-based HIPE systems.

References

[1] CALDERO G, LLINAS M, JOSE GARCIA-CELMAM, et al. Studies on controlled release of hydrophilic drugs from W/O high internal phase ratio emulsions [J].Journal of Pharmaceutical Sciences, 2010, 99(2): 701-711.
[2] PARK CI, CHO WG, LEE S J. Emulsion stability of cosmetic creams based on water-in-oil high internal phase emulsions [J]. Korea-Australia Rheology Journal, 2003, 15(3): 125-130.
[3] VELEZ-ERAZO E M, BOSQUI K, RABELO R S, et al. High internal phase emulsions(HIPE) using pea protein and different polysaccharides as stabilizers [J]. Food Hydrocolloids, 2020, 105: 105775.
[4] ZHANG L L, TANG C H, et al. Two-step emulsification method improves the stability of protein-based high-phase-inclusion emulsions [J]. Modern Food Technology, 2020, 36(11): 180-187.
[5] REHMAN A, LIANG Q F, KARIM A, et al. Pickering high internal phase emulsions stabilized by biopolymeric particles: from production to high-performance applications [J]. Food Hydrocolloids, 2024, 150: 109751.
[6] LIU W, GAO H, MCCLEMENTS D J, et al. Stability, rheology, and beta-carotene bioaccessibility of high internal phase emulsion gels [J]. Food Hydrocolloids, 2019, 88: 210-217.
[7] LEE M C, TAN C, RAVANFAR R, et al. Ultrastable water-in-oil high internal phase emulsions featuring interfacial and biphasic network stabilization [J]. ACS Applied Materials and Interfaces, 2019, 11(29): 26433-26441.
[8] WIJAYA W, ZHENG H, ZHENG T, et al. Improved bioaccessibility of polymethoxyflavones loaded into high internal phase emulsions stabilized by biopolymeric complexes: A dynamic digestion study via TNO's gastrointestinal model [J]. Current Research in Food Science, 2020, 2: 11-19.
[9] LI W, NIAN Y, HUANG Y, et al. High loading contents, distribution and stability of beta-carotene encapsulated in high internal phase emulsions [J]. Food Hydrocolloids, 2019, 96: 300-309.
[10] HU Y Q. Fabrication and characterization of Pickering emulsions and Pickering high internal emulsions stabilized by gliadin colloid particles [D]. Guangzhou: South China University of Technology, 2016.
[11] MA L, ZOU L, MCCLEMENTS D J, et al. One-step preparation of high internal phase emulsions using natural edible Pickering stabilizers: Gliadin nanoparticles/gum Arabic [J]. Food Hydrocolloids, 2020, 100: 105381.
[12] JIN YS. Preparation, characteristic and application of high internal phase emulsion stabilized by soybean protein isolate [D]. Guangzhou: South China University of Technology, 2019.
[13] TRIPATHI S, BHATTACHARYA A, SINGH R, et al. Rheological behavior of high internal phase water-in-oil emulsions: Effects of droplet size, phase concentration and aging mass fractions, salt [J]. Chemical Engineering Science, 2017, 174: 290-301.
[14] CHEN Y B. Freeze-thaw stability of high internal phase emulsions stabilized by soy protein isolate particles [D]. Guangzhou: South China University of Technology, 2018.
[15] ZHANG L L, TANG C H. Improving the stability of protein-based high internal phase emulsions by two-step emulsifying method [J]. Modern Food Science and Technology, 2020, 36(11): 180-187.
[16] WANG J, DENG S M, DAI Y, et al. Research progress in the food-grade delivery systems in different encapsulating technology loading beta-carotene [J]. Science and Technology of Food Industry, 2017, 38(3): 380-385.
[17] MA Z, BOYE J I. Advances in the design and production of reduced-fat and reduced-cholesterol salad dressing and mayonnaise: A review [J]. Food and Bioprocess Technology, 2013, 6(3): 648-670.
[18] VAN DER GOOT A J, PELGROM P J M, BERGHOUT J A M, et al. Concepts for further sustainable production of foods [J]. Journal of Food Engineering, 2016, 168: 42-51.
[19] CHEN Q H, ZHENG J, XU Y T, et al. Surface modification improves fabrication of Pickering high internal phase emulsions stabilized by cellulose nanocrystals [J]. Food Hydrocolloids, 2018, 75: 125-130.