Preparation of High Internal Phase Emulsions (HIPEs) and Their Applications in the Daily Chemical Industry

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Abstract. High internal phase emulsions (HIPEs) are a special type of emulsion system with a high dispersed phase volume fraction. Due to their unique structure and properties, they have gained widespread attention in fields such as personal care, food, and pharmaceuticals. In recent years, with the increasing demand for efficient and eco-friendly products, the research and application of HIPEs have become a focal point. This paper reviews the preparation processes, stability factors, and performance testing methods of HIPEs, discussing in detail the effects of emulsifier selection, dispersed phase volume fraction, stirring speed, and temperature control on the stability of the emulsions. To address the challenges encountered during preparation, this paper proposes innovative strategies such as the introduction of nanoparticles, composite emulsifier systems, and interface modification to enhance emulsion stability. Finally, the paper looks into the future development directions of HIPE technology, particularly its potential applications in green chemistry and sustainability. By summarizing current research findings, this paper provides a theoretical foundation and practical guidance for the further development of HIPEs.

Keywords: High internal phase emulsions, surficial chemistry, daily chemical industry.

1. Introduction

High internal phase emulsions (HIPEs) are a special type of emulsion system, referring to emulsions where the dispersed phase exceeds 74.05%, and known as super-concentrated emulsions [1]. Since the volume fraction of the internal phase reaches the critical value of 74.05%, the dispersed phase droplets are closely packed, interconnected, and compressed, resulting in a tight packing effect and unique microstructure [2]. The distinct characteristics of HIPEs hold significant importance for the development of interfacial chemistry, making it a hot research topic in this field. Furthermore, its special properties have shown great potential for extensive applications in the daily chemical industry.

In recent years, there has been a growing demand for HIPEs in the food and cosmetics industries. HIPEs are widely used in cosmetics due to their refreshing and non-greasy feel and fast absorption, along with their strong stability, moisturizing, and antioxidant properties. They have become a potential innovation breakthrough in this field, satisfying the needs of diverse consumer groups. Developing more competitive products by reaching the full potential of HIPEs has become a booming hot topic [3].

Recently, Chinese and international scholars have conducted extensive research and exploration on the preparation and application of HIPEs, providing important references for a deeper understanding of relevant theories and practices. Current researches primarily focus on different stabilizers for HIPEs. For example, Han Yanan et al. explored the effects of different ethoxylation numbers and carbon chain lengths on emulsion performance through experiments, confirming that modified oil ethoxylates can effectively prepare HIPEs with potential applications in cosmetics and skincare products. In her study, Jie Yilin also demonstrated that cationic polysaccharide chitosan hydrochloride can efficiently stabilize O/W HIPEs. Overall, while significant progress has been made in the research of HIPE stabilizers, there is still a lack of systematic review on preparation methods. Therefore, this study will provide a review based on existing results, aiming to further advance the field of HIPEs [4].

The purpose of this paper is to review the preparation processes and stabilization methods of HIPEs, explore their potential applications in the daily chemical industry, and focus on analyzing the performance tests of HIPEs. By summarizing and reviewing existing research, this paper aims to provide a solid theoretical basis and practical experience for the further development of HIPEs, thereby expanding the knowledge outcomes in the current field of interfacial chemistry.

2. Preparation Methods of HIPEs

2.1. Basic Introduction to HIPEs

HIPEs refer to emulsions with a dispersed phase volume greater than 74.05%. The droplets in the dispersed phase are closely packed and compressed due to the high volume fraction, forming a unique microstructure very different from ordinary emulsions [5]. Based on the difference between the dispersed phase and the continuous phase, HIPEs can be classified into water-in-oil (W/O) emulsions and oil-in-water (O/W) emulsions [4]. When the continuous phase is water and the dispersed phase is oil, the emulsion is called an oil-in-water emulsion, and vice versa for water-in-oil emulsions [5]. Due to the higher viscosity of the oil phase compared to the water phase, oil-phase droplets are more likely to aggregate and settle, making water-in-oil HIPEs generally less stable than oil-in-water HIPEs.

Another classification method for HIPEs is based on the type of stabilizer used. Unlike ordinary HIPEs stabilized by surfactants, Pickering emulsions are stabilized by solid particles. Due to the irreversible adsorption of solid particles at the interface, they usually have better stability and stronger compatibility with biological and environmental systems [6,7].

2.2. Common Emulsifying Agents and Stabilizers

Emulsifying agents are essential components for the formation and stabilization of emulsions [8]. They can be classified into three categories: small molecule surfactants, solid particles, and synergistic stabilization by both. Small molecule surfactants are traditional emulsifying agents, but their kinetic instability requires a high concentration (about 20%) to stabilize HIPEs, which may have negative impacts on human health and the environment [8,9]. In contrast, solid particles are less toxic, and they cause less pollution, offer stronger stability. HIPEs stabilized by solid particles are also called Pickering emulsions, and solid particles obtained from biological sources have better biocompatibility. The relative hydrophilicity of surfactants directly affects their emulsifying performance, making the choice of the right stabilizer an essential step in product development and experimental operations. Modified ethoxylated compounds, as a common type of emulsifier, have been found to provide high stability, excellent oil-carrying capacity, and good resistance to external forces [2].

2.3. Preparation Techniques of HIPEs

There are three main methods for preparing HIPEs, with the most common and simplest being the one-step emulsification method. This method involves adding the dispersed phase to the continuous phase all at once while homogenizing it at high shear rates. Adjusting the shear rate and time can produce a stable HIPE. Studies show that increasing the shear rate and extending the shear time can reduce droplet size and improve the dispersibility, rheology, and stability of the emulsion. In contrast, the two-step emulsification method involves first preparing a low-internal-phase emulsion with high-energy input (such as microfluidization or high-pressure homogenization) and then increasing the dispersed phase with low-energy input to enhance the stability and storage performance of the emulsion. The concentration method involves reducing the external phase content by centrifugation or vacuum evaporation to prepare HIPEs, but this method is less commonly used due to the complexity of the process and difficulty in determining the volume fractions of the oil and water phases [9].

2.4. Performance Testing of HIPEs

Performance testing of HIPEs mainly includes stability, rheological behavior, and viscosity testing. Stability testing involves placing the prepared emulsions at (-5 ±1) ℃, (25 ±1) ℃, and (40 ±1) ℃ for 24 hours, then returning them to room temperature to observe their appearance and microstructure. Stable emulsions will exhibit no significant change in droplet size after storage and will retain a good internal network structure. Rheological behavior testing uses an advanced rotational rheometer to characterize the flow properties of the emulsion at (25 ±1) ℃ by recording viscosity changes under different shear rates to evaluate its thixotropic recovery performance. A recovery rate of over 80% indicates good thixotropic recovery performance. Viscosity testing is carried out at (25 ±1) ℃ using a digital rotational viscometer, and according to Stokes' law, the viscosity of the emulsion is proportional to its stability—higher viscosity results in slower sedimentation rates and better stability.

3. Application of HIPEs in the Daily Chemical Industry

HIPEs, due to their excellent moisturizing effect, pleasant skin feeling, and high stability, are widely used in skincare and cosmetic products. HIPEs can encapsulate high volumes of oil in water-oil emulsions, addressing the issue of greasy feel, while being suitable for encapsulating, stabilizing, and delivering hydrophobic bioactive ingredients. Because of their high oil content, HIPEs generally offer greater load capacity than traditional emulsions [3]. These features help form long-lasting moisturizing films on the skin, enhancing product longevity and user experience.

HIPEs are also used in shampoos and conditioners, improving the texture and dispersibility of the products, making shampoos easier to foam and conditioners more readily absorbed. Therefore, further development of HIPEs has significant potential in the cosmetics and personal care industry.

HIPEs are also now applied in delivering functional ingredients and as fat substitutes, showing promise in the food industry. However, their performance and sensory properties in food products still require further exploration to be further promoted [9].

Looking ahead, with increasing market demand and continuous technological innovations, the application of HIPEs in daily chemical products will further expand, particularly in the development of greener and more functional formulations with significant potential.

4. Challenges and Solution Strategies for Emulsions with a High Internal Phase

HIPEs are emulsions where the internal phase volume significantly exceeds that of the external phase, providing unique advantages across various applications. However, challenges in HIPE preparation, such as stability issues, delamination, flocculation, and oxidation, remain significant. This study will delve into these challenges, propose strategies for overcoming them through technological innovations, and explore future development directions for HIPE technology [10].

4.1. Main Challenges Encountered in the Preparation Process

The primary technical challenges in preparing HIPEs include stability, delamination, flocculation, and oxidation. Stability is a key concern due to the high internal phase volume, which often results in phase separation during storage and affects the emulsion's rheological properties and shelf life. The choice of emulsifier, typically amphiphilic molecules or Pickering particles, is critical in addressing this issue. Delamination occurs when changes in storage or usage conditions cause the oil phase to separate due to density differences, reducing performance. Flocculation arises from the aggregation of internal phase particles, forming larger agglomerates that disrupt emulsion homogeneity and fluidity, particularly when there is an insufficient quantity of Pickering particles. Oxidation, another concern, can alter the emulsion's color, odor, and active ingredients when exposed to air, making oxidation control essential for ensuring long-term emulsion stability [11].

4.2. Main Factors Affecting Emulsion Stability

The stability of HIPEs is influenced by several factors, including emulsifier concentration, oil phase volume fraction, stirring speed, and temperature control. The emulsifier concentration determines the coverage of oil droplets; insufficient emulsifier leads to interfacial instability and delamination, while excessive amounts can degrade emulsion performance, making precise concentration control essential. The oil phase volume fraction also impacts stability, as a high-volume fraction increases the risk of structural instability, delamination, and flocculation, requiring careful regulation [11]. Stirring speed affects emulsion homogeneity; optimal speed ensures emulsifier distribution, while excessively fast or slow speeds negatively affect stability. Temperature control is crucial, as high temperatures may degrade the emulsifier or alter emulsion composition and low temperatures can result in incomplete emulsification. Therefore, careful regulation of these factors is vital for maintaining HIPE stability.

4.3. Solution Strategies and Technological Innovations

To address the challenges in preparing HIPEs, researchers have developed several strategies and technological innovations. One key approach is the use of nanoparticles as co-stabilizers, which enhance emulsion stability due to their high surface area and excellent interfacial adsorption. Nanoparticles like nanosilica and nanoclay help form stable network structures, reducing delamination and flocculation. Another strategy involves using compound emulsifier systems that combine different emulsifiers, leveraging their synergistic effects to improve stability and compatibility. For instance, combining non-ionic and ionic emulsifiers allows emulsions to adapt to varying conditions. Additionally, interfacial modification techniques, such as adding surfactants or modifiers, enhance the oil-water interface, minimizing oxidation and delamination. Long-chain fatty acid esters, for example, can extend emulsion shelf life. Finally, the use of additives, such as antioxidants like vitamin E, slows oxidation, further enhancing emulsion stability [12].

4.4. Future Direction of Technological Development

The future development of HIPE preparation will focus on several key directions. First, improving production efficiency through advanced processes is essential. New mixing technologies and high-performance emulsification equipment, like ultrasonic emulsification, can enhance emulsion homogeneity and stability, reduce preparation time, and boost production capacity [13]. Second, the integration of green chemistry will play a pivotal role, with a shift towards eco-friendly materials and processes that lower environmental impact while increasing energy efficiency and resource utilization. For instance, using renewable resources and non-toxic raw materials can improve the sustainability of production. Lastly, sustainability efforts will become more prominent, with measures such as utilizing renewable resources, reducing energy consumption, and recycling waste being crucial for achieving long-term sustainable development and meeting market demand for environmentally friendly products [14].

5. Conclusion

HIPE have a wide range of potential applications in the cosmetics, food and biomedical industries due to their unique structure and stability. In this article, we have reviewed the preparation methods, factors influencing stability and performance testing of high internal phase emulsions, discussed their application prospects in everyday chemical products such as skincare products and shampoos, and analysed the challenges encountered in the preparation process with corresponding solution strategies. By discussing various aspects such as the selection of the emulsifier, control of the volume fraction of the oil phase, stirring speed and temperature regulation, technological innovations such as the introduction of nanoparticles, the composite emulsifier system and interfacial modification are proposed to improve the stability and performance of emulsions. In addition, future research into emulsions with a high internal phase content will focus on the development of efficient preparation processes, the application of green chemistry and the exploration of sustainable production methods. These development trends will promote the in-depth application of high internal phase emulsions in different fields and bring more innovation and development opportunities to related industries.

Authors Contribution

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

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