Advancements in Emulsification Technology: Enhancing Food Quality and Sustainability Through Nanoemulsification and Microencapsulation

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Abstract. The food industry extensively employs emulsification technology to enhance texture, stability, and longevity of food products. As consumer demands for food safety and quality increase, the role of emulsifiers—agents that stabilize immiscible substances like oil and water—becomes increasingly critical. This paper provides a comprehensive overview of the types and characteristics of emulsifiers used in the food industry, both natural and synthetic, and discusses their applications in various food processing techniques. It outlines the fundamental principles of emulsification, including physical and chemical mechanisms, and reviews common emulsification methods such as high-speed stirring, homogenization, and ultrasonic emulsification. The paper also explores the ongoing challenges in emulsifier safety, environmental impacts, and technological bottlenecks in emulsification processes. Moreover, it highlights innovative developments in emulsification technology, including nanoemulsification and microencapsulation, which promise enhanced stability and functionality of food products. By addressing these innovations and challenges, the paper underscores the significant role of emulsification in advancing food quality, safety, and sustainability in the modern food industry.

Keywords: Nanoemulsification; surfactant; food emulsion.

1. Introduction

Emulsifiers, typically surfactants, effectively promote the formation of uniform emulsions by stabilizing immiscible liquids such as oil and water, laying a foundation for comprehensive quality enhancement in food. Emulsification technology transforms these immiscible systems into stable emulsions, significantly optimizing the texture, taste, and aroma of foods. For instance, in dairy processing, it enhances the smoothness and gloss of the products. Additionally, emulsifiers form protective barriers that extend the shelf life of foods by blocking microbial invasion and proliferation, ensuring freshness and safety. Furthermore, emulsification facilitates the dissolution and absorption of nutrients, particularly in infant formulas, thereby enhancing the utilization rates of fats and proteins. The widespread application of emulsification not only enhances food quality and safety but also greatly enriches the diversity and innovation of the food market. This article introduces the basic principles and methods of food emulsification technology and focuses on its applications and innovations in the food sector [1].

2. Current Situation and Issues

2.1. Current Status

The food industry utilizes a wide variety of emulsifiers, primarily divided into natural and chemically synthesized categories, including polyol fatty acid esters, phospholipids and their derivatives, salts, and other types. Polyol fatty acid esters are the most commonly used and consumed type. The key to the preparation research of this class of food emulsifiers lies in enhancing the selectivity of the reaction. In recent years, enzymes, as highly efficient and specific biocatalysts, have been used for the enzymatic synthesis of polyol fatty acid esters, offering advantages such as mild reaction conditions, high reaction selectivity, and non-toxicity.

Emulsions are increasingly utilized in the food and beverage industry. In addition to the preparation of conventional cooked meat products such as Frankfurt sausages, sausages, salamis, cream-based foods, and salad dressings requiring emulsifiers, many functional foods or additives like nutrients, flavors, colors, antimicrobials, and health supplements are also formulated into emulsions for use in food products.

2.2. Issues

Safety of Emulsifiers: The safety of emulsifiers has always been a focal point of consumer concern. Some emulsifiers may pose potential health risks, such as allergenicity and toxicity. With increasing consumer demands for food safety, there is a growing demand for natural products or additives [2].

Technological Bottlenecks: Challenges include further enhancing the stability and fineness of emulsion systems, reducing the usage and cost of emulsifiers, improving the physical properties of natural emulsifiers, and enhancing their emulsifying performance. Detailed classification of food products and the development of targeted emulsifiers based on the principles of food production are needed, along with research into emulsifier compound techniques.

Environmental Issues: Emulsification technology can generate waste and pollution during production. Reducing environmental pollution while ensuring food quality and achieving sustainable development are pressing issues that need resolution.

3. Basic Principles and Methods of Emulsification Technology

3.1. Physical and Chemical Principles of Emulsification

An emulsion is a dispersed system formed by droplets dispersed in another immiscible phase. Emulsions, composed of water and oil phases, generally come in two types: oil dispersed in water (O/W) and water dispersed in oil (W/O). These two types of emulsions are widely used in cosmetics, skincare, and pharmaceutical production, but W/O emulsions are more commonly used in food processing. Emulsifiers are essential for promoting the stability of emulsions, playing a crucial role by reducing interfacial free energy and forming robust emulsification films. By lowering interfacial free energy, droplet particles form spherically to maintain minimal surface area. The process of forming an emulsion involves creating a large number of new interfaces between the two phases, where smaller droplets mean larger new interfaces, thereby increasing the surface free energy [3].

Emulsifiers adsorb onto the droplet surfaces, effectively reducing surface tension or free energy. They orient themselves around the droplets to form a film, reducing the oil-water interfacial tension and effectively preventing droplet coalescence. The more orderly the arrangement of emulsifiers on the droplet surface, the more stable the emulsion film and, consequently, the emulsion. The aim of emulsification is to reduce the energy consumed in preparing the emulsion.

3.2. Common Emulsification Methods

3.2.1 High-Speed Stirring

High-speed stirring, also known as high-speed dispersion technology, involves intense shearing, impacting, and dispersing actions by a high-speed rotating disc in a container on liquid or liquid-solid phase materials. This technology effectively achieves material crushing, dispersion, emulsification, and mixing. Turbulent zones formed at the edge of the dispersion disc subject the material to intense shearing and impact, producing strong vortices and up-down currents, promoting full circulation and turnover of the material, and ultimately achieving uniform dispersion.

3.2.2 Homogenization

Homogenization is a process used to treat fluids or semi-fluid materials to achieve a microscopically uniform distribution of components. The main goal of homogenization is to break down and disperse particles, droplets, or bubbles in the mixture into the continuous phase to form a more stable and uniform system. Different homogenization equipment employs various working principles, such as high-pressure homogenizers that achieve homogenization through high-pressure shearing, impact, and turbulence effects, while ultrasonic homogenizers use the cavitation effects produced by high-frequency vibrations to disrupt particle structures.

3.2.3 Ultrasonic Emulsification

Ultrasound refers to sound waves with frequencies beyond the audible range (generally >20 kHz). Ultrasonic emulsification technology utilizes the cavitation effects produced by ultrasound in liquids to achieve emulsification. Ultrasound produces hundreds of thousands of vibrations per second in a liquid, shattering it into a multitude of tiny bubbles. These bubbles grow rapidly under continuous action and suddenly collapse, generating strong shockwaves and local high-temperature, high-pressure conditions. This physical phenomenon effectively mixes immiscible liquids into a dispersed system, allowing one liquid to be uniformly distributed in another. Prodromos Prodromidis and others treated Tw20 and mg structure emulsions with different ultrasound intensities, finding that high-intensity ultrasound can form structurally strong emulsions, while low-intensity ultrasound can delay crystallization to the solid phase, forming weaker emulsions.

3.3. Physical and Chemical Principles of Emulsification

The physical and chemical principles are summarized in Table 1.

Table 1. The physical and chemical principles of emulsification

		Features	Scope of application
synthesis	Span80	Low molecular weight polyol lipophilic nonionic surfactant	Commonly used in the production of water-in-oil foods[4]
	Tween80	Hydrophilic and lipophilic nonionic surfactant	HBL value is large, often used to make water-in-oil type food
	Monoglyceride of fatty acid	It is inexpensive, has a wide hydrophilic-lipophilic balance value, and has good antibacterial effect in neutral and slightly alkaline environments. It is a highly effective preservative [4]	Medicine, food, cosmetics, textile printing and dyeing, and petroleum industries
	Sucrose fatty acid esters	Amphiphilic, low toxicity, odorless, low irritation, and easily biodegradable [5]	Starch, ice cream, hydrophilic products
natural	Lecithin	Small molecules	Oil in water
	Gum Arabic	Emulsification, dispersion of flavors and pigments, stabilization of carbon dioxide	drinks
	Whey protein	After compounding, the emulsification effect is better	

4. Application of Emulsification Technology in the Food Field

As a quality improver, it prevents the hydrophobic effect of amylose in flour, thereby preventing dough aging and regeneration; promotes the formation of gluten tissue and enhances toughness; improves foaming properties and disperses and compacts pores; promotes the emulsification and dispersion of shortening, improving texture and taste. In the cake production process, adding an appropriate amount of emulsifier for whipping to quickly rise can promote air to enter the cake batter in a very short time, turning it into rich and delicate foam. After baking, a soft and large cake is obtained, and the cake effectively improves the elasticity and taste of the cake [6].

Emulsifiers can emulsify and disperse the added oils and fats, improve the delicate taste, and at the same time make the surface of the product frosted, prevent adhesion to the packaging paper, and prevent sugar crystallization, improving the taste of chocolate and candy. 4.3 Application in Beverages Some beverages (such as soy milk, peanut milk, etc.) also contain a lot of fat. Emulsifiers can emulsify the fat in the beverage to form a stable emulsified system, which plays the role of flavoring, solubility, emulsification and dispersion, and anti-oxidation.

Emulsifiers can control the size and growth rate of fat crystals, improve the product structure, etc. Juliana Gobbi de LIMA et al. added beta-carotene-loaded solid lipid microparticles to ice cream and obtained a product with strong stability [7].

Salad dressing, mayonnaise, ketchup, etc. Through emulsification, the oil phase and the water phase can form a stable emulsion, making the sauce rich in taste and easy to spread. The addition of emulsifiers can also improve the stability and shelf life of the sauce.

Emulsification technology is widely used in the production of butter, cream, yogurt, cheese, etc. Through emulsification, fat can be evenly dispersed in whey or milk solids, improving the taste and texture of the product. For example, when making cream, emulsifiers can keep fat globules stable and prevent fat from floating and stratifying. Extend shelf life. Anni B. Hougaard et al. found that adding DSP to cheese can extend the shelf life of cheese [8].

5. Innovation and Development of Emulsification Technology

5.1. Nanoemulsification Technology

Nanoemulsion is a transparent dispersion of oil and water, stabilized by the interfacial film of surfactant and co-surfactant molecules, with a droplet size of 10-200 nm. Thermodynamically stable transparent or translucent homogeneous dispersion system [9].

Anand Prakash et al. used citral nanoemulsion composite edible coating to reduce microbial growth rate and extend the microbial quality of fresh-cut pineapple for 12 days [10]. Safa Dghais et al. prepared a stable nanoemulsion with cinnamon and turmeric as raw materials, which has good antioxidant and antibacterial activity and can greatly extend the shelf life of minced beef [11].

5.2. Microencapsulation Technology

Microencapsulation technology is a technology that encapsulates trace substances in polymer films. Its core is to completely encapsulate a certain target (core or inner phase) with a continuous film of various natural or synthetic polymer compounds (wall or outer phase) without damaging the original chemical properties of the target.

Xiao Zuobing et al. used the high thermal stability of maltodextrin microcapsules in high-concentration solids to make maltodextrin microcapsules widely used, determined the influence of core materials on microcapsules, and provided research directions for the selection of wall materials. [12]. Natallia Varankovich et al. prepared pea alginate protein microcapsules containing Lactobacillus rhamnosus R0011 and L. helveticus R0052 by extrusion method and tested their survival ability in in vitro gastrointestinal environment. Compared with unencapsulated bacteria, both microcapsule formulations showed significant protective effects on cells incubated in synthetic gastric fluid at 37°C for 2 hours and then in simulated intestinal fluid for 3 hours [13].

5.3. Smart Emulsifier System

Smart emulsifiers are chemical substances that can adapt and optimize the emulsification effect by changing their molecular structure under changing external conditions (such as temperature, light, pH, etc.). Zofia Hordyjewicz-Baran et al. developed a smart detergent for fruits and vegetables using a non-ionic surfactant: poly(oxyethylene) alkyl ether. Consumers wash at a temperature close to body temperature (about 37 °C) and rinse in relatively cold water (about 22 °C). Taking into account consumer behavior, the composition of the designed detergent was adjusted to achieve the highest solubility in water during the rinse process so that the detergent can be removed from the surface. Good solubility in water is achieved due to hydrogen bonding between the solvent and the ether oxygen atoms on the chain. As the temperature increases, the poly(oxyethylene) chains are desolvated, resulting in a decrease in the solubility of the compound [14].

6. Challenges and Solutions Faced by Emulsification Technology

6.1. Safety Issues of Emulsifiers

Some emulsifiers may contain chemical ingredients that are harmful to the human body, such as synthetic surfactants, which may have potential effects on consumer health when used for a long time or in excessive amounts. To solve these problems, we should try to use emulsifiers from natural sources, such as lecithin and monoglycerides, which are relatively safe and beneficial to human health. The government should strengthen the supervision of emulsifiers and their products, formulate strict safety standards and testing methods, and ensure the safety of emulsifiers. The government popularizes relevant knowledge about emulsifiers through media, the Internet and other channels to improve consumers' health awareness and self-protection ability.

6.2. Cost and Sustainability

Emulsification technology improves food quality while also increasing production costs. The procurement of emulsifiers, the purchase and maintenance of emulsification equipment, and the research and development and optimization of emulsification processes all require a lot of money. How to reduce production costs while ensuring food quality is a major challenge facing emulsification technology. Through technological innovation and process optimization, emulsification efficiency can be improved and production costs can be reduced. For example, use advanced emulsification equipment to improve the emulsification effect and reduce the amount of emulsifiers. Strengthen the treatment and utilization of waste in the emulsification process to achieve the recycling of resources. Encourage and support the research and development and application of green emulsifiers to reduce dependence on traditional emulsifiers.

6.3. Technical Bottlenecks

By improving the structure and linear speed of the emulsification equipment, the emulsification effect can be improved, so that the droplet size formed is narrower and the distribution is more uniform. By adjusting the emulsification process parameters such as temperature, pressure, stirring speed, etc., the emulsification process can be optimized to improve the stability and uniformity of the emulsion. Develop and apply new emulsifiers, such as polymer emulsifiers and bio-based emulsifiers, which have better stability and uniformity and can improve the quality of the emulsion.

7. Conclusion

The application of emulsification technology in the food field is extremely extensive and important. It is one of the key technologies to improve food quality, safety and market diversity. This paper reviews the basic principles, common methods, types and characteristics of emulsifiers, and application examples of emulsification technology in various foods. In addition, this article also discusses the innovation and development trends of emulsification technology, including cutting-edge technologies such as nanoemulsification technology, microencapsulation technology and intelligent emulsification system. These technologies further improve the stability and functionality of emulsions, extend the shelf life of food, and enhance the nutritional value and taste experience of food. However, emulsification technology also faces challenges such as emulsifier safety, high production costs, technical bottlenecks and environmental protection issues in the process of development. To solve these problems, it is necessary to increase the development and application of natural emulsifiers, improve the safety and biocompatibility of emulsifiers; reduce production costs through technological innovation and process optimization; and strengthen the treatment of emulsification waste and resource recycling to achieve sustainable development of emulsification technology.

In general, emulsification technology has broad application prospects in the food field, and its continuous innovation and development will continue to promote the progress of the food industry. At the same time, in the face of existing challenges, researchers, enterprises and policymakers need to work together to take effective measures to ensure the safety and efficient sustainable development of emulsification technology.

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