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Scope of nanoemulsions in food industry: A review

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Abstract
Nanoemulsions, a type of emulsion with droplet sizes in the nanometer range, have emerged as a promising technology in the food industry. Due to their unique properties and advantages, nanoemulsions have found diverse applications in various food products. This review highlights the scope of nanoemulsions in the food industry, focusing on their formulation, preparation methods, stability, and potential benefits. Nanoemulsions offer improved solubility, enhanced bioavailability, and controlled release of bioactive compounds, such as flavors, antioxidants, and antimicrobials, leading to improved sensory attributes and extended shelf life of food products. Additionally, nanoemulsions can serve as delivery systems for lipophilic vitamins and nutraceuticals, enhancing their absorption and efficacy. Moreover, nanoemulsions can be employed for encapsulation and delivery of functional ingredients, including essential oils, plant extracts, and bioactive peptides, to improve their stability and controlled release in food matrices. Furthermore, the use of nanoemulsions as carriers for fat-soluble vitamins and fortification of foods with lipophilic compounds has gained significant attention. The incorporation of nanoemulsions in food products holds promise for improving the quality, functionality, and health benefits of food. However, challenges related to production scale-up, long-term stability, and regulatory aspects need to be addressed to ensure the successful implementation of nanoemulsions in the food industry.

Keywords: Scope, nanoemulsions, food industry

1. Introduction

The increasing demand for fresh foods with fewer synthetic additives or preservatives, and a low ecological footprint has led scientists and researchers to develop innovative and more eco-friendly processing technologies which will further contribute in improving the environment. Taking this into consideration, the use of nanoemulsions represents a great step forward in eliminating physical packaging materials (Espitia *et al.*, 2019) [14]. Emulsions are classified as coarse emulsions, microemulsions, or nanoemulsions based on the size and stability of their droplets (Komaiko & McClements, 2016) [28]. All of these types of emulsions and their properties have been listed below in Table 1. Nanoemulsions are one of the most known formulation systems in the pharmaceutical, cosmetic and food industries. A significant interest in nanoemulsions has driven rapid development for the administration of active substances or drugs in system due to their attractive properties such as higher stability, appealing nature, high performance, and sensorial advantage (Marzuki *et al.*, 2019) [34].

Nanoemulsions serve as a system of colloidal particles in the range that works as a carrier for active incorporation of ingredient molecules. Two types of nanoemulsions most commonly used are: oil-in-water type nanoemulsion and water in oil type nanoemuslion. Their size ranges from 10 to 1000 nm with a condition of carriers to be solid spheres, with amorphous surface or lipophilic with a negative charge. The term "nanoemulsions" also refers to as mini-emulsion, which is a fine dispersion of either oil in water or water in oil that is stabilized by transparent film of droplet sized molecules of range of 20 to 600 nm (Jaiswal *et al.*, 2015) [21]. Nanoemulsions are thermodynamically metastable because phase separation happens over time. These have kinetic stability due to the lack of gravitational separation and droplet aggregation caused by the lower attractive attraction between the microscopic droplets (McClements and Rao, 2011) [37]. Unlike thermodynamically stable microemulsions, nanoemulsions are unaffected by physical and chemical changes such as temperature and pH. The amount of surfactants required for their preparation is less. The droplet size of a nanoemulsion determines its rheological and release behaviour in addition to its optical properties and stability. As a result, nanoemulsions are more appropriate for many applications than microemulsions. Functional chemicals and active substances, such as antioxidants and nutraceuticals, can be encapsulated using nanoemulsions.

They are also useful for releasing taste ingredients in foods in a controlled manner (Velikov & Pelan, 2008; McClements & Rao, 2011; Ines *et al.*, 2015) [47, 37, 18]. In this review, we will discuss about the different preparation methods of nanoemulsions and their applications in food industry.

Table 1: Types of emulsions - physiochemical properties, preparation method and stability (Aswathanarayan & Vittal, 2019) [4]

Types of emulsions	Droplet Size	Preparation Method	Effect of Temperature and pH	Thermodynamic Stability
Macro or coarse emulsions	1–100µM	High energy and low energy methods	No change	Metastable
Micro-emulsions	10–100 nm	Low energy methods	Effected by change in pH and temperature	Stable
Nano-emulsions	<200 nm	High energy and low energy methods	No change	Metastable

2. Methods of Formulation

Nanoemulsions can be prepared using either a high-energy dissipation method or a low-energy dissipation method. The amount of energy used in these two ways is different. The high-intensity method uses mechanical devices to generate large disruptive forces. The low energy technique, on the other hand, modifies the system's physiochemical properties to produce nanosized particles (Cinar *et al.*, 2017) [11]. High-energy approaches have been the only option for researchers since the discovery of nanoemulsions due to their ease of manufacture. Due to the demand of temperature-sensitive components, such as medicinal compounds, low-energy approaches have recently become desirable (Koroleva *et al.*, 2012) [29].

2.1 High-Energy method

Mechanical equipment such as micro fluidizers, high pressure homogenizers (HPH), and ultrasonicators are used to make nanoemulsions using the high energy method. Large disruptive forces are used in these mechanical devices to produce nanodroplets (Anton *et al.*, 2008) [3]. They are industrially scalable, but they need a lot of energy, which means they have significant production costs. For microfluidizers, ultrasonicators, and HPH, the operating principles included colloidal mill operation, high frequency sound waves (20 kHz and higher), and the action of high pressure displacement pump (500–50,000 psi). Some of these high energy methods are:-

2.1.1 Sonication

One of the methods utilized for producing kinetically stable nanoemulsions involves sonication or ultrasonic homogenization. This technique involves bringing a sonicator probe in contact with a surfactant and co-surfactant dispersion of liquids to generate mechanical vibration and cavitation, providing the necessary energy input for forming small-sized droplets. Sonication or ultrasound processing is commonly employed in small-scale production of nanoemulsions. However, it is crucial to exercise caution to prevent shear-induced coalescence during the process (Delmas *et al*., 2011) [12].

The particle size of the dispersed phase in nanoemulsions produced by sonication decreases with longer durations of ultrasonic homogenization, higher power levels, and increased surfactant concentration (Kentish *et al*., 2008) [27]. Achieving a droplet size of around 20 nm requires optimization of various factors, including the design of ultrasonic reaction chambers, operating conditions, and the formulation of the product, which encompasses surfactant concentration, type, and content of the oil phase (Kumar & Singh, 2012) [30].

2.1.2 High Pressure Homogenization

This method is widely used for the production of nanoemulsions. It utilizes several forces such as hydraulic shear, intense turbulence and cavitation. A high pressure homogenizer is used in this technique where the macroemulsion is directed through a narrow orifice at an operating pressure ranging from 500 to 5000 psi and the nanoemulsions produced by this approach usually have a very small particle size, which can be as small as 1 nm because forces such as hydraulic shear, severe turbulence, and cavitation work together to form nanoemulsions with extremely small droplet sizes (Lovelyn & Attama, 2011; Chime *et al*., 2014) [32, 9]. This process harnesses the combined effects of hydraulic shear, intense turbulence, and cavitation, leading to the formation of highly diminutive droplets in the nanoemulsion, and these forces work in concert to achieve the desired reduction in droplet size (Çinar, 2017) [11]. Despite its efficiency, this approach has the disadvantage of consuming a lot of energy and causing the emulsion temperature to rise throughout processing (Bhatt & Madhav, 2011) [7].

2.1.3 Microfluidization

This mixing technique utilizes a high-pressure displacement pump (ranging from 3.45 to 137.89 MPa) to generate finely dispersed nanoemulsions (Jasmina *et al*., 2017) [22]. In this process, the application of high pressure drives the macroemulsion into the interaction chamber, facilitating the production of submicron-sized nanoemulsion particles (Çinar, 2017) [11]. To achieve uniform nanoemulsion production, the process can be repeated multiple times while adjusting the operating pressure to attain the desired particle size (Chime *et al*., 2014; Jaiswal *et al*., 2015) [9, 21]. The oil and water phases flow through opposing microchannels, converging at a common impingement area where the high pressure induces significant shear forces. The crude emulsion is repeatedly passed through the microfluidizer's interaction chamber until the desired droplet size is achieved (Setya *et al*., 2014) [41]. To ensure uniform droplet size within the nanoemulsion's internal phase, the crude emulsion is subjected to filtration under a nitrogen atmosphere to remove larger droplets (Jincy *et al*., 2015) [24]. The droplet size of the dispersed phase in nanoemulsions produced using the microfluidizer diminishes with increasing homogenization pressure, multiple passes through the microchannel devices, higher surfactant concentration, and a decrease in the viscosity ratio between the dispersed and continuous phases (Kentish *et al*., 2008) [27].

2.2 Low Energy Method

Low energy methods are used to make nanoemulsions by making use of the system's inherent chemical energy (or chemical potential of components). Chemical energy generated during emulsification is thought to be the cause of the low-energy method phenomena. This occurs as a result of the surfactant molecules' spontaneous curvature changing from negative to positive (oil in water) or positive to negative (water in oil) (Jadhav *et al.*, 2015) [20]. Spontaneous emulsification, phase inversion composition, phase inversion temperature, microemulsion dilution, and D phase emulsification are all included in this method. The low-energy method entails just stirring at a slower rate (1600 rpm), which uses less energy. Isothermal and thermal methods are the two types of low-energy methods. Isothermal methods are suitable for bioactive compounds which are thermally sensitive (Anton & Vandamme, 2009) [3]. It mainly includes spontaneous emulsification, phase inversion composition, microemulsion dilution and D phase emulsification. Thermal method is mainly applicable to solid lipid nanoparticles where heating is essential to maintain liquid phase (Solans & Solé, 2012) [43]. Some of the low energy methods of formulation are explained below:

2.2.1 Phase Inversion Method

Phase inversion or condensation method, is based on transition of phases during the emulsification process. These techniques harness the chemical energy released during the emulsification process, which is attributed to phase transitions (Anandharamakrishnan, 2014) [2]. The desired phase transitions can be achieved by modifying the composition while maintaining a constant temperature or by adjusting the temperature while keeping the composition constant (Thakur *et al*., 2013) [45]. These phase transitions occur as a result of changes in the surfactant's spontaneous curvature and can be achieved through two methods. The first method, known as the phase inversion temperature (PIT) method, involves changing the spontaneous curvature of non-ionic surfactants with temperature while maintaining a constant composition. This method is widely used in the industry. The second method, known as the emulsion inversion point (EIP) method, involves varying the composition of the system while keeping the temperature constant. However, these methods have certain limitations including complexity, the need for precision, and the use of synthetic surfactants (Izquierdo *et al*., 2005) [19]. Phase transitions can be induced by either increasing the temperature while maintaining a constant composition or by altering the composition while keeping the temperature constant (Setya *et al*., 2014) [41].

2.2.2 Spontaneous emulsification

Spontaneous emulsification is a low energy method for the preparation of nanoemulsions. This method takes advantage of the chemical energy released during the dilution process with the continuous phase. Unlike other methods, this process occurs at a constant temperature without any phase transitions in the system. It offers the advantage of producing nanoemulsions at room temperature without the need for specialized equipment. The success of this method relies on various factors such as interfacial tension, viscosity of the interfacial and bulk phases, the phase transition region, surfactant structure, and surfactant concentration. (Solans & Sole, 2012; Setya *et al*., 2014) [43, 41]. Nanoemulsions can be easily prepared using the spontaneous emulsification method at room temperature without requiring specialized equipment. The process involves adding water into a solution containing oil and surfactant gradually, while maintaining a constant temperature and gently stirring the mixture. This results in the formation of oil-in-water nanoemulsions. The success of the emulsification process depends on various factors such as interfacial tension, interfacial and bulk viscosity, phase transition region, surfactant structure, and surfactant concentration (Bouchemal *et al*., 2004) [5]. However, it is important to note that this method has limitations, including the restricted amount of oil phase that can be incorporated and the presence of a solvent in the system (Koroleva & Yurtov, 2012; Maali & Mosavian, 2013) [29, 33].

2.2.3 Solvent Displacement Method

The production of nanoemulsions using this method involves the addition of an organic phase, which contains oil dissolved in a solvent such as ethanol or acetone, into an aqueous phase containing surfactants. Emulsification occurs spontaneously due to the diffusion of the organic solvent, which can be subsequently removed through vacuum evaporation. To achieve small droplet sizes, a high ratio of solvent to oil is required (Setya *et al*., 2014; Fryd & Mason, 2012) [41, 15]. Several parameters, including flow rate, pressure, density of interface, temperature, time of emulsification, and speed of rotation, need to be optimized to obtain the desired formulation of nanoemulsions (Jaiswal *et al*., 2015) [21].

The solvent displacement method takes advantage of the differences in solubility between the solvent and the aqueous phase. The solvent used is typically immiscible with water and has a lower density than water, allowing it to form a separate phase (Kumari & Kumar, 2022) [31]. As the solvent is added, it forms droplets within the aqueous phase, and the surfactants present at the interface help stabilize the droplets by reducing the interfacial tension. The choice of solvent is crucial in this method as it should be compatible with the oil phase and have a low enough boiling point to be easily removed afterward. Common solvents used include ethanol, acetone, and chloroform. Once the emulsion is formed, the solvent can be removed through methods such as evaporation or dialysis, leaving behind the desired nanoemulsion (Fryd & Mason, 2012) [15].

2.2.3 Advantages and Challenges Associated with Nanoemulsions

Nanoemulsions are gaining popularity in the food industry due to their advantageous properties, including efficient encapsulation and targeted delivery of bioactive compounds. They offer improved solubilization, bioavailability, and sustained release capabilities (Karthik *et al*., 2015; Jasmina *et al*., 2017) [16, 22]. Nanoemulsions are characterized by their small size, typically measured in nanometers, which results in a larger surface area and distinctive morphological features. Even though nanoemulsions have many advantages, it also includes some challenges which may limit its use in food industry if not formulated or used properly within the standard limits. Some of the main advantages and challenges faced in application of nanoemulsions in food industry are listed in Table 2.

Table 2: Advantages and challenges associated with nanoemulsion technology (Karthik *et al.*, 2015) [26]

S. No.	Advantages	Challenges
1.	Increased bioavailability of bioactive compounds.	Coalescence of components in the food system
2.	Targeted delivery	Sedimentation
3.	Efficient encapsulation of flavour, nutraceuticals and essential oils.	'Ostwald ripening' which causes change in the initial ratio of components inside emulsion droplets.
4.	Solubilization of low solubility substances.	Flocculation of emulsions
5.	Entrapment of bioactive compounds	Phase Separation in food system

4. Applications of Nanoemulsions in Food Industry

The application of nanoemulsions is an in-development technology and is already introduced in many food industries as it is a more viable method to increase multiple healthier aspects of a food product. Using the Nanoemulsion technology for encapsulating functional compounds can ameliorate the bioavailability of the compounds and can delay the degradation process which can have a direct positive effect on the shelf life and enhance the overall quality of the product (Silva *et al.*, 2011) [44]. The practical application of nanoemulsions in the food system has been a challenging procedure, as the stability of the nanoemulsion system being a major problematic factor (Maali & Mosavian, 2013) [33]. Other limitations that can be observed for bioactive compound delivering system are low solubility and bioavailability (Aswathanarayan & Vittal, 2019) [14]. Some of the applications in food industry are mentioned below:

4.1 Modulation of Product's Shelf Life

Prevention of contamination and control of bacterial growth on fresh produce has always been a crucial task for maintaining public health. In total there have been almost 37 outbreaks from 1980 through 2009 involving 3485 persons affected by food poisoning and the most common factor for foodborne illness was bacterial contamination (Rao Vemula *et al.*, 2012) [39]. The current technique applied in food industry is washing the product with dilute chlorine aqueous. However problems related to chlorine by-products are a major health concern, so it is become a necessity to explore natural bioactive compounds with strong antimicrobial capacity. Because of their predominant properties nanoemulsions are eligible candidate for avoiding food spoilage (Jin *et al.*, 2016) [13].

The implementation of this technique was done and was reported by Bhargava *et al.*, 2015 [6] which indicated that an oregano oil nanoemulsion was applied for controlling the food-borne bacteria on fresh lettuce. There were different types of lettuce which got initially contaminated by three microbials, including *Salmonella typhymurium*, *E. coli* and *Listeria monocytogenes.* After the observed contamination the Lettuce were immersed in Oregano oil nanoemulsions for 1 min followed by drying for 30 minutes. There was a significant inhibition of the microbial growth due to the oregano oil nanoemulsions treatment. A nanoemulsion based on Eugenol- sesame oil prepared by ultrasound emulsification was added to fresh orange juice and on the evaluation and analysis of the juice, this addition showed promising results with enhanced in situ antimicrobial activity (Ghosh *et al.*, 2014) [16]. To control the stability of vegetable cream and chicken broth, nanoemulsions were used which were prepared with d-limonene and nisin (Mate *et al.*, 2015) [35]. Nanoemulsions were investigated to be capable of maintaining the quality and extending the shelf life of king mackerel steaks stored at 20 °C, the nanoemulsion was based on Sunflower oil (Joe *et al.*, 2012) [25].

4.2 Intercepting the Contamination of Products

The process has already been discovered that can produce nanoemulsions to act as antimicrobials in the food field. Nanoemulsions have widely reported to have antimicrobial activity in the food industries to prevent packaging, equipments and products from contamination specially focused on the non-thermal prevention methods, which are intended to retain the nutritional values and textural properties at the maximum level (Jin *et al.*, 2016) [13]. The most widely used antimicrobial nanoemulsions are O/W type and have average droplet size in between 200nm and 500nm (Saranya *et al.*, 2012) [40].

Currently utilization of new preservation methods based on natural origin are the topic of interest in researches. One of the natural compounds is essential oils which show promising outcomes when incorporated in food systems because they show strong antimicrobial anti-viral and anti- fungal activities (Amaral & Bhargava, 2015) [1]. The fact has been confirmed by many researches that nanoemulsions are having a wide antimicrobial activity against various food pathogens including bacteria like (*E.coli*, *S. aureus* and *Vibrio cholera*), fungi like (*Dermatophytes* and *Candida albicans*), viruses like (Influenza A and Herpes simplex) and spores like (*Bacillus cereus* and *Bacillus anthracis*) and so on (Jin *et al.*, 2016) [13]. These essential oils are mainly incorporated in the food system using nanoemulsion process. Essential oils including, cinnamon oil, basil oil, clove oil are some common naturally occurring anitimicrobial agents. These oils can endow high antimicrobial activity in the nanoemulsion because of the components like eugenol, carvacrol, α-pinene, benzaldehyde, limonene, menthol, vanillin, thymol and carvone (Ghosh *et al.*, 2013) [17]. The antimicrobial activity is also affected by particle size of nanoemulsion. It is also found that nanoemulsions with smaller diameter showed higher microbial activity because of the faster movement through cell membrane of the target microorganism.

4.3 Fortification and Optimization of Food Products

There are many essential micronutrients which are important human health such as lipophilic vitamins. As a result of increasing awareness among the consumers there has been growing demand of vitamin fortified foods to prevent common life threatening diseases. To be focusing at how susceptible vitamins are due to their lack of heat stability, chemical stability and the quantity is also affected by losses due to transportation and storage, there is a stronger requirement of protective encapsulation technology for vitamins to enhance their bioavailability in the human gastrointestinal system and also prevent degradation. The most promising candidate as described by researchers for encapsulating and stabilizing lipophilic vitamins is Oil-in-water based nanoemulsion (Öztürk, 2017) [38]. There are many challenges realted to food fortification of bioactive compounds since there are factors involved in the process like the compatibility of food system and encapsulation system without creating any adverse effects on the physiochemical and sensory qualities of the product. Then there comes the maintenance of the bioactives during the processing and storage conditions so that it retains its original properties before consumption (Siegerist *et al.*, 2008) [42].

4.4 Hydrophobic Nutraceuticals Delivery System

There are various naturally occurring functional compounds like pigments and Nutraceuticals having excellent biological and physiochemical properties. Some of these compounds are- Flavonoids, carotenoids, fatty acids, polyphenols, coenzymes. But there are many factors which affect the efficiency of the incorporation of these Nutraceuticals which can be overcome using nanoemulsion encapsulation method. Bioactivity reduction of these bioactive compounds during processing can have adverse effects on the application and hence not a preferred method (Wang *et al.*, 2008) [48]. Some of the proven advantages of nanoemulsions as delivering system or nutraceuticals are bioavailability increment, physical stability improvement, maintenance of bioactivity and enhancement of chemical stability (Jin *et al.*, 2016) [13].

4.5 Delivery of Flavours and Colours

The delivery of flavors and colors in food systems is a very challenging topic, which should take into account the preservation and persistence of highly volatile molecules over the entire shelf life of the product and their controlled release during food preparation and consumption, which in turn impacts how they are perceived by consumers. The problem of citral preservation upon addition to acidic beverages has solicited the interest of food scientists. Citral is an important lemon-like aroma compound, widely used in the food and drink industry. However, due to its molecular structure, citral is highly susceptible to degradation to off-flavors, primarily p-cymene, p-cresol, and p-methylacetophenone, during storage in a low pH or oxidative environment (Tian *et al.*, 2017) [46], typical of carbonated beverages.

Preserving the stability of citral in low-pH conditions has presented significant challenges for the food industry in recent decades. To address this issue, emulsion-based encapsulation has emerged as a simple yet effective solution. Various approaches, including the selection of suitable emulsifiers (Choi *et al*., 2010) [10], the deposition of multiple biopolymer layers, and the incorporation of antioxidant molecules, have shown promise in preserving citral (Yang *et al*., 2012) [49]. The optical properties of emulsions are influenced by their colloidal characteristics, including droplet size, refractive index, and concentration. These factors play a role in light scattering, absorption, and the presence of chromophoric materials (McClements, 2017) [36]. Specifically, the lightness of an emulsion increases with higher droplet concentration, smaller droplet size, and lower dye concentration, while chromaticness exhibits the opposite behavior (Chanamai & McClements, 2001) [8]. When a light beam interacts with an emulsion, some of the light is absorbed or transmitted, while some is scattered or reflected. Light scattering affects the turbidity, opacity, or lightness of the dispersed system, while absorption contributes to its chromaticness, such as blueness, greenness, or redness (McClements, 2017) [36]. Generally, nanoemulsions with diameters below approximately 60 nm are optically transparent, making them suitable for use in clear foods and beverages. On the other hand, nanoemulsions with diameters ranging from about 60 to 100nm tend to be turbid or opaque. Considering these factors, utilizing nanoemulsions to control the color of food systems requires careful management of various properties, including mean droplet size, droplet size distribution, refractive index, concentration, and stability of chromophoric components. Precise control over these parameters is crucial to achieve the desired color effects while maintaining stability and functionality in the food product.

5. Conclusion and Future Scope

The future of nanoemulsions in the food industry holds significant promise and potential. Nanoemulsions offer various advantages such as improved stability, enhanced bioavailability, controlled release, and increased solubility of bioactive compounds. These properties make them suitable for a wide range of applications in the food industry. One of the key areas of future exploration is the development of nanoemulsions as delivery systems for functional ingredients and nutraceuticals. Nanoemulsions can encapsulate and protect sensitive bioactive compounds, allowing for controlled release and targeted delivery. This opens up opportunities for fortifying food products with vitamins, antioxidants, antimicrobial agents, and other beneficial components.

Moreover, nanoemulsions can contribute to the development of healthier food products by reducing fat content while maintaining desirable sensory attributes. They can serve as effective carriers for fat-soluble flavors, colors, and aromas, enabling the creation of low-fat products without compromising taste and texture. Another exciting area of research is the application of nanoemulsions in food safety and preservation. Nanoemulsions possess antimicrobial properties and can be used to inhibit the growth of pathogens and spoilage microorganisms, thereby extending the shelf life of perishable food items. Furthermore, nanoemulsions have the potential to revolutionize food packaging by providing barrier properties against oxygen, moisture, and light. This can help preserve the quality and freshness of food products, reduce food waste, and enhance the overall sustainability of the food industry.

In conclusion, the future of nanoemulsions in the food industry looks promising, with opportunities for the development of functional and healthier food products, improved food safety, and enhanced packaging solutions. Continued research and development in this field will further unlock the potential of nanoemulsions and contribute to advancements in the food industry.

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