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NANOEMULSIONS IN THE FOOD INDUSTRY: DEVELOPMENT, CHARACTERIZATION AND APPLICATIONS – A REVIEW

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ABSTRACT

Nanoemulsions are nanoscale colloidal dispersions of immiscible liquids that have emerged as promising delivery systems in the food industry due to their enhanced stability, transparency, and ability to improve the solubility and bioavailability of bioactive compounds. This review summarizes the fundamental principles of nanoemulsion systems, including their composition, preparation methods, characterization techniques, and applications in food products. Both high-energy and low-energy emulsification approaches are discussed, together with key evaluation parameters such as droplet size distribution, polydispersity index, zeta potential, viscosity, and encapsulation efficiency. Particular emphasis is placed on the role of nanoemulsions in the encapsulation and delivery of nutraceuticals, vitamins, antioxidants, essential oils, and other functional ingredients. The review highlights their potential to improve food quality, stability, shelf life, and nutrient bioavailability while enabling the development of innovative functional foods. Current challenges associated with large-scale production, long-term stability, safety assessment, and regulatory approval are also examined. Overall, nanoemulsions represent a versatile and effective technology for food applications, and continued advances in formulation strategies and safety evaluation are expected to support their broader industrial adoption.

KEYWORDS: Nanoemulsion, Encapsulation, Bioactive Compounds, Food Industry, Emulsification Techniques, Stability, Functional Foods.

INTRODUCTION

An emulsion is a lyophobic colloidal system composed of two immiscible liquids, commonly oil and water, in which one liquid is uniformly dispersed within the other in the form of spherical globules. The surrounding liquid acts as the continuous phase, while the dispersed droplets generally range from 0.01 to 100 µm in diameter. Based on droplet size and stability, emulsions are broadly classified into nanoemulsions, microemulsions, and macroemulsions (coarse emulsions).[24]

Nanoemulsions are colloidal dispersions of two immiscible liquids, usually oil and water, where one phase is dispersed as nanosized droplets within the other. Their droplet size generally ranges below 500 nm, although some studies define the upper limit as 100 or 200 nm.[10] Due to their small droplet size, high kinetic stability, and large surface area, nanoemulsions are widely used for encapsulation, controlled release, and enhanced bioavailability of lipophilic bioactive compounds in pharmaceutical, cosmetic, biotechnology, and food industries.[13] Figure 1 shows the structure of nanoemulsion.

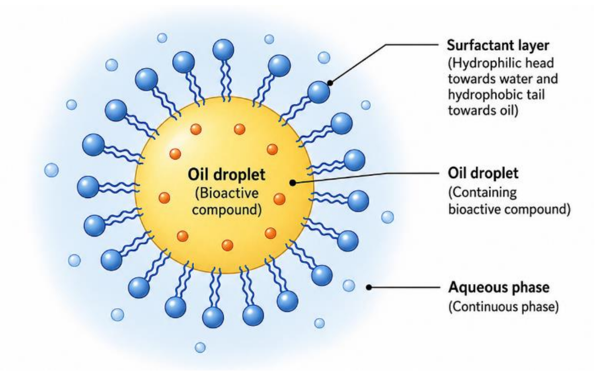


Fig. 1 Structure of nanoemulsion.

Depending on droplet size, nanoemulsions may appear transparent or slightly turbid. Droplet size significantly influences optical properties, stability, rheology, and release behaviour, thereby improving the physicochemical stability of formulations.[25] Nanoemulsions mainly consist of an aqueous phase, oil phase, and emulsifier. Water is commonly used as the aqueous phase, while the oil phase may include essential oils, fatty acids, lipophilic compounds, vitamins, and other non-polar substances.[8] Nanoemulsions are generally classified as water-in-oil (W/O) or oil-in-water (O/W) systems. In W/O nanoemulsions, water droplets are dispersed in a continuous oil phase, whereas in O/W nanoemulsions, oil droplets are dispersed within a continuous aqueous phase.[12]

Kinetically stable, optically transparent, and isotropic nanoemulsions have emerged as promising systems in food processing and packaging applications. They are widely utilized for the encapsulation, protection, and delivery of lipophilic bioactive compounds, including nutraceuticals, drugs, vitamins, antioxidants, and antimicrobial agents. Compared to conventional emulsions, nanoemulsions exhibit several advantages such as enhanced stability, larger oil–water interfacial area, improved bioavailability, low toxicity, and non-irritant nature.[21] Bioactive compounds must remain protected during food processing, storage, and gastrointestinal transit to ensure effective delivery at the target site within the body. Nanoencapsulation plays an important role in protecting sensitive food ingredients from heat, moisture, and pH variations. In the food industry, nanoemulsions are widely used to encapsulate bioactive compounds within nanosized capsules, improving their stability, solubility, bioavailability, and controlled release without adversely affecting the taste or texture of foods. Additionally, nanoencapsulation enhances the delivery and health benefits of nutraceutical compounds.[5]

ADVANTAGES OF NANOEMULSIONS

1. Enhanced Solubility and Bioavailability

One of the major advantages of nanoemulsions is their ability to improve the solubility and bioavailability of poorly water-soluble bioactive compounds. The nanosized droplets provide a large interfacial surface area, facilitating enhanced dissolution and absorption of lipophilic compounds. As a result, nanoemulsions have been widely employed for the delivery of vitamins, nutraceuticals, antioxidants, and pharmaceutical compounds, leading to improved therapeutic and nutritional efficacy.[20,24]

2. Improved Stability of Bioactive Compounds

Nanoemulsions can protect encapsulated bioactive compounds from environmental factors such as light, oxygen, moisture, and pH variations. This protective effect minimizes degradation and preserves the functional properties of sensitive ingredients during processing, storage, and gastrointestinal transit. Consequently, nanoemulsions contribute to increased shelf life and enhanced stability of food and pharmaceutical products.[5]

3. Controlled and Targeted Delivery

The large surface area and nanoscale droplet size of nanoemulsions facilitate efficient transport of encapsulated compounds across biological membranes. These systems can provide controlled, sustained, and targeted release of active ingredients, resulting in improved therapeutic performance and reduced dosing frequency. Such properties make nanoemulsions attractive carriers for drug delivery and functional food applications.[24]

4. Enhanced Gastrointestinal Absorption

Nanoemulsions improve the distribution and absorption of bioactive compounds within the gastrointestinal tract. The fine oil droplets are rapidly dispersed and absorbed, promoting better uptake of encapsulated ingredients while reducing gastrointestinal irritation. This enhanced absorption contributes to more reproducible plasma concentration profiles and improved bioavailability of active compounds.[20]

5. High Kinetic Stability

Compared with conventional emulsions, nanoemulsions exhibit superior kinetic stability due to their small droplet size. They are less susceptible to instability phenomena such as creaming, flocculation, coalescence, and sedimentation. This stability ensures the maintenance of product quality and functionality throughout storage.[24]

6. Optical Transparency and Aesthetic Properties

Because the droplet size in nanoemulsions is often smaller than the wavelength of visible light, many formulations appear transparent or translucent. This optical clarity is particularly desirable in food, beverage, cosmetic, and pharmaceutical applications where product appearance is an important quality attribute.[20]

7. Versatility and Formulation Flexibility

Nanoemulsions can be incorporated into various dosage forms, including liquids, creams, gels, foams, and sprays. They are also widely used as precursor systems for the preparation of nanocapsules, nanospheres, liposomes, and other advanced colloidal delivery systems. Their versatility has expanded their applications across food, pharmaceutical, cosmetic, and biotechnology industries.[5]

8. Biocompatibility and Safety

Nanoemulsions are generally composed of biocompatible oils, surfactants, and aqueous phases, making them safe and well tolerated for both human and veterinary applications. Their non-toxic and non-irritating nature further supports their use as effective delivery vehicles for a wide range of bioactive compounds.[24]

COMPONENTS OF NANOEMULSION

Nanoemulsions are typically composed of four major components: an oil phase, an aqueous phase, surfactants, and co-surfactants. The selection and concentration of these components significantly influence the physicochemical properties, stability, and performance of the final formulation.

1. Oil Phase

The oil phase plays a crucial role in determining the characteristics of nanoemulsions and influences the selection of other formulation components. Oils are primarily chosen based on their ability to solubilize the active ingredient and provide adequate drug-loading capacity. [6] Commonly used oils include vegetable oils (olive oil, soybean oil, corn oil, sesame oil, and peanut oil), mineral oils, free fatty acids, modified vegetable oils, and medium-chain triglycerides (MCTs). MCTs are particularly preferred because of their superior solvent capacity, enhanced emulsification properties, and greater resistance to oxidative degradation compared with long-chain triglycerides (LCTs).[15]

2. Surfactants

Surfactants are essential for reducing interfacial tension between the oil and aqueous phases and stabilizing nanoemulsion droplets. Hydrophilic surfactants with high hydrophilic–lipophilic balance (HLB >10) are generally used to prepare oil-in-water (O/W) nanoemulsions, whereas lipophilic surfactants with lower HLB values are preferred for water-in-oil (W/O) systems. Commonly employed surfactants include Tween 80, Span 80, Cremophor® EL, Gelucire®, lecithin, whey protein isolate, and caseinate. Depending on the formulation requirements, surfactants may be synthetic, natural, protein-based, phospholipid-based, or peptide-based.[22]

3. Protein and Phospholipid Surfactants

Natural surfactants such as proteins and phospholipids are widely used in food-grade nanoemulsions due to their biocompatibility and excellent emulsifying properties. Phospholipids, particularly lecithin derived from soybeans and egg yolk, provide steric stabilization and improve long-term emulsion stability. Similarly, proteins such as whey protein isolate and caseinate adsorb at the oil–water interface, forming protective layers around droplets and enhancing stability through electrostatic and steric repulsion.[11]

4. Co-surfactants

Co-surfactants are often incorporated when surfactants alone cannot sufficiently reduce interfacial tension. They improve the flexibility of the interfacial film, facilitate spontaneous nanoemulsion formation, and enhance formulation stability. Commonly used co-surfactants include ethanol, propylene glycol, polyethylene glycol, glycerol, ethylene glycol, and Transcutol-P. These compounds help reduce interfacial tension and promote the formation of fine and stable nanoemulsion droplets.[7]

5. Aqueous Phase

The aqueous phase usually consists of purified water and may contain hydrophilic additives such as carbohydrates, proteins, minerals, acids, bases, and co-solvents. The composition of the aqueous phase can influence droplet stability, viscosity, and overall nanoemulsion performance.[18] Table 1 illustrates major components of nanoemulsion and their functions.

Table 1: Components of nanoemulsion and their functions.

Component	Examples	Function
Oil Phase	Olive oil, soybean oil, corn oil, sesame oil, MCT oil	Solubilizes lipophilic compounds and forms the dispersed phase
Aqueous Phase	Purified water, buffer solutions	Forms the continuous phase in O/W nanoemulsions
Surfactants	Tween 80, Span 80, Cremophor EL, Lecithin, Whey protein isolate	Reduce interfacial tension and stabilize droplets
Co-surfactants	Ethanol, Propylene glycol, Glycerol, Polyethylene glycol	Enhance interfacial flexibility and facilitate nanoemulsion formation
Aqueous Phase	Purified water, buffer solutions	Forms the continuous phase in O/W nanoemulsions

METHODS OF NANOEMULSION PREPARATION

1. High-Energy Methods

High-energy methods are widely employed for nanoemulsion preparation because they use intense mechanical forces to break coarse droplets into nanosized droplets. These techniques provide excellent control over droplet size, stability, rheological properties, and appearance. Common high-energy methods include high-pressure homogenization, microfluidization, sonication, jet dispersers, and high-amplitude ultrasonication.[9]

High-Pressure Homogenization

High-pressure homogenization is one of the most widely used techniques for nanoemulsion production. It utilizes hydraulic shear, turbulence, and cavitation generated by forcing a coarse emulsion through a narrow valve under high pressure. This method is suitable for both laboratory and industrial-scale production and can produce nanoemulsions with very small droplet sizes. However, it requires high energy input and may generate heat that can affect thermosensitive compounds.[29]

Microfluidization

Microfluidization involves passing the oil and aqueous phases through microchannels at high pressure, where they collide and generate intense shear forces. Repeated processing produces nanoemulsions with uniform droplet size distribution. Although highly efficient, the technique is relatively expensive and less suitable for large-scale manufacturing.

Sonication

Sonication uses ultrasonic waves to generate cavitation forces that reduce droplet size and form kinetically stable nanoemulsions. The droplet size is influenced by sonication time, power intensity, and surfactant concentration. This method is primarily suitable for laboratory-scale production due to scale-up limitations.[9]

Jet Disperser

Jet dispersers reduce droplet size by forcing streams of coarse emulsion through opposing nozzles, generating strong collision forces. These systems can operate at very high pressures and effectively produce fine droplets without moving mechanical components.

High-Amplitude Ultrasonication

High-amplitude ultrasonication is an alternative to high-pressure homogenization that utilizes ultrasonic cavitation to generate nanosized droplets. It is commonly used for preparing pharmaceutical nanoemulsions and liposomal systems but is generally limited to small-scale applications.[18]

2. Low-Energy Methods

Low-energy emulsification methods utilize the internal physicochemical properties of the system to form nanoemulsions, requiring only mild agitation and significantly less energy than high-energy techniques. These methods are particularly suitable for thermally sensitive bioactive compounds and include phase inversion emulsification and self-emulsification techniques.[31]

Phase Inversion Emulsification Method

Phase inversion emulsification is based on changes in surfactant curvature caused by variations in temperature or composition. The major approaches include Phase Inversion Temperature (PIT), Phase Inversion Composition (PIC), and Emulsion Inversion Point (EIP) methods.

- **PIT Method:** Phase inversion occurs due to temperature-induced changes in surfactant affinity, resulting in the formation of fine nanoemulsion droplets.
- **PIC Method:** Nanoemulsions are formed through gradual changes in system composition, usually by adding water to an oil–surfactant mixture.
- **EIP Method:** Phase inversion is driven by changes in the dispersed phase volume fraction, leading to the transition from W/O to O/W nanoemulsions.[18]

Self-Nanoemulsification Method

Self-nanoemulsification, also known as spontaneous emulsification, occurs when surfactants and co-surfactants rapidly diffuse between phases, generating nanosized droplets without external energy input. This principle is widely applied in self-nanoemulsifying drug delivery systems (SNEDDS), which spontaneously form fine O/W nanoemulsions upon contact with aqueous media. [1] Figure 2 shows the methods of preparation of nanoemulsion.

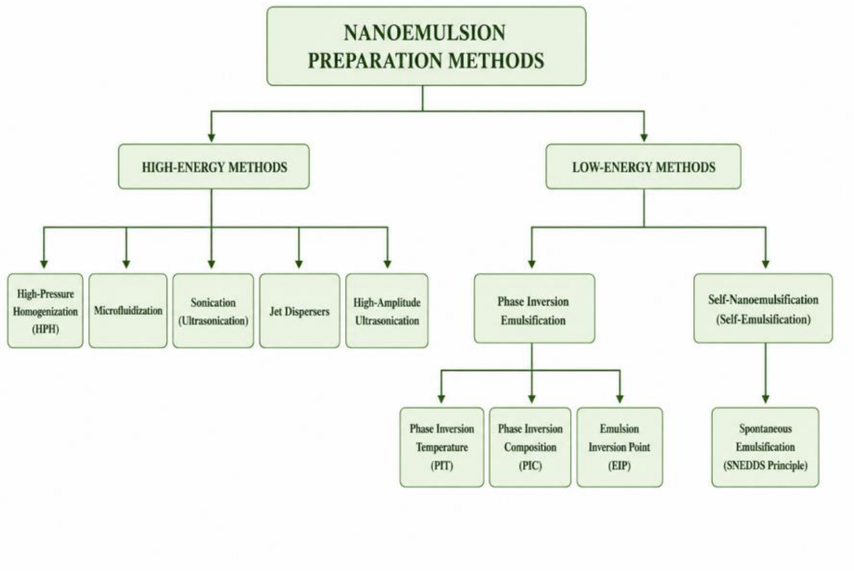


Fig. 2: Nanoemulsion preparation methods.

CHARACTERIZATION AND EVALUATION OF NANOEMULSIONS

The physicochemical properties of nanoemulsions are evaluated using several analytical techniques.

1. Dye solubilization tests

They are employed to identify the emulsion type, where water-soluble dyes preferentially dissolve in the aqueous phase and oil-soluble dyes dissolve in the oil phase.[26]

2. Droplet size and polydispersity index (PDI)

They are among the most important parameters and are commonly measured using dynamic light scattering (DLS). These parameters provide information regarding droplet size distribution, uniformity, and formulation stability. Smaller droplet sizes and lower PDI values generally indicate a more stable nanoemulsion.[17,23]

3. Interfacial tension

These measurements are used to assess the interaction between oil and water phases and can be determined using a spinning-drop tensiometer. Low interfacial tension is essential for the formation and stability of nanoemulsions.[3]

4. Refractive index

These measurements provide information about the transparency and isotropic nature of nanoemulsions and are commonly determined using an Abbe refractometer.[16]

5. Viscosity

It is another important parameter that influences flow behaviour, stability, and application characteristics. It is typically measured using a Brookfield viscometer.[2]

6. Drug Loading Capacity

Drug loading capacity indicates the amount of active pharmaceutical ingredient successfully incorporated into the nanoemulsion system. It is typically determined by extracting the drug from the formulation using a suitable solvent and quantifying it through spectrophotometric analysis or high-performance liquid chromatography (HPLC).[27]

7. Entrapment Efficiency

Entrapment efficiency (EE%) represents the percentage of drug successfully encapsulated within the nanoemulsion droplets. It is calculated by measuring the amount of unentrapped drug present in the aqueous phase. Entrapment efficiency is an important parameter as it directly influences drug stability and release behaviour.[28]

8. In Vitro Permeation Studies

In vitro permeation studies are performed to evaluate the ability of nanoemulsions to enhance drug transport across biological membranes. These studies are commonly conducted using diffusion cells, where the cumulative amount of drug permeated through the membrane is measured over time. The permeation profile and steady-state permeation rate provide valuable information regarding the effectiveness of the nanoemulsion as a drug delivery system.[30]

NANOEMULSIONS IN FOOD INDUSTRY

Nanoemulsions have gained considerable attention in the food and beverage industry because of their compositional versatility, nanoscale droplet size, transparency, and excellent stability. Compared with conventional emulsions and microemulsions, nanoemulsions exhibit enhanced stability against droplet aggregation and gravitational separation, making them suitable for the incorporation of bioactive compounds into optically clear products such as fortified beverages and functional drinks. Additionally, nanoemulsions can be formulated to produce viscous or gel-like systems even at low droplet concentrations, enabling the development of low-fat foods with desirable textures. Their ability to improve the stability of encapsulated ingredients and inhibit microbial growth also contributes to extended product shelf life. For instance, nanoemulsions prepared using sunflower oil have been reported to enhance the preservation of Indo-Pacific king mackerel steaks by suppressing microbial growth and extending storage life.[20,14]

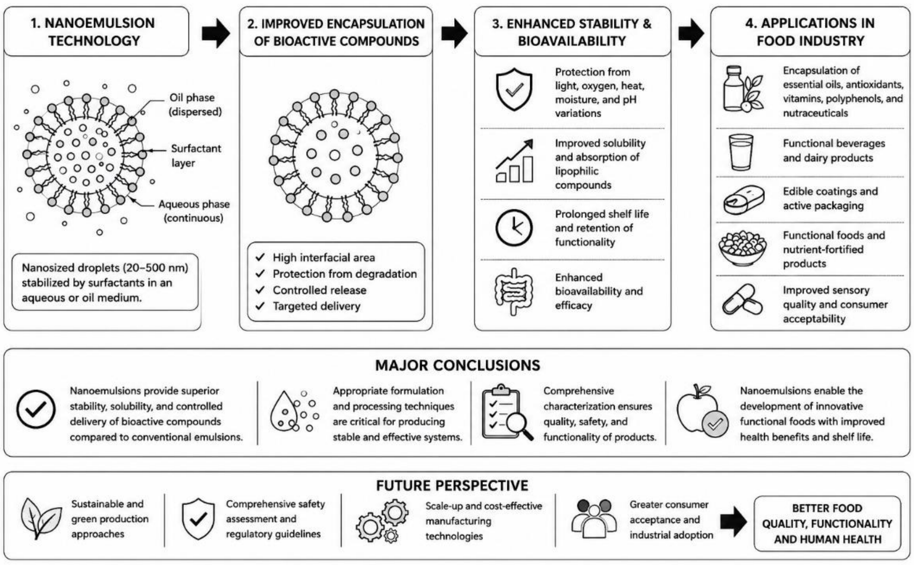
CONCLUSION

Nanoemulsions have emerged as highly effective colloidal delivery systems with considerable potential in the food industry. Their nanoscale droplet size, large interfacial surface area, optical transparency, and enhanced kinetic stability provide significant advantages over conventional emulsions. These characteristics improve the solubility, stability, bioavailability, and controlled release of encapsulated bioactive compounds, making nanoemulsions valuable carriers for vitamins, antioxidants, essential oils, nutraceuticals, and other functional ingredients.

The review demonstrates that both high-energy and low-energy emulsification techniques can successfully produce stable nanoemulsion systems with desirable physicochemical properties. Appropriate selection of oils, surfactants, co-surfactants, and preparation methods is essential for achieving optimal formulation performance. Furthermore, advanced characterization techniques play a critical role in evaluating nanoemulsion quality, stability, and functionality.

In food applications, nanoemulsions offer promising opportunities for the development of functional foods, fortified beverages, edible coatings, and innovative delivery systems with improved nutritional and sensory properties. Their ability to enhance nutrient bioavailability, protect sensitive compounds, and extend shelf life highlights their growing importance in modern food processing and preservation.

Despite these advantages, challenges related to large-scale manufacturing, economic feasibility, safety assessment, consumer acceptance, and regulatory approval must be addressed before widespread commercialization can be achieved. Future research should focus on sustainable food-grade formulations, green production technologies, and comprehensive safety evaluations. Overall, nanoemulsion technology represents a transformative approach for next-generation food systems and is expected to play an increasingly important role in improving food quality, functionality, and human health.



Summary Illustration

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