



HAL
open science

Nanoemulsions as Carriers of Bioactive Compounds in Functional Foods: Preparation and Application

Prakasha R, Vinay G M, Pathiam Srilatha, Hridyesh Pandey

► **To cite this version:**

Prakasha R, Vinay G M, Pathiam Srilatha, Hridyesh Pandey. Nanoemulsions as Carriers of Bioactive Compounds in Functional Foods: Preparation and Application. *European Journal of Nutrition and Food Safety*, 2025, 17 (1), pp.78-95. 10.9734/ejnfs/2025/v17i11621 . hal-04880691

HAL Id: hal-04880691

<https://hal.science/hal-04880691v1>

Submitted on 11 Jan 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Nanoemulsions as Carriers of Bioactive Compounds in Functional Foods: Preparation and Application

Prakasha R ^a, Vinay G M ^{a*}, Pathiam Srilatha ^a
and Hridyesh Pandey ^a

^a Department of Food Processing Technology, College of Food Processing Technology & Bioenergy,
Anand Agricultural University, Anand, Gujarat 388110, India.

Authors' contributions

This work was carried out in collaboration among all authors. Author HP given the idea. Author PS did the literature search & data collection. Author PR wrote the first draft of the manuscript. Author VGM critically revised the draft. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Article Information

DOI: <https://doi.org/10.9734/ejnfs/2025/v17i11621>

Open Peer Review History:

This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: <https://www.sdiarticle5.com/review-history/129395>

Review Article

Received: 04/11/2024

Accepted: 06/01/2025

Published: 09/01/2025

ABSTRACT

Nanoemulsions, characterised by their small droplet size and kinetically stable colloidal systems, are gaining widespread attention in the food industry. Their composition and structure can be precisely tailored to encapsulate and deliver bioactive lipophilic compounds effectively. In recent years, there have been significant advancements in the development of nanoemulsions, employing various approaches to achieve specific functional properties. These nanoemulsions play a pivotal role in preserving and enhancing the functionality and stability of bioactive components such as vitamins, antioxidants, proteins, lipids, and carbohydrates in functional foods. By encapsulating

*Corresponding author: Email: vinaygm26@gmail.com;

Cite as: R, Prakasha, Vinay G M, Pathiam Srilatha, and Hridyesh Pandey. 2025. "Nanoemulsions As Carriers of Bioactive Compounds in Functional Foods: Preparation and Application". *European Journal of Nutrition & Food Safety* 17 (1):78-95. <https://doi.org/10.9734/ejnfs/2025/v17i11621>.

bioactive chemicals, nanoemulsions act as carriers that protect sensitive compounds from processing conditions, offering a viable solution for the challenges posed by conventional processing methods. Their small droplet size facilitates improved bioavailability and absorption of these bioactive compounds, ensuring enhanced nutritional benefits for consumers. This review explores the recent studies in nanoemulsion development, highlighting diverse approaches and their functional properties. Emphasis is placed on the applications of nanoemulsions in food products, their role in encapsulating nutraceutical compounds, and their use as edible coatings in food packaging materials. The overarching goal is to underscore the transformative impact of nanoemulsions on the food industry, paving the way for novel and innovative food products with improved functionality and stability.

Keywords: Encapsulation; essential oil; active packaging; micro fluidization; nutraceutical compound.

1. INTRODUCTION

Richard Feynman introduced the idea of nanotechnology in 1959 (Sun, et al., 2020). Nario Taniguchi first used the word "nanotechnology" in a scientific meeting in 1974 to describe the manipulation of particles smaller than one millimetre (Taniguchi, 1974). The science of nanotechnology involves developing and controlling particle sizes below 200nm (He, et al., 2019). Nanotechnology has several uses in the chemical, pharmaceutical, engineering, and food sectors. An emulsion is an immiscible combination of two fluids, where the continuous phase is the liquid surrounding the suspended droplet in the dispersed phase (Sun-Waterhouse et al., 2013). Emulsions are of two major types: oil in water (o/w) and water in oil (w/o). The o/w emulsion is obtained by dispersing oil droplets in an aqueous solution. Emulsion systems enable the delivery of both hydrophobic and hydrophilic compounds. In water-in-oil emulsions, hydrophilic compounds are delivered by dispersing water droplets within the oil phase. Similarly, water-in-oil nanoemulsions are formed by dispersing the aqueous phase in the oil phase, providing an effective system for delivering hydrophilic compounds (Rashidi, 2021). Multiple emulsions such as water-in-oil-in-water (w/o/w) and oil-in-water-in-oil (o/w/o) are also available to ensure additional protection to the embedded or protected compounds (Abinash, et al., 2021). Emulsion in the food business aims to employ the emulsion principle to create and enhance facilities, processing, manufacturing methods, and food quality attributes. However, many culinary products are emulsified in the manufacturing process, such as creamers, sauces, soups, etc. (McClements, 2012). The stability of an emulsion is significantly influenced by factors such as droplet size, functionality, optical characteristics, rheology, and quality. Emulsions with droplet sizes ranging from 0.1 to

100 μm contain droplets comparable in diameter to the wavelength of light, resulting in substantial light scattering. Consequently, such emulsions appear optically turbid or opaque and are thermodynamically unstable (George, et al., 2022).

Nanoemulsions are made up of 20 to 200 nm droplets (Malode, et al., 2021) and are kinetically more stable compared traditional emulsion. It's also clearer than macroemulsion in terms of optics. It can withstand gravitational separation and aggregation because of its small droplet size (Sneha & Kumar, 2022). Nanoemulsions have been reported as superior carriers for lipophilic bioactive chemicals, with improved characteristics above normal emulsions. Among the several varieties of nanoemulsions, o/w nanoemulsions are presently widely used in the food processing sectors with very small droplet sizes ($r < 200$ nm). So they are highly bioavailable due to their small size droplets, which enhance their physical stability, and optical clarity (Agarwal, et al., 2019). Small droplet sizes give nanoemulsions a significant surface area, which allows them to interact effectively with biological components within the gut. Unlike conventional emulsions, nanoemulsions offer more binding sites for digestive enzymes such as lipase (Milani, 2019). Furthermore, the small droplet size may facilitate the quick transfers of hydrophobic bioactive that are naturally present. Considering the advantages of nanoemulsion over emulsion, in this review we focused on the preparation and application of nanoemulsion in the food sector.

2. COMPOSITION OF NANOEMULSION

A core-shell design can be used to describe an o/w nanoemulsion. The lipophilic component and amphiphilic surfactant make up the core and shell, respectively. A few examples of lipophilic substances are oils (acylglycerols) and some

other bioactive substances. Surface-active elements such as phospholipids, polysaccharides, proteins and minerals, may create the amphiphilic shell. The majority of nanoemulsions consist of an oil and aqueous component along with a surfactant (emulsifier/stabilizer). It also includes a texture adjuster, a weighing agent, and a ripening retardant, in addition to the three basic components (McClements & Rao, 2011). Several physicochemical properties of an oil phase, like solubility, density, viscosity, interfacial and surface tension, optical properties, phase behaviour, chemical stability, etc. have an impact on the continuous generation of nanoemulsion and their characteristics (Anton & Vandamme, 2009). Oil component includes acylglycerols, essential oils, flavor oils, free fatty acids, and mineral oils that can be used for preparation. Triacylglycerol (TAG) oils are commonly utilized in the food business because of their low cost as well as availability concerns. Soybean oil, sesame oil, almond oil, sunflower oil, flaxseed oil, olive oil, and fish oils are some of the most commonly used oils with nutritional value. Among triacylglycerols, long-chain TAGs are the most common, but short-chain and medium-chain TAGs are also investigated in the food industry (McClements & Rao, 2011). Water and other polar substances such as polyalcohols, proteins, minerals, saccharides, acids, and bases make up the majority of the aqueous phase, and the stability of the nanoemulsion depends on the physicochemical characteristics of the aqueous phase. The aqueous phase's composition can be used to enhance the generation and stability of nanoemulsions.

Oil and water components in nanoemulsions can separate over time, so these materials are stabilized with various stabilizers that help to lower interfacial tension by adhering to droplet surfaces, enabling their breakup, and protecting against aggregation (Kralova & Sjoblom, 2009). In addition to physical factors such as temperature pH and ionic strength, the type of emulsifier utilized in a nanoemulsion will also affect its stability. As a result, selecting an appropriate emulsifier or emulsifier combination is regarded as a crucial aspect of achieving a stable nanoemulsion. Small molecule surfactants, phospholipids, polysaccharides and proteins are the most common forms of emulsifiers used in the food sector for nanoemulsion preparation. Proteins and polysaccharides are natural ingredients that are safe in nanoemulsion manufacturing. Surfactants

are classified into three groups based on their electrical properties: ionic, nonionic, and zwitterionic (McClements, 2007).

Surfactants with an ionic charge that is cationic or anionic are known as ionic surfactants. When compared to cationic edible surfactants like lactoglobulin and lauric arginate, anionic edible surfactants like citric acid esters of mono- and diglycerides of fatty acids, sodium dodecyl sulfate, sodium caseinate, and sodium lauryl sulfate, have various benefits. However, at high concentrations, they tend to irritate the skin, restricting their use in applications that require high surfactant levels (McClements & Rao, 2011). Non-ionic surfactants are essential for the production of food-grade nanoemulsions due to their low toxicity, minimal irritation, and ability to create stable nanoemulsions. Examples include polyglycerol esters of fatty acids, sorbitan monooleate, and sucrose monopalmitate (Jafari, et al., 2007, McClements & Rao, 2011). While employing high and low-energy techniques, a blend of lipophilic and hydrophilic surfactants aids in the creation of nanoemulsions. After the production of nanoemulsions, mixed-emulsifier systems serve to reduce instability owing to particle aggregation, commonly lecithin i.e. natural phospholipids are extensively utilized. Miscellaneous ingredients are also used while preparing the nanoemulsion along with the basic three components such as cosolvents, texture modifiers, ripening retarders, and weighting agents.

3. PREPARATION OF NANOEMULSION

The surface area of nanoemulsions is increased by the numerous droplets. As a result, a significant quantity of energy is required to build an additional surface. As a result, nanoemulsion creation is not spontaneous and necessitates the use of energy. The energy required to generate nanoemulsions (1 G) is calculated using the formula $\Delta G = \Delta A\gamma - T\Delta S$, where ΔA represents an increase in interfacial area, γ denotes surface tension and $T\Delta S$ represents the entropy of dispersion (Tadros, et al., 2004; Schramm, 2006). Two high-energy and low-energy processes can be used to form nanoemulsions. Depending on the contents, operating conditions, and preparation method, the size of the emulsion will vary. During emulsification, a surfactant is adsorbed, droplets are broken down into smaller ones, and they collide with one another. As a consequence of adsorption kinetics, the stability and droplet size of nanoemulsions are also

affected (Silva, et al., 2015). By using high-energy methods, it is possible to disturb the oil phase, allowing it to interact with the water phase by exerting an enormous amount of stress by mechanical devices, which interrupts the oil phase. High-energy technologies are used by most food companies to produce oil-in-water nanoemulsions (Gutiérrez, et al., 2008). These techniques utilize high-pressure valve homogenizers, microfluidizers, and sonication treatments to provide intense disruptive forces that break up oil droplets (Gutiérrez, et al., 2008, Leong, et al., 2009, McClements, 2010). It is possible to make nanoemulsions with low energy inputs by changing the temperature or composition of the oil-water mixture, while the chemical potential of the different components provides the energy input (Bouchemal, et al., 2004). When the conditions of the solution or ambient environment are altered, low-energy approaches, such as phase inversion and solvent mixing techniques, are dependent upon the spontaneous formation of minute oil droplets within mixed oil, water, and surfactant systems (Anton, et al., 2008; Yin et al., 2008). Several factors influence the choice of emulsification strategy and the minimum droplet size achievable, including the properties of the emulsifier, the emulsifier-to-emulsion ratio, the composition of the oil phase, and the viscosity of the phases involved.

3.1 High Energy Approach

A mechanical device, such as a high-pressure valve homogenizer, sonication, and microfluidizer, as illustrated in Fig. 1, generates disruptive forces that effectively blend and disturb the oil and water phases, resulting in the formation of microscopic oil droplets. To produce food-grade nanoemulsions, high-energy

techniques are most appropriate as they permit the utilization of a diverse range of oils, including flavor, triacylglycerol, and essential oils, alongside various emulsifiers such as polysaccharides, proteins, phospholipids, and surfactants. While the particle size produced may vary depending on the properties of the oil and the emulsifier employed, the characteristics of the oil play a significant role. Oil phases with low viscosity and/or interfacial tension, such as flavor oils, essential oils, or alkanes, are often employed to facilitate the creation of small droplets (McClements & Rao, 2011).

3.1.1 High pressure valve homogenization (HPH)

The HPH method is one of the most commonly used methods in the preparation of nanoemulsions on an industrial scale, in addition to breaking down droplets, it also improves stability. A positive displacement pump, interaction chambers and pressure valve are involved in the HPH process. An emulsion is drawn into an interaction chamber by a pump. Homogenization chambers can be constructed using simple orifice plates and colliding jets (Donsi, et al., 2009). As the homogenizer valve is operating under a high pressure of up to 300 MPa, the coarse emulsion is being pushed out of the small aperture of micrometric size. At this stage, coarse emulsions are broken by turbulence, shear stress, and cavitation with increased surface area (Tesch, et al., 2003, Schultz, et al., 2004). A droplet in the interaction chamber becomes stabilized when emulsifier molecules are added and adsorb at newly formed interfaces which reduces the interfacial tension and viscosity ratio. HPH method might not be suitable for high viscous lipids (Witthayapanyanon, et al., 2006).

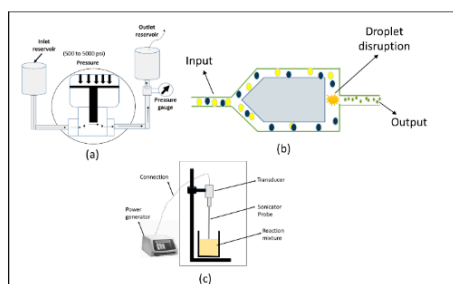


Fig. 1. Schematic diagram of High energy methods of (a) High pressure homogenizer (b) Microfluidizer and (c) Ultrasonicator

3.1.2 Microfluidization

Emulsification by microfluidization is similar to HPH, with the exception that it is based on the use of a specific microchannel with dimensions of 50 to 300 μm . To produce small droplets, it pumps coarse emulsion premix via high pressure. The coarse emulsion, on the other hand, is prepared to flow via a different channel within the device, the fine emulsion is formed shortly after passing through the tiny orifice in microfluidizers. Microfluidizers separate coarse emulsion flows into streams, which then flow through two channels under high pressure before colliding in an interaction chamber at high speeds. Large droplets are broken down into very small emulsion droplets due to the severe disruptive forces created in the interaction chamber. Several researchers have noticed that microfluidizers might be used to make food-grade nanoemulsions (Henry, et al., 2010). The size of the resultant emulsion's droplets tends to decrease with increasing pressure, the number of passes, and the concentration of the emulsifier (Wooster, et al., 2008). HPH and microfluidizer produce similar size of droplets, however, HPH requires multiple passes to reach the lowest size, despite this, with a microfluidizer, the higher impinging jets are responsible for high-shear stresses, which can cause the droplet to deform and breakdown during the first pass. A major advantage of this method comes from its ability to produce extremely high peak shear rates as well as a high rate of volumetric throughput of nanoscale droplets while maintaining a uniform size distribution (Mason, et al., 2006). However, microfluidizers are quite costly and have a high rate of equipment wear, which reduces the efficiency of production (Leong, et al., 2009).

3.1.3 Ultrasonication

Ultrasonication techniques employ high-frequency sound waves of 20 kHz or higher to produce emulsions with extremely minute droplets (Sneha & Ashwini, 2022). Cavitation occurs when high-frequency sound waves interact with two immiscible liquids in the presence of a surfactant. This phenomenon generates significant shock waves in the surrounding liquid and facilitates the rapid formation of emulsion droplets due to the action of liquid jets (Silva, et al., 2012). The development and collapse of vapour cavities is a key feature of this method in a flowing liquid. Two steps are involved in ultrasonic emulsification. The action of an acoustic field formed by

interfacial waves led to the oil phase. Emulsification by ultrasonic technique involves two processes. The effect of an acoustic field created by interfacial waves first caused the dispersion of the oil phase (in the form of droplets) in the continuous phase. Second, the creation and subsequent collapse of microscopic bubbles brought on by straightforward variations in sound wave pressure produce a remarkable quantity of intensely localized turbulence (Gadhve, 2014). Turbulent microimplosions fragment primary droplets into submicron sizes. Even though sonic cavitation permits high shear stress, the final size of the nanoemulsion droplet is determined by the interaction between the shear rate and emulsion rheology (Nakabayashi, et al., 2011). Thus, continuous ultrasonication is the most popular choice for manufacturing large quantities of fine emulsions. Ultrasonic techniques are most commonly used with low-viscosity fluids; however, they are less suitable for high-viscosity fluids (Piorkowski & McClements, 2014), because as construction of a cooling system is needed with a sonication chamber due to the release of heat energy caused by the splitting of air bubbles, which causes an increase in the temperature of the emulsion (Abbas, et al., 2013).

3.2 Low Energy Approach

3.2.1 Phase inversion temperature

The temperature at which an o/w emulsion changes into a w/o emulsion, or vice versa, is known as the phase inversion temperature (PIT) and was developed in 1968 by Shinoda and Saito (Feng, 2020). The molecular structure and solubility of nonionic surfactants are affected by temperature (Dhandhi, et al., 2022). Rapid cooling at PIT leads nanoemulsion droplets to break apart. The surfactant monolayer creates oil-swollen emulsions (o/w nanoemulsions) with extra oil at low temperatures, which may coexist alongside emulsions. Whereas at high temperatures, a negative spontaneous curvature is seen, and water-swollen reverse micelles (without nanoemulsion) develop, coexisting with the surplus water phase (Jiang, et al., 2020). This causes spontaneous curvature to nearly zero at intermediate temperatures, resulting in a bicontinuous layer nanoemulsion where surplus water and oil components coexist with similar proportions of water-and-oil phases. A minimum droplet size and an extremely low interfacial tension are reached at the PIT (Tadros, et al., 2004). As a result, rapidly cooling or heating (by

25–30°C) nanoemulsions can produce nanoemulsions with very tiny droplet sizes and narrow size distributions (Solans, et al., 2012). These processes have the advantages of consisting of a simple process, preventing bioactive degradation during the processing, requiring little energy, and being able to scale up properly for industrial applications.

3.2.2 Phase inversion composition

This technique is similar to PIT, but instead of modifying the temperature, the composition of the system is adjusted to alter the curvature of the surfactant (Kumar, et al., 2021). An o/w emulsion stabilized with an ionic surfactant becomes a w/o emulsion by adding salt. The electrical charge on the surfactant head groups is then screened by the salt ions, altering the packing parameter from $p < 1$ to $p > 1$ (Ozogul, et al., 2022). A w/o emulsion with a high salt concentration can also be phase inverted by diluting it with water, lowering the ionic strength below a critical limit. Surface tension, phase transition, bulk viscosity, surfactant structure, and concentration are all associated with the creation of nanoemulsion. This technique, which includes raising the volume fraction of the dispersed phase, is also referred to as catastrophic inversion (Safaya & Rotliwala, 2020).

3.2.3 Membrane emulsification

In the method, as a specially designed glass membrane, Shirasu porous glass (SPG) is used as an emulsifying agent (i.e., boric acid, volcanic ash, and calcium carbonate, which are formed from Shirasu, volcanic ash, and calcium carbonate) (Vladisavljević, 2019, Dhaval, et al., 2022). As the emulsion droplets pass through the membrane during membrane emulsification, they are dispersed into an immiscible continuous phase. Depending on the hydrophobicity or hydrophilicity of the membrane, this process can produce either water-free or water-based emulsions. To separate liquid drops from the membrane surface, shear is used at the membrane surface. There are two factors governing droplet size in membrane emulsification: continuous phase flow and surfactant adsorption kinetics (Oh et al., 2011). The liquid phase of this emulsion can be converted into a solid phase by subjecting it to a process/reaction or further formulated into a multiple emulsion through secondary emulsification (Vladisavljević & Williams, 2005). According to Silva et al. (2012), this technique

utilizes a lower amount of surfactants than high-energy methods and creates emulsions with a narrow range of size distribution. The main disadvantage of this approach is the low dispersed phase flow across the membrane, which makes scaling up difficult.

4. APPLICATION OF NANOEMULSION

There are significant technological limitations to the development of functional foods, including low solubility, stability, and bioavailability of bioactive compounds. When food is processed and stored, bioactive ingredients in foods may degrade and oxidize (Xianquan, et al., 2005; Shahidi and Zhong, 2010). The majority of bioactive molecules have low solubility and fast metabolism, reducing their bioavailability, some are volatile and highly susceptible to processing conditions (McClements & Li, 2010, Jin et al., 2016). To address these problems, nanoemulsions can encapsulate bioactive chemicals for use in food matrixes. Hence bioactive chemicals can be stabilized, bioavailable, and released at a controlled rate when encapsulated in an oil phase or emulsifier nanoemulsions (McClements, et al., 2007). Ideally, nanoemulsions should be compatible with food matrixes and should not adversely affect their organoleptic properties, such as their flavor, appearance, or texture. Encapsulation of bioactive compounds provide protection against processing conditions, as well as oxidative degradation under long-term storage conditions caused by temperature, light, pH, etc. Nanoemulsion delivery systems must be economically viable as an industrial process before they can be applied to food applications (Borthakur, et al., 2016).

In nanoemulsion, bioactive compounds are encapsulated, Nanoencapsulation is a technology that enables the packaging of substances in miniature by using nanocomposites, nanoemulsions and nanostructures, and provides final products with controlled release of their contents. Bioactive components such as vitamins, antioxidants, proteins, lipids, and carbohydrates can be preserved with this approach, giving functional food with improved functionality and stability. Several techniques for producing nanocapsules have been described along with examples of their applications (Sekhon, 2010). Nanoliposomes, nanocochleates, and archaeosomes are lipid-based nanoencapsulation systems that can preserve

Table 1. Methods of preparation and applications of nanoemulsions

| S. No | Essential oil | Type of nanoemulsion & emulsifiers | Method used for preparation | Particle size | End uses or applications | Reference |
|-------|---|---|---|--------------------|--|-------------------------|
| 1. | Sichuan pepper essential oil | Oil-in-water; Tween-80 & caprylic/capric triglyceride | High-pressure homogenization | 125.07 nm | <ul style="list-style-type: none"> ✓ Improved water solubility and inhibitory effect on <i>E. coli</i> and <i>S. aureus</i>. ✓ The emulsion found application in soy sauce and cooking wine. | Shi, et al., 2022 |
| 2. | Laurus nobilis essential oil | Oil-in-water; Tween 80 | Ultrasonication (20 KHz/500 W/72 amplitudes/ 15 min) | 247.52 nm | <ul style="list-style-type: none"> ✓ Demonstrated antimicrobial activity against gram-positive pathogenic bacteria such as <i>S. aureus</i> and <i>E. faecalis</i>. ✓ Serves as a natural food antimicrobial preservative agent effective against foodborne pathogens and spoilage bacteria. | Ozogul, et al., 2022 |
| 3. | Vitamin D-encapsulated cinnamon oil | Oil-in-water; Tween 80 | Ultrasonication (20 kHz/400W/10 min) | 40.52 and 48.96 nm | <ul style="list-style-type: none"> ✓ Cytotoxic, genotoxic and antibacterial potential. ✓ Cinnamon oil is used as a carrier to deliver vitamin D in nanoscale. | Meghani, et al., 2018 |
| 4. | Eugenol oil in chitosan matrix (1:1) | Oil-in-water; Tween 20 | Ultrasonication (450 W/6 min) | <100 nm | <ul style="list-style-type: none"> ✓ Strong bactericidal effect on gram-positive bacterial strains [<i>Staphylococcus aureus</i>] and gram-negative bacterial strains [<i>E. Coli</i> O157:H7, <i>Pseudomonas aeruginosa</i> and <i>Salmonella</i>]. | Shao, et al., 2018 |
| 5. | Basil oil with ethanolic saponin extract | Oil-in-water; Saponin | Ultrasonication (amplitude 15 μ m/2 min) | 37.7–57.6 nm | <ul style="list-style-type: none"> ✓ Shows inhibition against food spoilage fungi like <i>P. chrysogenum</i> and <i>A. flavus</i>. | Gundewadi, et al., 2018 |
| 6. | Linalool | Oil-in-water; Tween 80 | Ultrasonic-assisted emulsification (f 50 kHz/250 W/10 min/30 s pulse) | 10.9 nm | <ul style="list-style-type: none"> ✓ Antibacterial and antibiofilm activities against <i>S. typhimurium</i>. | Prakash, et al., 2019 |
| 7. | Whey protein isolate-guar gum stabilized cumin seed oil | Oil-in-water | Ultrasonication (20 KHz/200 W/15 min/1 min pulse) | 75 nm | <ul style="list-style-type: none"> ✓ Killing <i>E. coli</i> and <i>S. aureus</i> and good antifungal activity against <i>A. flavus</i>. ✓ Alternative to synthetic | Farshi, et al., 2019 |

| S. No | Essential oil | Type of nanoemulsion & emulsifiers | Method used for preparation | Particle size | End uses or applications | Reference |
|-------|--|------------------------------------|---|---------------|--|------------------------|
| 8. | Wheat germ oil in maltodextrin aqueous phase | Oil-in-water; Tween 20 | High shear mix at 12,500 rpm for 5 min followed by ultrasonication (60 % amplitude/10 min) | 114.7 nm | ✓ preservative. The treatment successfully preserved the oil quality of the cooked fish fillets, resulting in enhanced stability and maintained overall quality. | Ceylan, et al., 2020 |
| 9. | Sage essential oil | Oil-in-water; Tween 80 | Ultrasonication (/500 W/72 amplitudes/ 15 min) | 204.4 nm | ✓ Effective on <i>S. aureus</i> , <i>S. paratyphi</i> A and <i>P. mirabilis</i> . | Yazgan, 2020 |
| 10. | Oliveria decumbens | Oil-in-water: Tween 80 | Ultrasonication (200 W) | 45.71 nm | ✓ Good antimicrobial and antioxidant activity. ✓ Gram-positive bacteria are more sensitive compared to gram-negative bacteria. ✓ Bactericidal effect on <i>P. aeruginosa</i> & <i>S. aureus</i> . | Nikravan, et al., 2021 |
| 11 | D-limonene | Oil-in-water; Sodium caseinate | High shear mix at 20,000 rpm for 10 min followed by High-pressure homogenization (60, 70, 80, and 90 MPa at 7, 10, 13, and 16 cycles) | 130 nm | ✓ Good storage stability for 60 days. ✓ Antibacterial activity of D-limonene against <i>S. aureus</i> was significantly increased by 5-fold. | Qi, et al., 2022 |
| 12. | Henna (<i>Lawsonia inermis</i>) extract | Oil-in-water: Tween 80 & SDS | Ultrasonic emulsification (700 W, 3 min/ 50 % amplitude) | 90 nm | ✓ Preservative against bacteria and fungi. ✓ Preserve yoghurt for 15 days of cold storage. | Ghazy, et al., 2023 |
| 13. | Fenugreek oil | Oil-in-water: Tween 80 | Ultrasonic emulsification (20-kHz/ 130 W/72 % amplitude) | 135.2 nm | ✓ Potential antibacterial activity against two gram-positive <i>S. aureus</i> and <i>B. subtilis</i> and two gram-negative bacteria <i>E. Coli</i> and <i>P. aeruginosa</i> . ✓ No toxicity on human hepatic cells. | Mansuri, et al., 2023 |
| 14. | Betel leaf (Piper betle L.) Essential oil | Oil-in-water: Tween 20 | Ultrasonication (20-kHz/750 W) | 50+ 8nm | ✓ Natural antimicrobial agent. ✓ Rupture & shrinkage of <i>Bacillus cereus</i> was observed. | Roy & Guha., 2018 |
| 15. | Cinnamon and | Oil-in-water; Tween 40 or | Sonication for 30 min and Ultra- | 89 nm and | ✓ Nano-encapsulated essential oils | Dghais, et |

| S. No | Essential oil | Type of nanoemulsion & emulsifiers | Method used for preparation | Particle size | End uses or applications | Reference |
|-------|------------------------|------------------------------------|-----------------------------|---------------|---|-----------|
| | Curcuma essential oils | Tween 80 | homogenization for 1 min | 151 nm | effectively prevent lipid oxidation in meat. ✓ Demonstrated significant inhibition of bacterial growth and methemoglobin formation. ✓ Shelf life of ground meat was extended. | al., 2023 |

and deliver foods and nutraceuticals. In addition to encapsulating and releasing food materials into nanoparticles. Nanoliposomes can be used as carrier vehicles for nutrients, nutraceuticals, enzymes, food additives, and antimicrobials (Sekhon, 2010). Various applications of nanoemulsion are discussed in Table 1.

4.1 Encapsulation of Flavor and Coloring Agents

Various flavoring compounds and coloring compounds in food are susceptible to oxidative and photolytic degradation due to their aldehyde, ketone, and ester functional groups. These deleterious effects can be prevented and the shelf life of these products enhanced by encapsulating them in nanoemulsions (Goindi, et al., 2016). Beta-carotene is a natural colorant and antioxidant that is utilized as a precursor to vitamin A in the food industry. This molecule can help prevent serious illnesses like cancer, cardiovascular disease, and macular degeneration. It degrades easily when exposed to heat, light, and oxygen due to its labile nature. After being encapsulated in nanoemulsions stabilized by modified starch, the β -carotene powders were spray-dried to powders after the emulsification process. There was a good dissolution of the powders in water, and the reconstituted nanoemulsions exhibited similar particle sizes to the fresh nanoemulsions. β -carotene powders were stored at 25.0°C for 30 days to investigate the effect of relative humidity (RH) on storage stability. The results indicate that modified starches having a lower oxygen permeability will retain more β -carotene over time. β -Carotene degradation was also affected by the glass transition temperature of powder at different relative humidity levels. This research can help you choose wall materials and storage settings that can safeguard nutraceuticals in delivery systems and improve their stability (Liang, et al., 2013).

Carotenoids are natural lipophilic pigments that reduce certain cancers and are called "eye protectors" (Johnson, 2002). Food industries make use of carotenoids to restore the color lost while processing. On the other hand, carotenoids are antioxidants that help prevent oxidation in oil-in-water and water-in-oil emulsions such as mayonnaise, salad dressings, and fat and dairy spreads (Santos & Meireles, 2010). Cantaloupe melon was used to extract carotenoids. The carotenoid nanoemulsion improved the color stability and water solubility.

The average particle size of the o/w carotenoids nanoemulsions encapsulated in porcine gelatin and whey protein isolate ranged from 70–160 nm. Gelatin acts as a texture modifier & it improved the water solubility of carotenoids. As a natural coloring agent, these nanoemulsions remained stable for more than 60 days in yoghurt (Medeiros, et al., 2019). A ternary conjugate of soy protein isolate(-)-epigallocatechin gallate-maltose emulsion was prepared using ultrasound. The β -carotene nanoemulsion has superior stability and prevents degradation of β -carotene by external environment (Geng, et al. 2023, Bu et al. 2023, Ashokkumar, 2015).

Essential oils are fragrant, volatile, semiliquid, or liquid-based substances extracted from whole plants or plant parts such as seeds, flowers, leaves, buds, fruits, barks, resins, and roots. Since essential oils possess significant antimicrobial properties and may have positive health consequences, they are being increasingly used in food preservation and safety. (Lohith, et al. 2017). The essential oil can be pre-dissolved in the oil phase and then emulsified in the aqueous phase with dissolved emulsifiers using high-energy techniques during the manufacture of essential oil-based nanoemulsions (Artiga-Artigas et al. 2017). Under normal storage conditions, d-limonene, an essential oil obtained from citrus fruit with chemopreventive properties, loses its lemony flavor due to oxidation. According to Lu et al. (2016), d-limonene nanoemulsions in water can inhibit oxidative degradation, with particle sizes ranging from 20 to 50 nm, the nanoemulsions were stable.

4.2 Encapsulation of Nutraceutical Compounds

Encapsulation of Nutraceuticals, a nutraceutical is a food-derived product with additional health benefits in addition to its basic nutritional value. Grape skins, blueberries, raspberries, and so on are high in resveratrol, a natural polyphenol. It has a set of possible benefits, including antioxidant, cardioprotective, neuroprotective, anti-inflammatory, anticancer, and antiobesity properties (Neves, et al., 2013). An investigation of spontaneous emulsification of resveratrol nanoemulsions containing 10% oil phase (grape seed oil plus orange oil) and 10% surfactant (Tween-80) had been conducted recently. Resveratrol was encapsulated in nanoemulsions and protected against UV light-induced isomerization and degradation using a low-

energy processing technique as a result of this research (Davidov-Pardo & McClements, 2015). It has been possible to fortify dairy emulsions with edible nanoemulsions of vitamin D (cholecalciferol) by using edible nanoemulsions of vitamin D. A high-pressure homogenizer was used to prepare nanoemulsions of mean diameters <200 nm using emulsifiers polysorbate 20, soybean lecithin and their mixtures and dispersed oil phases of soybean oil or cocoa butter mixtures. Vitamin D3 (0.1–0.5 g/mL) is encapsulated in an oil core of stable nanoemulsions (Golfomitsou, et al., 2018). For a period of ten days, fortified whole-fat milk was resistant to particle development and gravitational separation. It has also been found that curcumin nanoemulsions have enhanced antioxidant properties. A curcumin nanoemulsion stabilized with lecithin had 75% encapsulation efficiency and stability of 86 days when compared to a curcumin nanoemulsion stabilized with Tween 20 (Bhosale, et al., 2014). Demisli et al. (2020) developed a nanoemulsion-based hydrogel for the encapsulation of curcumin and cholecalciferol. The dispersion of the aforementioned compound in nanoemulsion caused the increase in oil droplet size. Both compounds participated in a surfactant monolayer and the nanoemulsion do not exhibit any cytotoxic effects. The emulsion and hydrogel were stable up to 60 days at 25°C. The nanoemulsified curcumin was used to treat osteoarthritis. The combination of 20% Tween 80, 0.4 M NaCl and 0.0052 M MgCl₂ was used to prepare a nanoemulsion with Vitamin C as a supplement. The prepared nanoemulsion had a particle size of 214 nm and 17 fold increase in curcumin absorption (Rivera-Pérez, et al 2023). Several technologies are currently available in the food industries that use nanoemulsions. The company focuses on enhancing the nutritional value of foods and beverages (Silva, et al., 2012; NutraLease, 2011). Through nanosized self-assembled structured liquids (NSSL) and self-assembled nanoemulsion technology, NutraLease Ltd. Develops carriers for nutraceuticals to be incorporated into food products and cosmetic formulations. To improve bioavailability, NSSL technology progresses the solubility of various chemicals in water-based or oil-based media. Lycopene, -carotene, lutein, phytosterols, Co-Q10, lipoic acid, and docosahexaenoic acid (DHA)/eicosapentaenoic acid are among the nutraceuticals included in the carriers (EPA). Spigno et al. (2013) encapsulated a phenolic grape marc extract to improve its lipid solubility and antioxidant activity for use as a

natural preservation agent in hazelnut paste. Hazelnut paste is used in foods such as ice cream, confectionery, and bread goods. When hazelnuts are processed into paste, they become more likely to oxidize due to an increase in exposed surfaces to oxygen and damaged structures that accelerate the process of deterioration. Encapsulation boosted phenolic efficacy against lipid oxidation by enhancing extract dispersibility in the paste with keeping antioxidant activity.

The encapsulation of lactic acid bacteria has been successfully accomplished using emulsions. As a result of the encapsulation of probiotic microorganisms in emulsion droplets, microorganisms have been observed to survive best in simulated stomach and intestinal conditions. Under simulated gastrointestinal tract conditions, enclosing lactic acid bacteria into sesame oil emulsion droplets improved the cell viability rate approximately 104 times in comparison to an unencapsulated control (Hou, et al. 2003). IgG is an antioxidant found in bovine colostrum and has many health benefits. This active substance is easily inactivated during heat treatment and is susceptible to acid. The encapsulation of this compound helps in inhibiting fat oxidation and it can withstand gastric acid, thereby improving its bioavailability. The encapsulated IgG can be found in direct application in liquid milk (Zhang, et al., 2023). Garcia-Becerra et al. (2023) developed a Coenzyme Q10 nanoemulsion for infants as a supplement. The emulsion has 90 days of stability, excellent solubility compared to CoQ10 powder, and do not possess any cytotoxicity.

4.3 Active Packaging

The nanoemulsion has huge applications in edible coatings. nanoemulsion integrated with edible chitosan has found application in extending the shelf life of bananas at 25°C for 7 days as this emulsion has antimicrobial properties (Das et al. 2023). Tabassum et al. (2023) studied the application of nanoemulsion coating to extend the shelf life of fresh-cut papaya. An active packaging film was developed by Rashid et al. (2023) by incorporating curcumin and orange essential oil. The film had higher water vapour permeability and tensile strength. The film possesses bacteriostatic effect against *Staphylococcus aureus* and *Escherichia coli*. The studies conducted by Otoni et al. (2014b) by incorporating clove bud and oregano essential oils into edible methylcellulose films,

nanoemulsions of the oils with 180-250 nanometre droplet size had improved antimicrobial activity. Further it prevented the growth of yeasts and moulds and improved bread shelf life. The addition of ginger essential oil nanoemulsions to gelatin-based active packaging films has been shown to improve the film's physical properties (Alexandre, et al., 2016). Preparation of capsaicin (oleoresin capsicum) nanoemulsions with Tween 80 as an aqueous phase was achieved by homogenization and ultrasonication under high pressure. High-pressure homogenization resulted in nanoemulsions with a particle size below 65 nm, whereas ultrasonication produced particles with improved physical properties, while high-pressure homogenization produced nanoemulsions with good inhibitory activity against *S. aureus* and *E. coli* (Akbas, et al., 2018).

5. CONCLUSIONS

The scope of nanotechnology in food processing is vast. It has the potential to transform the food sector by enhancing food quality, safety, and shelf life. Due to improved characteristics of nanoemulsions over normal emulsions, these are extensively used in food processing with very small droplet sizes of <200 nm. Nanoemulsions provide benefits such as improved taste, texture and preservative effect. But the use of these emulsions in food raises concerns about their safety, regulatory approval, and potential long-term effects. Hence formulation of regulations is necessary to ensure the safety behind the usage of these chemicals in food processing. The future of nanoemulsions relies on innovations to develop food products that meet consumer requirements for safe and healthy food.

AVAILABILITY OF DATA AND MATERIALS

The data will be made available from the corresponding author upon reasonable request.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology.

Details of the AI usage are given below:

1. ChatGPT

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

- Abbas S, Hayat K, Karangwa E, Bashari M, Zhang X (2013) An overview of ultrasound-assisted food-grade nanoemulsions. *Food Eng Rev* 5: 139–157.
<https://doi.org/10.1007/s12393-013-9066-3>
- Abinash V, Rahul T, Antoniraj MG, Moses JA, Anandharamakrishnan C (2021) Nanotechnology approaches for food fortification. In *Food, Medical, and Environmental Applications of Polysaccharides*: 161-186.
<https://doi.org/10.1016/B978-0-12-819239-9.00007-5>
- Agarwal S, Vivekanandan S, David T, Mitra M, Palanivelu J, Chidambaram R (2019) Nanoemulsions: Industrial production and food-grade applications. *Polymers for Agri-Food Applications*: 159-182.
https://doi.org/10.1007/978-3-030-19416-1_10
- Akbas E, Soyler B, Oztop MH (2018) Formation of capsaicin loaded nanoemulsions with high pressure homogenization and ultrasonication. *Lwt* 96: 266–273.
<https://doi.org/10.1016/j.lwt.2018.05.043>
- Alexandre EMC, Lourenço RV, Bittante AMQB, Moraes ICF, do Amaral Sobral PJ (2016) Gelatin-based films reinforced with montmorillonite and activated with nanoemulsion of ginger essential oil for food packaging applications. *Food Packaging and Shelf Life* 10: 87–96.
<https://doi.org/10.1016/j.foodpack.2016.10.004>
- Anton N, Benoit JP, Saulnier P (2008) Design and production of nanoparticles formulated from nano-emulsion templates—a review. *Journal of Controlled Release* 128(3): 185–199.
<https://doi.org/10.1016/j.jconrel.2008.02.007>
- Anton N, Vandamme TF (2009) The universality of low-energy nano-emulsification. *International journal of pharmaceutics* 377(1-2): 142-147.

- <https://doi.org/10.1016/j.ijpharm.2009.05.014>
- Artiga-Artigas M, Acevedo-Fani A, Martín-Belloso O (2017). Improving the shelf life of low-fat cut cheese using nanoemulsion-based edible coatings containing oregano essential oil and mandarin fiber. *Food Control* 76: 1–12. <https://doi.org/10.1016/j.foodcont.2017.01.001>
- Ashokkumar M (2015) Applications of ultrasound in food and bioprocessing. *Ultrasonics sonochemistry*, 25, 17-23. <https://doi.org/10.1016/j.ultsonch.2014.08.012>
- Bhosale RR, Osmani RA, Ghodake PP, Shaikh SM, Chavan SR (2014) Mastitis: an intensive crisis in veterinary science. *International Journal of Pharma Research and Health Sciences* 2(2): 96–103.
- Borthakur P, Boruah PK, Sharma B, Das MR (2016) Nanoemulsion: preparation and its application in food industry. In *Emulsions*, Elsevier, pp 153–191. <https://doi.org/10.1016/B978-0-12-804306-6.00005-2>
- Bouchemal K, Briançon S, Perrier E, Fessi H (2004) Nano-emulsion formulation using spontaneous emulsification: solvent, oil and surfactant optimisation. *International Journal of Pharmaceutics* 280(1–2): 241–251. <https://doi.org/10.1016/j.ijpharm.2004.05.016>
- Bu G, Zhao C, Wang M, Yu Z, Yang H, Zhu T (2023) The development and properties of nanoemulsions stabilized with glycosylated soybean protein for carrying β -carotene. *Journal of Food Engineering*: 111411. <https://doi.org/10.1016/j.jfoodeng.2023.111411>
- Ceylan Z, Meral R, Kose YE, Cavidoglu I (2020) Wheat germ oil nanoemulsion for oil stability of the cooked fish fillets stored at 4° C. *Journal of food science and technology* 57: 1798-1806. <https://doi.org/10.1007/s13197-019-04213-7>
- Das SK, Vishakha K, Das S, Ganguli A (2023) Antibacterial and antibiofilm activities of nanoemulsion coating prepared by using caraway oil and chitosan prolongs the shelf life and quality of bananas. *Applied Food Research*: 100300. <https://doi.org/10.1016/j.afres.2023.100300>
- Davidov-Pardo G, McClements DJ (2015) Nutraceuical delivery systems: Resveratrol encapsulation in grape seed oil nanoemulsions formed by spontaneous emulsification. *Food Chemistry* 167: 205–212. <https://doi.org/10.1016/j.foodchem.2014.06.082>
- Demisli S, Mitsou E, Pletsas V, Xenakis A, Papadimitriou V (2020) Development and study of nanoemulsions and nanoemulsion-based hydrogels for the encapsulation of lipophilic compounds. *Nanomaterials* 10(12): 2464. <https://doi.org/10.3390/nano10122464>
- Dghais S, Ben Jemaa M, Chouchen M, Jallouli S, Ksouri R, Falleh H (2023) Nano-Emulsification of Cinnamon and Curcuma Essential Oils for the Quality Improvement of Minced Meat Beef. *Foods* 12(2): 235. <https://doi.org/10.3390/foods12020235>
- Dhandhi Y, Chaudhari RK, Naiya TK (2022) Development in separation of oilfield emulsion toward green technology—A comprehensive review. *Separation Science and Technology* 57(10): 1642-1668. <https://doi.org/10.1080/01496395.2021.1995427>
- Dhaval M, Vaghela P, Patel K, Patel S, Parmar R (2022) Lipid-based emulsion drug delivery systems—a comprehensive review. *Drug Delivery and Translational Research*: 1-24 <https://doi.org/10.1007/s13346-021-01071-9>
- Donsi F, Ferrari G, Maresca P (2009) High-pressure homogenization for food sanitization. In *Global issues in food science and technology*: 309–352. <https://doi.org/10.1016/B978-0-12-374124-0.00019-3>
- Farshi P, Tabibiazar M, Ghorbani M, Mohammadifar M, Amirkhiz MB, Hamishehkar H (2019) Whey protein isolate-guar gum stabilized cumin seed oil nanoemulsion. *Food bioscience* 28: 49-56. <https://doi.org/10.1016/j.fbio.2019.01.011>
- Feng J, Rodríguez-Abreu C, Esquena J, Solans C (2020) A concise review on nano-emulsion formation by the phase inversion composition (pic) method. *Journal of Surfactants and Detergents* 23(4): 677-685. <https://doi.org/10.1002/jsde.12414>
- Gadhawe AD (2014) Nanoemulsions: formation, stability and applications. *International Journal for Research in Science and Advanced Technologies* 3(2): 38–43.

- García-Becerra C, Rojas A, Höcht C, Bernabeu E, Chiappetta D, Tevez S, Tripodi V (2023) Characterization and bioavailability of a novel coenzyme Q10 nanoemulsion used as an infant formula supplement. *International Journal of Pharmaceutics* 634: 122656. <https://doi.org/10.1016/j.ijpharm.2023.122656>
- Geng M, Feng X, Wu X, Tan X, Shang B, Huang Y, Li Y (2023) Characterization and utilization of soy protein isolate-(−)-epigallocatechin gallate–maltose ternary conjugate as an emulsifier for nanoemulsions: Enhanced physicochemical stability of the β-carotene nanoemulsion. *Food Chemistry* 417: 135842. <https://doi.org/10.1016/j.foodchem.2023.135842>
- George JS, Jibin KP, Prajitha V, Remya VR, Thomas S (2022) Nanotechnology: An Emerging Technology for Therapeutics. In *A Holistic and Integrated Approach to Lifestyle Diseases: 1st edn.* Tylor and francis, 79-90.
- Ghazy OA, Fouad MT, Morsy TA, Kholif AE (2023) Nanoemulsion formulation of *Lawsonia inermis* extract and its potential antimicrobial and preservative efficacy against foodborne pathogens. *Food Control* 145: 109458. <https://doi.org/10.1016/j.foodcont.2022.109458>
- Goindi S, Kaur A, Kaur R, Kalra A, Chauhan P (2016) Nanoemulsions: an emerging technology in the food industry. In *Emulsions*, Elsevier, pp 651–688. <https://doi.org/10.1016/B978-0-12-804306-6.00019-2>
- Golfomitsou I, Mitsou E, Xenakis A, Papadimitriou V (2018) Development of food grade O/W nanoemulsions as carriers of vitamin D for the fortification of emulsion based food matrices: A structural and activity study. *Journal of Molecular Liquids* 268: 734–742. <https://doi.org/10.1016/j.molliq.2018.07.109>
- Gundewadi G, Sarkar DJ, Rudra SG, Singh D (2018) Preparation of basil oil nanoemulsion using *Sapindus mukorossi* pericarp extract: Physico-chemical properties and antifungal activity against food spoilage pathogens. *Industrial Crops and Products* 125: 95-104. <https://doi.org/10.1016/j.indcrop.2018.08.076>
- Gutiérrez JM, González C, Maestro A, Sole I, Pey CM, Nolla J (2008) Nano-emulsions: New applications and optimization of their preparation. *Current Opinion in Colloid & Interface Science* 13(4): 245–251. <https://doi.org/10.1016/j.cocis.2008.01.005>
- He X, Deng H, Hwang HM (2019) The current application of nanotechnology in food and agriculture. *Journal of food and drug analysis* 27(1): 1-21. <https://doi.org/10.1016/j.jfda.2018.12.002>
- Henry JVL, Fryer PJ, Frith WJ, Norton IT (2010) The influence of phospholipids and food proteins on the size and stability of model sub-micron emulsions. *Food Hydrocolloids* 24(1): 66–71. <https://doi.org/10.1016/j.foodhyd.2009.08.006>
- Hou RCW, Lin MY, Wang MMC, Tzen JTC (2003) Increase of viability of entrapped cells of *Lactobacillus delbrueckii* ssp. *bulgaricus* in artificial sesame oil emulsions. *Journal of Dairy Science* 86(2): 424–428. [https://doi.org/10.3168/jds.S0022-0302\(03\)73620-0](https://doi.org/10.3168/jds.S0022-0302(03)73620-0)
- Jafari S M, He Y, Bhandari B (2007) Optimization of nano-emulsions production by microfluidization. *European Food Research and Technology* 225(5): 733–741. <https://doi.org/10.1007/s00217-006-0476-9>
- Jiang T, Liao W, Charcosset C (2020) Recent advances in encapsulation of curcumin in nanoemulsions: A review of encapsulation technologies, bioaccessibility and applications. *Food Research International* 132: 109035. <https://doi.org/10.1016/j.foodres.2020.109035>
- Jin W, Xu W, Liang H, Li Y, Liu S, Li B (2016) Nanoemulsions for food: properties, production, characterization, and applications. In *Emulsions*, Elsevier, pp 1–36. <https://doi.org/10.1016/B978-0-12-804306-6.00001-5>
- Johnson EJ (2002) The role of carotenoids in human health. *Nutrition in Clinical Care* 5(2): 56–65. <https://doi.org/10.1046/j.1523-5408.2002.00004.x>
- Kralova I, Sjoblom J (2009) Surfactants used in food industry: a review. *Journal of Dispersion Science and Technology* 30(9): 1363–1383.

- <https://doi.org/10.1080/01932690902735561>
 Kumar N, Verma A, Mandal A (2021) Formation, characteristics and oil industry applications of nanoemulsions: a review. *Journal of Petroleum Science and Engineering* 206: 109042.
<https://doi.org/10.1016/j.petrol.2021.109042>
- Leong TSH, Wooster TJ, Kentish SE, Ashokkumar M (2009) Minimising oil droplet size using ultrasonic emulsification. *Ultrasonics Sonochemistry* 16(6): 721–727.
<https://doi.org/10.1016/j.ultsonch.2009.02.008>
- Li PH, Lu WC (2016) Effects of storage conditions on the physical stability of D-limonene nanoemulsion. *Food Hydrocolloids* 53: 218–224.
<https://doi.org/10.1016/j.foodhyd.2015.01.031>
- Liang R, Huang Q, Ma J, Shoemaker C F, Zhong F (2013) Effect of relative humidity on the store stability of spray-dried beta-carotene nanoemulsions. *Food Hydrocolloids* 33(2): 225–233.
<https://doi.org/10.1016/j.foodhyd.2013.03.015>
- Lohith Kumar DH, M Anush S, JaganMohan Rao L, B Sowbhagya H (2017) Microwave impact on the flavour compounds of cinnamon bark (cinnamomum cassia) volatile oil and polyphenol extraction. *Current Microwave Chemistry* 4(2): 115–121.
- Malode MGP, Chauhan SA, Bartare SA, Malode LM, Manwar JV, Bakal RL (2021) A critical review on nanoemulsion: Advantages, techniques and characterization. *Journal of Applied Pharmaceutical Sciences and Research* 4(3): 6-12.
<https://doi.org/10.31069/japsr.v4i3.2>
- Mansuri A, Chaudhari R, Nasra S, Meghani N, Ranjan S, Kumar A (2023) Development of food-grade antimicrobials of fenugreek oil nanoemulsion—bioactivity and toxicity analysis. *Environmental Science and Pollution Research* 30(10): 24907–24918.
<https://doi.org/10.1007/s11356-022-19116-y>
- Mason TG, Wilking JN, Meleson K, Chang CB, Graves SM (2006) Nanoemulsions: formation, structure, and physical properties. *Journal of Physics: Condensed Matter* 18(41): R635.
<https://doi.org/10.1088/0953-8984/18/41/R01>
- Mcclements DJ (2007) Critical review of techniques and methodologies for characterization of emulsion stability. *Critical Reviews in Food Science and Nutrition* 47(7): 611–649.
<https://doi.org/10.1080/10408390701289292>
- Mcclements DJ (2012) Fabrication, characterization and properties of food nanoemulsions. In *Nanotechnology in the food, beverage and nutraceutical industries*: 293-316.
<https://doi.org/10.1533/9780857095657.2.293>
- Mcclements DJ, Decker EA, Weiss J (2007) Emulsion-based delivery systems for lipophilic bioactive components. *Journal of Food Science* 72(8): R109–R124.
<https://doi.org/10.1111/j.1750-3841.2007.00507.x>
- Mcclements DJ, Li Y (2010) Review of in vitro digestion models for rapid screening of emulsion-based systems. *Food & Function* 1(1): 32–59.
<https://doi.org/10.1039/C0FO00111B>
- Mcclements DJ, Rao J (2011) Food-grade nanoemulsions: formulation, fabrication, properties, performance, biological fate, and potential toxicity. *Critical Reviews in Food Science and Nutrition* 51(4): 285–330.
<https://doi.org/10.1080/10408398.2011.559558>
- Medeiros AKDOC, de Carvalho Gomes C, de Araújo Amaral MQ, de Medeiros LDG, Medeiros I, Porto DL, Passos TS (2019) Nanoencapsulation improved water solubility and color stability of carotenoids extracted from Cantaloupe melon (*Cucumis melo* L.). *Food Chemistry* 270: 562-572.
<https://doi.org/10.1016/j.foodchem.2018.07.099>
- Meghani N, Patel P, Kansara K, Ranjan S, Dasgupta N, Ramalingam C, Kumar A (2018) Formulation of vitamin D encapsulated cinnamon oil nanoemulsion: Its potential anti-cancerous activity in human alveolar carcinoma cells. *Colloids and Surfaces B: Biointerfaces* 166: 349-357.
<https://doi.org/10.1016/j.colsurfb.2018.03.041>
- Milani J (2019) Some New aspects of colloidal systems in foods. *BoD–Books on Demand*.

- Nakabayashi K, Amemiya F, Fuchigami T, Machida K, Takeda S, Tamamitsu K, Atobe M (2011) Highly clear and transparent nanoemulsion preparation using surfactant-free conditions using tandem acoustic emulsification. *Chemical Communications* 47(20): 5765–5767. <https://doi.org/10.1039/C1CC10558B>
- Neves AR, Lucio M, Martins S, Lima JLC, Reis S (2013) Novel resveratrol nanodelivery systems based on lipid nanoparticles to enhance its oral bioavailability. *International Journal of Nanomedicine* 8: 177. <https://doi.org/10.2147/IJN.S37840>
- Nikravan L, Maktabi S, Ghaderi Ghahfarrokhi M, Mahmoodi Sourestani M (2020) The comparison of antimicrobial and antioxidant activity of essential oil of *Oliveria decumbens* and its nanoemulsion preparation to apply in food industry. *Iran. Vet. J.* 17(72): 78-87. <https://doi.org/10.22055/IVJ.2021.297017.2384>
- NutraLease 2011 Nano-Sized Self-assembled Liquid Structures (NSSL) Supplements. IOP publishing huge domainweb. <http://www.nutralease.com/Nutra/Template/s/showpage.asp?DBID=1&LNGID=1&TMID=84&FID=767>. Accessed 29 April 2023.
- Oh DH, Balakrishnan P, Oh YK, Kim DD, Yong CS, Choi HG (2011) Effect of process parameters on nanoemulsion droplet size and distribution in SPG membrane emulsification. *International Journal of Pharmaceutics* 404(1–2): 191–197. <https://doi.org/10.1016/j.ijpharm.2010.10.045>
- Otoni CG, Pontes SFO, Medeiros EAA, Soares NdeFF (2014) Edible films from methylcellulose and nanoemulsions of clove bud (*Syzygium aromaticum*) and oregano (*Origanum vulgare*) essential oils as shelf life extenders for sliced bread. *Journal of Agricultural and Food Chemistry* 62(22): 5214–5219. <https://doi.org/10.1021/jf501055f>
- Ozogul Y, Karsli GT, Durmus M, Yazgan H, Oztop HM, McClements DJ, Ozogul F (2022) Recent developments in industrial applications of nanoemulsions. *Advances in Colloid and Interface Science*: 102685. <https://doi.org/10.1016/j.cis.2022.102685>
- Piorkowski DT, McClements DJ (2014) Beverage emulsions: Recent developments in formulation, production, and applications. *Food Hydrocolloids* 42: 5–41. <https://doi.org/10.1016/j.foodhyd.2013.07.009>
- Prakash A, Vadivel V, Rubini D, Nithyanand P (2019) Antibacterial and antibiofilm activities of linalool nanoemulsions against *Salmonella typhimurium*. *Food bioscience* 28: 57–65. <https://doi.org/10.1016/j.fbio.2019.01.018>
- Qi H, Chen S, Zhang J, Liang H (2022) Robust stability and antimicrobial activity of d-limonene nanoemulsion by sodium caseinate and high pressure homogenization. *Journal of Food Engineering* 334: 111159. <https://doi.org/10.1016/j.jfoodeng.2022.111159>
- Rashid A, Qayum A, Liang Q, Kang L, Raza H, Chi Z, Ma H (2023) Preparation and characterization of ultrasound-assisted essential oil-loaded nanoemulsions stimulated pullulan-based bioactive film for strawberry fruit preservation. *Food Chemistry*: 136254. <https://doi.org/10.1016/j.foodchem.2023.136254>
- Rashidi L (2021) Different nano-delivery systems for delivery of nutraceuticals. *Food Bioscience* 43: 101258. <https://doi.org/10.1016/j.fbio.2021.101258>
- Rivera-Perez E, Escobar-Ortiz A, Perez-Ramírez IF, Regalado-Gonzalez C, Zubieta-Otero LF, Rodríguez-García ME, Camacho RR (2023) Encapsulation of spray-dried curcumin nanoemulsions to develop a supplement with ingredients for the control of osteoarthritis. *Journal of Drug Delivery Science and Technology* 82: 104299. <https://doi.org/10.1016/j.jddst.2023.104299>
- Roy A, Guha P (2018) Formulation and characterization of betel leaf (*Piper betle* L.) essential oil based nanoemulsion and its in vitro antibacterial efficacy against selected food pathogens. *Journal of food processing and preservation* 42(6): e13617. <https://doi.org/10.1111/jfpp.13617>
- Safaya M, Rotliwala YC (2020) Nanoemulsions: A review on low energy formulation methods, characterization, applications and optimization technique. *Materials Today: Proceedings* 27: 454-459. <https://doi.org/10.1016/j.matpr.2019.11.267>
- Santos DT, Meireles MAA (2010) Carotenoid pigments encapsulation: fundamentals, techniques and recent trends. *The Open Chemical Engineering Journal* 4(1). <https://doi.org/10.2174/1874123101004010042>

- Schramm LL (2006) Emulsions, foams, and suspensions: fundamentals and applications. John Wiley & Sons.
- Schultz S, Wagner G, Urban K, Ulrich J (2004) High-pressure homogenization as a process for emulsion formation. *Chemical Engineering & Technology: Industrial Chemistry-Plant Equipment-Process Engineering-Biotechnology* 27(4): 361–368.
<https://doi.org/10.1002/ceat.200406111>
- Sekhon BS (2010) Food nanotechnology—an overview. *Nanotechnology, Science and Applications* 3: 1.
<https://doi.org/10.2147/nsa.s12187498>
- Shahidi F, Zhong Y (2010) Lipid oxidation and improving the oxidative stability. *Chemical Society Reviews* 39(11): 4067–4079.
<https://doi.org/10.1039/B922183M>
- Shao Y, Wu C, Wu T, Li Y, Chen S, Yuan C, Hu Y (2018) Eugenol-chitosan nanoemulsions by ultrasound-mediated emulsification: formulation, characterization and antimicrobial activity. *Carbohydrate Polymers* 193: 144–152.
<https://doi.org/10.1016/j.carbpol.2018.03.101>
- Shi Y, Zhang M, Chen K, Wang M (2022) Nano-emulsion prepared by high pressure homogenization method as a good carrier for sichuan pepper essential oil: preparation, stability, and bioactivity. *Lwt* 154: 112779.
<https://doi.org/10.1016/j.lwt.2021.112779>
- Silva HD, Cerqueira MA, Vicente AA (2012) Nanoemulsions for food applications: development and characterization. *Food and Bioprocess Technology* 5(3): 854–867.
<https://doi.org/10.1007/s11947-011-0683-7>
- Silva HD, Cerqueira MA, Vicente AA. (2015) Influence of surfactant and processing conditions in the stability of oil-in-water nanoemulsions. *Journal of Food Engineering* 167: 89–98.
<https://doi.org/10.1016/j.jfoodeng.2015.07.037>
- Sneha K, Kumar A (2022) Nanoemulsions: Techniques for the preparation and the recent advances in their food applications. *Innovative Food Science & Emerging Technologies* 76: 102914.
<https://doi.org/10.1016/j.ifset.2021.102914>
- Solans C, Sole I (2012) Nano-emulsions: formation by low-energy methods. *Current Opinion in Colloid & Interface Science* 17(5): 246–254.
<https://doi.org/10.1016/j.cocis.2012.07.003>
- Spigno G, Donsi F, Amendola D, Sessa M, Ferrari G, De Faveri D M (2013) Nanoencapsulation systems to improve solubility and antioxidant efficiency of a grape marc extract into hazelnut paste. *Journal of Food Engineering* 114(2): 207–214.
<https://doi.org/10.1016/j.jfoodeng.2012.08.014>
- Sun-Waterhouse D, Wadhwa SS. Industry-relevant approaches for minimizing the bitterness of bioactive compounds in functional foods: a review. *Food and Bioprocess Technology*. 2013 Mar;6:607
- Sun X, Chen S, Liu J, Zhao S, Yoon JY (2020) Hydrodynamic cavitation: a promising technology for industrial-scale synthesis of nanomaterials. *Frontiers in Chemistry* 8: 259.
<https://doi.org/10.3389/fchem.2020.00259>
- Tabassum N, Aftab RA, Yousuf O, Ahmad S, Zaidi S (2023) Application of nanoemulsion based edible coating on fresh-cut papaya. *Journal of Food Engineering*: 111579.
<https://doi.org/10.1016/j.jfoodeng.2023.111579>
- Tadros T, Izquierdo P, Esquena J, Solans C (2004) Formation and stability of nano-emulsions. *Advances in Colloid and Interface Science* 108: 303–318.
<https://doi.org/10.1016/j.cis.2003.10.023>
- Taniguchi N (1974) On the basic concept of nanotechnology. *Proceeding of the ICPE*.
- Tesch S, Freudig B, Schubert H (2003) Production of Emulsions in High-Pressure Homogenizers—Part I: Disruption and Stabilization of Droplets. *Chemical Engineering & Technology: Industrial Chemistry-Plant Equipment-Process Engineering-Biotechnology* 26(5): 569–573.
<https://doi.org/10.1002/ceat.200390086>
- Vladisavljevic GT (2019) Preparation of microemulsions and nanoemulsions by membrane emulsification. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 579: 123709.
<https://doi.org/10.1016/j.colsurfa.2019.123709>
- Vladisavljevic GT, Williams RA (2005) Recent developments in manufacturing emulsions and particulate products using membranes. *Advances in Colloid and Interface Science* 113(1): 1–20.
<https://doi.org/10.1016/j.cis.2004.10.002>

- Witthayapanyanon A, Acosta EJ, Harwell JH, Sabatini DA (2006) Formulation of ultralow interfacial tension systems using extended surfactants. *Journal of Surfactants and Detergents* 9(4): 331–339. <https://doi.org/10.1007/s11743-006-5011-2>
- Wooster TJ, Golding M, Sanguansri P (2008) Impact of oil type on nanoemulsion formation and Ostwald ripening stability. *Langmuir* 24(22): 12758–12765. <https://doi.org/10.1021/la801685v>
- Xianquan S, Shi J, Kakuda Y, Yueming J (2005) Stability of lycopene during food processing and storage. *Journal of Medicinal Food* 8(4): 413–422. <https://doi.org/10.1089/jmf.2005.8.413>
- Yazgan H (2020) Investigation of antimicrobial properties of sage essential oil and its nanoemulsion as antimicrobial agent. *Lwt* 130: 109669. <https://doi.org/10.1016/j.lwt.2020.109669>
- Yin LJ, Chu BS, Kobayashi I, Nakajima M (2009) Performance of selected emulsifiers and their combinations in the preparation of β -carotene nanodispersions. *Food Hydrocolloids* 23(6): 1617–1622. <https://doi.org/10.1016/j.foodhyd.2008.12.005>
- Zhang AQ, Liu MQ, Li XY, Xu D, Yin YQ, Song NN Zhang YH (2023) Nanoemulsion: A novel delivery approach for thermosensitive IgG on inhibiting milk fat oxidation. *Food Research International* 165: 112545. <https://doi.org/10.1016/j.foodres.2023.112545>

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of the publisher and/or the editor(s). This publisher and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

© Copyright (2025): Author(s). The licensee is the journal publisher. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:

The peer review history for this paper can be accessed here:
<https://www.sdiarticle5.com/review-history/129395>