Review Article

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

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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 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

UNDER PEER REVIEW

1.0 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 controllingparticle 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)andare 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 and 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.

2.0 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 andminerals, 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 and 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 and 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 and 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 and 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

UNDER REVIEW

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 and 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 and 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.

3.0 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 an exerting 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 (Gutierrez 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*

UNDER PEER REVIEW

A mechanical device, such as a high-pressure valve homogenizer, sonication, and microfluidizer, as illustrated in Figure 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 and Rao, 2011).

3.1.1High pressure valve homogenization (HPH)

The HPH method is one of the most commonly used methods in the preparation of nanoemulsionson 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).

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 and Ashwini, 2022). Cavitation

UNDER PEER REVIEW

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(Gadhave, 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 and 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 withthe creation of nanoemulsion. This technique, which includes raising the volume fraction of the dispersed phase, is also referred to as catastrophic inversion (Safaya and Rotliwala, 2020).

UNDER PEER REVIEW

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 (Vladisavljevic´ and 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.

4.0 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 havelow solubility and fast metabolism, reducing their bioavailability, some are volatile and highly susceptible to processing conditions (McClements and Li, 2010; Jin et al., 2016). Toaddress 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 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 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 colorlost 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 and 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. Gelatinacts as a textutre modifier & it improved the water solubility of carotenoids. As a natural colouring agent, these nanoemulsions remained stable for more than 60 days in yoghurt (Medeiros et al., 2019). A ternaryconjugate of soy protein isolate-(−)-epigallocatechin gallate–maltose emulsion was prepared using ultrasound. The β-carotene nanoemulsionhas superior stability and prevents degradation of β-carotene by external environment (Geng et al. 2023; Bu et al. 2023).

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 Kumar 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

UNDER PEER REVIEW

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 and 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 (0.1–0.5g/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□. The nano-emulsified curcumin was used to treat osteoarthritis. The combination of 20% Tween80, 0.4 M NaCl and 0.0052 M $MgCl_2$ was used to prepare a nanoemulsion with Vitamin C as a supplement. The prepared nanoemlsion 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

UNDER PREVIEW

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 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 efect 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).

5.0 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.

6.0 Declarations

Ethical Approval: Not applicable

Availability of data and materials: the data will be made available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare that there is no conflict of interest regarding the publication of this paper.

Disclaimer (Artificial intelligence)

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UNDER PEER REVIEW

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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Details of the AI usage are given below:

1. ChatGPT

2.

3.

7.0 References

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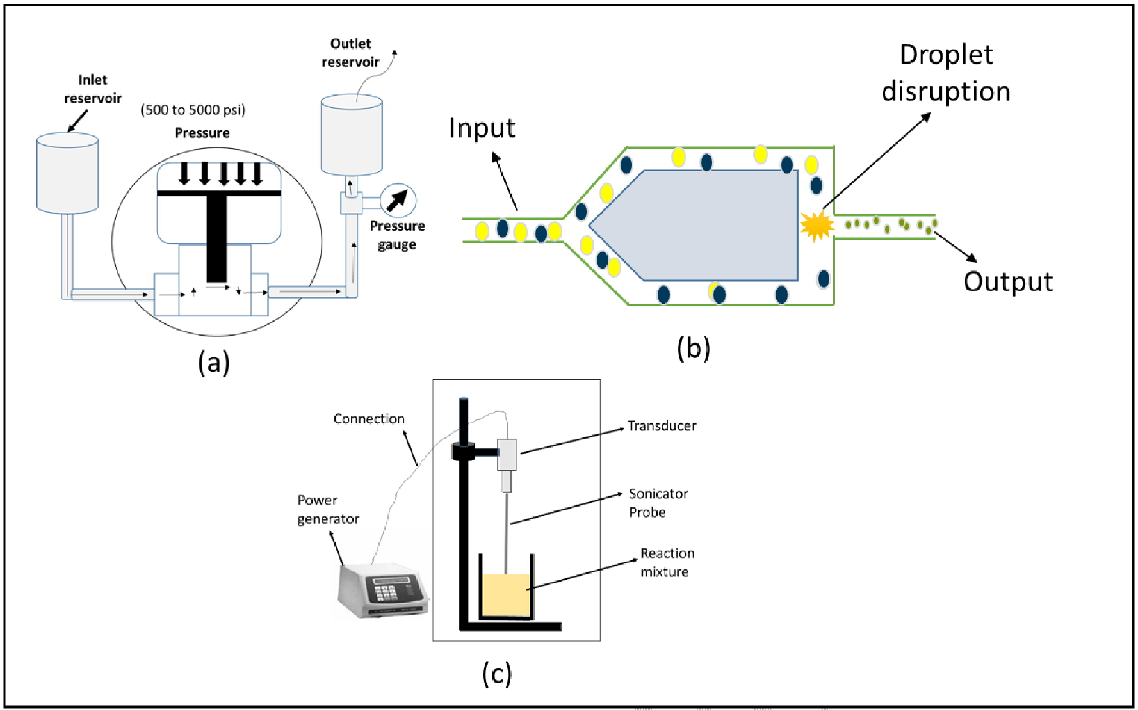

Fig.1 Schematic diagram of High energy methods of (a) High pressure homogenizer (b) Microfluidizer and (c) Ultrasonicator

UNDER PEER REVIEW

UNDER PEER REVIEW

UNDER PEER REVIEW

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	✓ Improved water solubility and inhibitory effect on *E. coli* and *S. aureus.* ✓ The emulsion found application in soy sauce and cooking wine.	Shi *etal*., 2022
2.	Laurus nobilis essential oil	Oil-in water; Tween 80	Ultrasonication (20 KHz/500 W/72 amplitudes/ 15 min)	247.52 nm	✓ Demonstrated antimicrobial activity against gram-positive pathogenic bacteria such as *S. aureus* and *E. faecalis*. ✓ Serves as a natural food antimicrobial preservative agent effective against foodborne pathogens and spoilage bacteria.	Ozogul *etal*.,2022
3.	Vitamin D-encapsulated cinnamon oil	Oil-in water; Tween 80	Ultrasonication (20 kHz/400W/10 min)	40.52 and 48.96 nm	✓ 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	✓ Strong bactericidal effect on gram-positive bacterial strains [*Staphylococcusaureus*] and gram-negative bacterial strains [*E. Coli* O157:H7, *Pseudomonasaeruginosa* and *Salmonella*].	Shao *et al*., 2018
5.	Basil oil with ethanolic saponin extract	Oil-in-water; Saponin	Ultrasonication (amplitude 15 µm/2 min)	37.7–57.6 nm	✓ Shows inhibition against food spoilage fungi like *P. chrysogenum* and *A. flavus.*	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	✓ Antibacterial and antibiofilm activities against *S. typhimurium*.	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	✓ Killing *E. coli* and *S. aureus* and good antifungal activity against *A. flavus*. ✓ Alternative to synthetic preservatory.	Farshi*et al.*, 2019
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**	✓ **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 *S. aureus*, *S.* paratyphi A and *P. mirabilis*.	Yazgan, 2020
10.	Oliveriadecumbens	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 *P. aeruginosa* &*S. aureus* .	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 *S. aureus* was significantly increased by 5-fold.	Qi *et al.*, 2022
12.	Henna (*Lawsoniainermis*) 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

UNDER PEER REVIEW

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 *S. aureus* and *B. subtilis* and two gram-negative bacteria *E. Coli* and *P. aeruginosa.*** ✓ **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 *Bacillus cereus* was observed.	Roy and Guha., 2018
15.	Cinnamon and Curcuma essential oils	Oil-in-water; Tween 40 or Tween 80	Sonication for 30 min and Ultra-homogenization for 1 min	89 nm and 151 nm	✓ Nano-encapsulated essential oils effectively prevent lipid oxidation in meat. ✓ Demonstrated significant inhibition of bacterial growth and methemoglobin formation. ✓ Shelf life of ground meat was extended.	Dghais*et al.*, 2023

Table 1-Methods of preparation and applications of nanoemulsions

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