Nanobiotechnology for Plant Protection

Series editor: Kamel A. Abd-Elsalam

Bio-Based Nanoemulsions for Agri-Food Applications

Edited by

Kamel A. Abd-Elsalam and Kasi Murugan

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BIO-BASED NANOEMULSIONS FOR AGRI-FOOD APPLICATIONS

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CHAPTER

20

Candelilla wax nanoemulsions with plant-based antioxidants, nutraceuticals, and its effects on the organoleptic parameters

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1. Introduction

Nowadays, consumers worldwide are demanding natural products of high nutritional quality and greater effectiveness in improving health. Food nanotechnology applications have improved the development, quality, andI safety of food as well as reduced suffering from chronic diseases. A natural alternative to maintaining the biological and beneficial properties of foods and natural bioactive compounds is the use of nanoemulsions based on food ingredients that are made with high- and low-energy methods. Nanoemulsions manages to encapsulate and mask the aroma and flavor of the bioactives for their subsequent release at the desired site with greater absorption and bioavailability dueto the reduced size of the particles (10–9) (De Souza Simões et al., 2017; Bora et al., 2018). To develop nanoemulsions, polysaccharides, proteins, lipids, and other types of food polymers are used as matrices to encapsulate the active principles, such as antioxidants and nutraceuticals (Rao and Khanum, 2016). Candelilla (*Euphorbia antisyphilitica* Zucc.) is an endemic species from the semiarid regions of the border between Mexico and the United States. From this plant, a wax generally recognized as safe (GRAS) by the US Food and Drug Administration (FDA) is obtained (Saucedo-Pompa et al., 2009). Nanoemulsions can be fabricated using either a top-down or bottom-up approach (Ezhilarasi et al., 2013). The top-down approach involves the size reduction of particles using energy-intensive mechanical processes by combining one or more of the three types of forces (compression, impact, and shear). On the other hand, the bottom-up approach involves the self-assembly of small particles to form nanoparticles (Mishra et al., 2010). In this chapter, the preparation methods of food-grade nanoemulsions, including low-energy and high-energy methods, are described. The chapter also gives a description of recent advances in the role of candelilla wax nanoemulsions in processes for the encapsulation and delivery of plant-based natural antioxidants and nutraceuticals in addition to the effect of the organoleptic and sensory parameters of food nanosystems.

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TABLE 1 Main properties between emulsion, microemulsion, and nanoemulsion systems.

	Colloidal system		
Main properties	**Emulsion**	**Microemulsion**	**Nanoemulsion**
Particle size (nm)	>200	<100	<200
Stability	Metastable	Thermodynamic	Metastable
Optical property	Turbid	Transparent	Translucent

2. Preparation methods of food-grade nanoemulsions

Nanoemulsions are kinetically stable colloidal systems formed from a hydrophilic phase, a lipophilic phase, and the use of surface-active compounds commonly known as surfactants (Gupta et al., 2016). Surfactants are amphiphilic molecules that have functional groups with different affinities in their chemical structure (hydrophilic head and hydrophobic tail) (Dantas et al., 2019). From these components, it is possible to obtain oil droplets dispersed within an aqueous medium (oil in water; O/W nanoemulsions) and water droplets dispersed in an oil medium (water in oil; W/O nanoemulsions). Despite being formed by the same components (oil, water, and surfactant), emulsions, microemulsions, and nanoemulsions are different colloidal systems. Knowing their differences favors their correct manufacture. The main differences between these systems are particle size and stability (Table 1). There are numerous reports in the specialized literature that have not been completely clear about the classification of these systems, and there has been great confusion when referring to them (Komaiko and McClements, 2016).

In the past decade, nanoemulsions have become an outstanding option for several applications in different areas such as pharmaceutics, cosmetics, and the food and agriculture industries. Particularly in food and agriculture science and technology, the main attractions of nanoemulsions are their characteristics and design flexibility. These characteristics make them very helpful as carrier vehicles of poorly water-soluble bioactives that otherwise could not be incorporated into the products (Liu et al., 2019). Additionally, within this area, nanoemulsions can be useful at solving several problems such as packaging, flavors, pigments, nutraceuticals, antioxidants, shelf life, preventing the growth of spoilage microorganisms, food supplements, pesticide formulations, and more.

As an example of food application, Asensio et al. (2020) prepared oregano essential oil nanoemulsions to evaluate the inhibitory effect of these systems on bacteria that cause foodborne diseases such as *Pseudomonas aeruginosa* and *Staphylococcus aureus*. The authors reported the preparation of nanoemulsions with soy lecithin as a surfactant. They found physically stable systems with a droplet size of 62.6nm and a polydispersity index of 0.3. The results showed that oregano essential oil nanoemulsions caused an inhibitory effect on bacteria. These systems could be used as a food preservation technique, reducing communication among Gram-negative bacteria and hence food deterioration. Meanwhile, in agriculture applications, Zhang et al. (2021), concerned about the increase of synthetic pesticides in crops and environmental decay, developed a novel plant-based pesticide by preparing carvacrol O/W nanoemulsions for treatment on spinach leaves and evaluating plant health status. The results showed an inverse relationship between carvacrol concentration within nanoemulsions and spinach leaf health because by increasing the carvacrol concentration from 0.005%–0.5% (where plants remain healthy) to 5%, there was a significant reduction in plant integrity (biomass and chlorophyll content). Therefore, the use of essential oil nanoemulsions at an adequate concentration could be an effective plant-based pesticide.

The nanoemulsion formation strongly depends on the surfactant type and its interaction with the oil or water phase. Surfactants can be cationic (positive charge), anionic (negative charge), nonionic (no charge), or zwitterionic (positive and negative charge) in nature. However, in food and agriculture applications, nonionic surfactants are usually accepted due to their low toxicity and because they are less affected by external factors (such as pH and ionic strength) (Mustafa and Hussein, 2020). The selection of nonionic surfactants can be achieved by knowing their hydrophilic–lipophilic balance (HLB) because a low HLB value tends to be an oil-soluble surfactant whereas a high HLB value tends to be a water-soluble surfactant (Miller, 2016). One of the most significant advantages of nanoemulsions is that they require less surfactant concentration (5%–10%) than microemulsion systems (20%) (Mustafa and Hussein, 2020).

Nanoemulsions do not form spontaneously, so it is necessary to apply external energy in the formation process. The applied energy allows the initially separated components (large oil or water droplets) to turn into smaller colloidal structures. Nanoemulsions are mainly formulated by two different approaches: low- and high-energy methods. Low energy methods involve drop formation when the system composition (water-surfactant-oil) or environmental conditions (e.g., temperature) change. High-energy methods use mechanical instruments to ensure the fusion of oil and water phases by applying intense disruptive forces (McClements and Jafari, 2018).

2.1 Low-energy methods

These methods are based on phase behavior and transitions during the emulsification procedure as well as the component properties of nanoemulsion development. Low-energy methods employ the stored internal chemical energy of the system and only gentle component stirring is needed due to the high surfactant concentration required for their formation. However, this limits their application in the food industry (McClements, 2021). Low-energy methods include phase inversion emulsification methods and spontaneous emulsification methods. Phase inversion emulsification methods involve both phase inversion temperature (PIT) and phase inversion composition (PIC). The main difference between these methods is that in PIC, any surfactant can be used, whereas in PIT, only temperature-sensitive surfactants such as polyoxyethylene are suitable (Mustafa and Hussein, 2020).The PIT method implies temperature modifications to change surfactant solubility and thus their affinities for oil or water phases, namely the hydrophilicity or lipophilicity of surfactant molecules. Initially, oil, water, and surfactant (with polyoxyethylene groups) are mixed at room temperature, forming an O/W microemulsion. However, as the temperature increases, the water solubility of the surfactant decreases due to the dehydration of its polar head groups, leading to a transition from an O/W to a W/O nanoemulsion. Additionally, as temperature increases, interfacial surface tension decreases, favoring droplet size reduction (Aswathanarayan and Vittal, 2019); Nirmala and Nagarajan, 2017). The HLB temperatures of nonionic surfactants have shown an important role in PIT methods because at an intermediate temperature, surfactants show a similar affinity for oil and water phases, so to achieve a kinetically stable nanoemulsion, rapid cooling and heating processes can be applied to modify the HLB of nonionic surfactants. Hasan et al. (2015) applied a PIT method to prepare nanoemulsions of virgin coconut oil using cremophor RH 40 as a nonionic surfactant. A temperature cycle of the cooling–heating process was applied (90-60-90-60-90°C) to reach the inversion process. The authors found that at 75°C, the system appeared as a translucent nanoemulsion containing 25% coconut oil and 30% cremophor RH 40 with a particle size of 48.63nm anda zeta potential value of −3.14mV (surface charge).

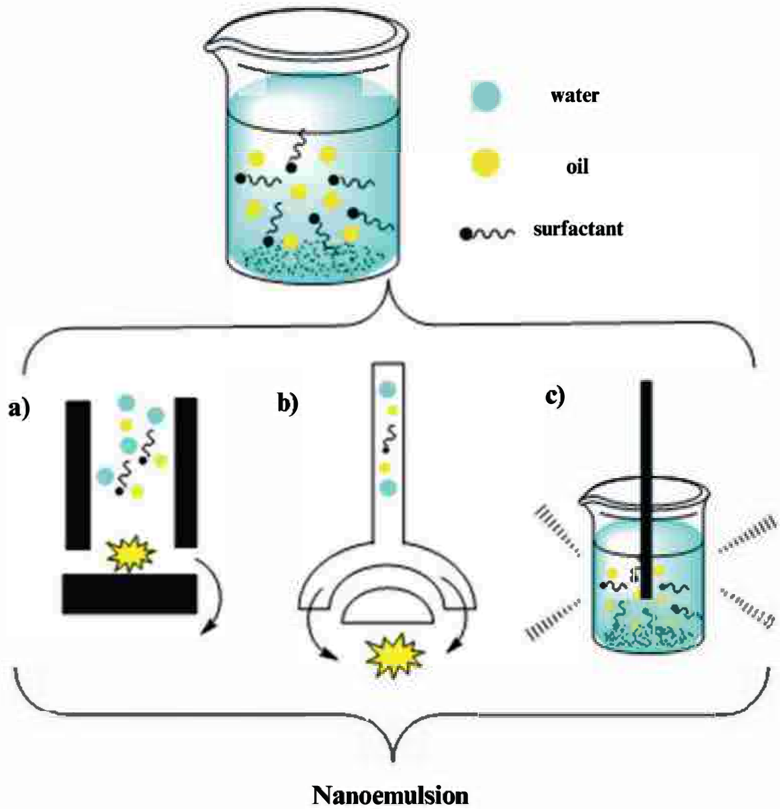
A study compared two low-energy methods to prepare black pepper essential oil nanoemulsions: emulsion phase inversion (EPI) and PIT, evaluating the stability, droplet size, and oil loading efficiency (Hien and Dao, 2021). The results showed that through the PIT method, the droplet size increased after 2weeks of evaluation (82.4nm) with respect to EPI (32.4nm). In terms of stability, EPI hada more homogeneous appearance and higher loading efficiency (92.13%) after 4weeks at 30°C than PIT, which hada creamy appearance and significantly lower loading (81.52%).

On the other hand, in the PIC method, the main principle is the variation of composition rather than temperature to achieve nanoemulsion formation in which either water or oil is added to the oil-surfactant or water-surfactant mixture, respectively. Once a dispersed phase is gradually mixed with a continuous phase and the addition continues, the system is reorganized by changing its composition, leading to nanoemulsion formation (Solans and Solé, 2012). Farshbaf-Sadigh et al. (2021) investigated the effects of stirring (100–1000rpm) and water addition rate (1–10mL/min) on the physicochemical properties (droplet size and surface charge) of a ginger oil in water nanoemulsion formation, using Tween 80 as a surfactant. The authors found that the preparation variables at which nanoemulsions with the smallest droplet size (9.81nm) and maximum stability (higher zeta potential value, −9.15mV) were obtained were at stirring and water addition rates of 736 rpm and 8.18 mL/min, respectively. The spontaneous emulsification method is another technique in which nanoemulsions can be obtained. First, a homogeneous phase is constructed by oil, a lipophilic surfactant or water, and a hydrophilic surfactant. Water or oil is added while the mixtures are kept under magnetic stirring, forming an O/W ora W/O emulsion. Following that, evaporation under reduced pressure is used to remove any excess aqueous or oil phase. However, there are some modifications to this method reported in the literature. Gulotta et al. (2014) studied the influence of cosolvent aqueous composition (glycerol and propylene glycol) on the formation and stability of fish oil nanoemulsions by the spontaneous emulsification method. The smallest droplet sizes were obtained when an oil phase (a mixture of fish oil and lemon oil) was added toan aqueous phase containing 40% glycerol and propylene glycol. Droplet sizes were 51 and 99nm, respectively. The use of cosolvents could improve the stability of nanoemulsions.

2.2 High-energy methods

These methods include high-pressure homogenization, microfluidization, and sonication (Fig. 1). High-pressure homogenization is the most common procedure to fabricate nanoemulsions for food, pharmaceutical, and

FIG. 1 Schematic representation of high-energy methods for nanoemulsion preparation: (A) high-pressure homogenization method, (B) microfluidization method, and (C) sonication method.



biotechnological applications. Initially, a mixture of surfactant as well as continuous and dispersed phases (namely oil or water) is passed through a device that operates at high pressure (500–5000psi), applying different forces (mainly turbulence and cavitation) to produce small droplet nanoemulsions (up to 1nm) (Kumar et al., 2019). Despite the efficiency of this method to reduce droplet size, it is important to consider that nanoemulsion stability highly depends on surfactant concentration. In addition, extreme forces applied could cause premature component degradation. The properties of nanoemulsions obtained by high-pressure homogenization methods strongly rely on operating conditions (energy intensity, time, and temperature) (McClements, 2021). Ozturk et al. (2014) studied the effects of oil composition, surfactant type, and surfactant concentration on droplet size and stability in vitamin E acetate nanoemulsions using high-pressure homogenization. The oil phase was a mixture of orange oil with vitamin E acetate (0%–100%) while the surfactants used were lecithin and quillaja saponin with a concentration variation of 0.00005%–5%. At 50% of vitamin E acetate, minimum droplet sizes were obtained with both surfactants, 0.13m for lecithin and 0.12m for quillaja saponin. However, a lower concentration of quillaja saponin was needed to obtain the smallest droplet size. Both nanoemulsions were stable at a temperature range of 30–90°C. Lewińska (2021) compared two high-energy preparation methods for cannabidiol (CBD) encapsulation within O/W nanoemulsions: sonication and high-pressure homogenization. The results showed that besides the importance of the behavior and chemical nature of the surfactant, it is essential to choose the preparation method correctly. Both methods showed nanodroplets with spherical morphology; however, the obtained particle size was much larger by the sonication method (216–1418nm) than by high-pressure homogenization (128–880nm).

Microfluidization is another high-energy method to develop nanoemulsions and is a technology based on mixture and collision. To create nanoemulsions by this method, a device called a microfluidizer is used. Similar to the previous method, the mixture of water, oil, and surfactant is introduced to the microfluidizer at high pressure (500–20,000psi). The mixture is immediately distributed through microchannels (50–300μm) in the device, which allows the homogenization of the mixture (Trujillo et al., 2013). The microchannel guides the components toward the interaction chamber where the collision takes place, favoring nanoemulsion formation. This procedure can be carried out as many times as necessary until the desired droplet size is reached. Microfluidizer devices could facilitate nanoemulsion formation using low surfactant concentrations.

The sonication technique employs an apparatus composed of a probe that emits ultrasonic waves (frequency >20kHz) that apply acoustic cavitation forces to the initial emulsion (oil, water, and surfactant mixture), breaking it up to transform it into a nanoemulsion. Through this method, it is possible to obtain nanoemulsions with desirable droplet size and stability by modifying the applied cavitation force, time, and surfactant concentration. The main disadvantages of this technique are that it is suitable only for fluids with low viscosity and that it must be used on a laboratory scale.

As shown in the previous review, nanoemulsions can be prepared by different methods. However, it should not be excluded that these techniques can also be used synergistically. Miastkowska et al. (2020) proposed a novel biofungicide based on essential oil (cinnamon, thyme, manuka, and tea tree) nanoemulsions against diverse strains of pathogenic fungi of plants (*F. culmorum* and *Ph. cactorum*) and compared the fungicidal activity of nanoemulsions with pure essential oils. Nanoemulsions were obtained using both low-energy (PIC) and high-energy (ultrasonication) methods. As a result, it was found that nanoemulsions prepared by the high-energy method showed better fungicidal effects compared to the low-energy method and with pure oil. These results could be attributed to the fact that the nanoemulsion system allowed the reduction of the concentration of oil while maintaining and protecting it against oxidation and other external factors.

3. Encapsulation and delivery of plant-based natural antioxidants and waxes

Anthropogenic influence, among other things, tends to be one of the most challenging life-changing situations that affects mainly important sectors such as health, food, and agriculture. Consequently, this phenomenon has forced science and technology to develop new strategies to improve the processes involved throughout the chain of activities in these types of applications (Vermeulen et al., 2012). Plant-based compounds (such as carotenoids, vitamins, phenolic compounds) have characteristics in common; one of the most outstanding is the antioxidant activity (Lourenço et al., 2019). Plant-based antioxidants can protect cells from autooxidative reactions initiated by reactive oxygen species (ROS) that can cause damage and increase the risk for a great number of diseases such as cancer. The use of plant-based antioxidants not only contributes in health applications but could also contribute to the maintenance of food products that are exposed to oxidation reactions (Chabert et al., 2014). However, despite the positive characteristics of these compounds, their application is limited as they are highly unstable to light, oxygen, and heat while most are hydrophobic in nature. The use of bio-based nanoemulsions as encapsulation and delivery systems for bioactive ingredients as antioxidants has been a recent innovation that could provide stability and protection to natural compounds. Additionally, bio-based nanoemulsions could contribute to the improvement of agri-food processes such as antifungal activity, pesticide delivery systems, packaging, flavors, pigments, nutraceuticals, shelf life, food supplements, against the growth of spoilage microorganisms, etc. (Iqbal et al., 2020). Plant-based antioxidants can be classified into three major groups: vitamins, phenolic compounds, and carotenoids. Despite having access to these compounds in nature, their use is limited dueto their low stability attributable to external physical and chemical factors. The nanoencapsulation of vitamins, phenolic compounds, and carotenoids would focus on maintaining and protecting their properties (Lourenço et al., 2019).

3.1 Vitamins

Vitamins (Fig. 2), defined as micronutrients, play an important role in human health as food supplements, regulating metabolic functions, improving nutrition, and preventing some diseases (Dhakal and He, 2020). The most important ones are vitamins C and E. Vitamin C, or ascorbic acid, is a water-soluble compound present in many foods (fruits and vegetables) while vitamin E is a liposoluble compound constituted of tocopherol and tocotrienols.

Saberi et al. (2013) investigated the parameters involved in the composition and preparation conditions of vitamin E acetate nanoemulsions using the spontaneous emulsification technique. The authors evaluated the effect of surfactant type (Tween 20, 40, 60, 80, and 85) on particle size where the smallest particle size (<50nm) was obtained with

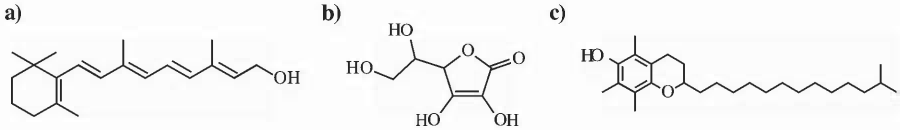


FIG. 2 Chemical structures: (A) vitamin A; (B) vitamin C, and (C) vitamin E.

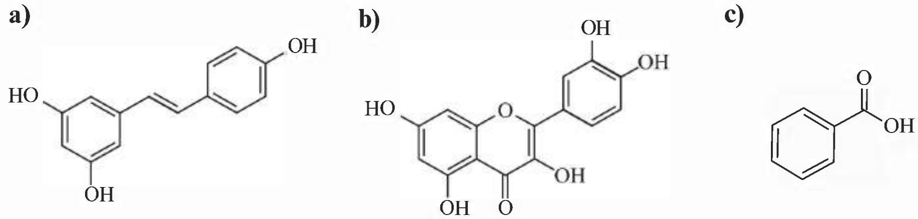


FIG. 3 Chemical structures of phenolic compounds: (A) resveratrol; (B) quercetin, and (C) gallic acid.

Tween 80 and 8wt% of vitamin E acetate. Another highly liposoluble vitamin is the one found in egg yolks or fish, vitamin D (Bartusik et al., 2016). Guttoff et al. (2015) reported the preparation of O/W nanoemulsions using the spontaneous emulsification method when an oil-surfactant mixture (vitamin D dissolved within medium-chain triglycerides) was titrated into an aqueous phase. The influence of system composition and preparation conditions on the particle size and stability of vitamin D nanoemulsions was evaluated. Nanoemulsions with droplet size <200nm using Tween 80 as a surfactant and at high stirring speeds (800rpm) were obtained. Akkam et al. (2021) proposed the development of pea protein nanoemulsions as a vitamin D stabilizer because these systems could protect vitamin D from UV light and heat; a large portion of the vitamin is degraded in food processing techniques, so its food benefits are poorly exploited. The fortification of different food formulations such as orange juice and banana milk was exposed to pea protein nanoemulsions and the particle size, antioxidant activity, and phenolic content were evaluated. The results showed that pea protein nanoemulsions with a droplet size of 21.8nm protect vitamin D in all evaluated food products without affecting the sensory characteristics.

3.2 Phenolic compounds

These compounds (around 10,000) are secondary metabolites derived from plants and are constituted mainly by aromatic rings and hydroxyl groups. They can be found in several foods (fruits, chocolate, green tea, red wine, horticultural crops, etc.). Phenolic compounds (Fig. 3) are classified as flavonoids and nonflavonoids, and their major importance in application relies on pigments, flavors, and textures in food products (Chabert et al., 2014; Lourenço et al., 2019).

As previously mentioned, antioxidants present instability due to different factors, including exposure to light. Resveratrol is a flavonoid that has this limitation. Some studies indicate the dissolution of resveratrol in a mixture of orange and grape seed oil and 10% Tween 80 as a surfactant to make oil-in-water emulsions (Davidov-Pardo and McClements, 2015). The nanoemulsions were created using the spontaneous emulsification method, resulting in a small droplet system (<100nm) and improved chemical stability to UV light exposure, thereby protecting resveratrol from degradation. Another important characteristic of some antioxidants is their low water solubility. Thus, O/W nanoemulsion production could improve the solubility of the compounds, providing better use of them. Later, in order to improve the solubility of curcumin and quercetin, Iqbal et al. (2020) developed food-grade O/W nanoemulsions using modified starch as a surfactant. The effects of processing conditions such as surfactant concentration, ionic strength, and pH on the droplet size and stability were evaluated. The results showed that nanoemulsions prepared with 5% starch were the most stable formulation, with a droplet size of 175.44nm. Meanwhile, curcumin and quercetin solubility improved 39 and 2.07 times, respectively, compared to their water solubility.

3.3 Carotenoids

Carotenoids also belong to the group of liposoluble antioxidants. In the same way as the above-mentioned antioxidants, carotenoids are found in foods such as tomatoes and carrots and are responsible for imparting color to them (red, orange, and yellow). Despite the fact that more than 600 carotenoids have been identified, research on their nanoencapsulation focuses only on some of them, such as α-carotene, β-carotene, and lycopene (Fig. 4) (Dasgupta and Ranjan, 2018; Liu et al., 2019).

In order to improve the physical and chemical stability of β-carotene in food applications, Borba et al. (2019) created a stable nanoemulsion by high-pressure homogenization of-carotene, Span 80, and corn oil in the oil phase and Tween 20 and water in the aqueous phase. The nanoemulsions demonstrated physical stability after pasteurization and sterilization processes, retaining 70%–80% of the carotenoids. Surh et al. (2017) investigated factors that intervene in lutein-loaded nanoemulsion formation, such as oil type, surfactant type, and surfactant concentration. Researchers

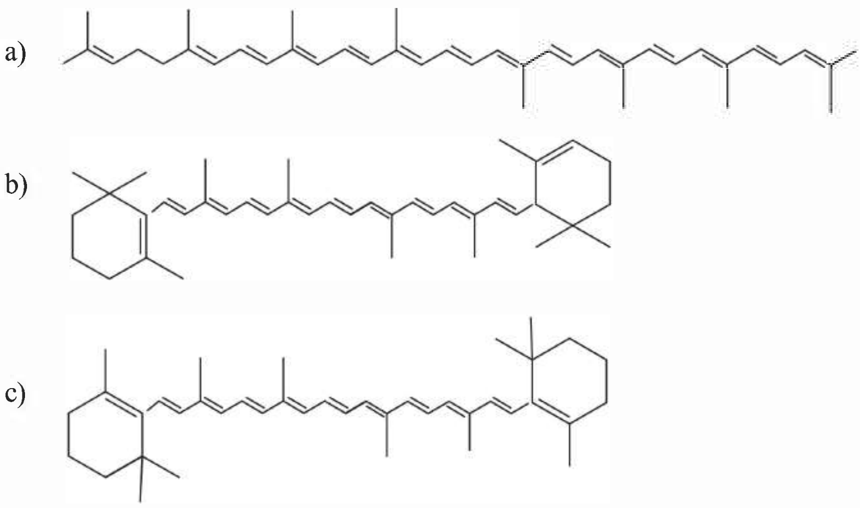


FIG. 4 Chemical structures: (A) lycopene; (B) α-carotene, and (C) β-carotene.

discovered that using medium-chain triglycerides as the oily phase instead of long-chain triglycerides resulted in the smallest droplet sizes (<200nm) (0.12 wt% lutein and 9.88wt% medium-chain triglycerides). Additionally, 10wt% of Tween 80 (as a surfactant) was enough to avoid droplet aggregation (in storage) for 1 month. In addition to antioxidants, other naturally extracted compounds can be used in nanoemulsion manufacture. These are waxes and are a complex mixture of esters, alcohols, aliphatic acids, hydrocarbons, and triterpene diols. They can be used in several applications, but mainly as films and coatings for food preservation. However, the physicochemical characteristics of waxes could be modified by changing their particle size (nanometric scale), thus expanding their applications (Silva et al., 2017). Some of the most outstanding plant-based waxes are candelilla wax, carnauba wax, rice bran wax, sunflower wax, etc. Furthermore, some of these natural waxes have been approved by the FDA as GRAS compounds (Lan, 2019).

Recently, Sislioglu et al. (2021) reported the use of candelilla wax nanoemulsions as a precursor for nanostructured lipid carriers for bioactive release in the human gut. The oil phase, composed of various ratios of candelilla wax dispersed in corn oil (from 1% to 60%), and the aqueous phase, composed of 2% Tween 80 in distilled water, were mixed using sonication (5 min at 500 W, 60% amplitude, 20 kHz). In terms of the effect of oil phase compositions on the particle size of obtained nanostructured systems, it was discovered that smaller particles were obtained when the oil phase was pure candelilla wax (150nm). There was also a direct relationship between wax levels used and particle size, that is, when candelilla wax levels increased from 1%–20% to 40%–60%, the particle size range increased from 160–172nm to 179–201 nm. Carnauba wax nanoemulsions have currently been developed and the effect of surfactant concentration on particle size has been determined (Silva et al., 2017). The oil phase was composed of 5% carnauba wax and the aqueous phase was a mixture of water and surfactants (Tween 80 and soy lecithin). Both phases were homogenized by sonication (400 W) to form nanoemulsions. It was found that an increase in surfactant concentration favored smaller droplet formation (around 69nm).

4. Encapsulation and delivery of nutraceuticals

Nowadays, there is a growing interest in isolating and characterizing natural and edible bioactive compounds that offer a benefit to human health (Cicero and Colletti, 2016; Smeriglio et al., 2016; Bjørklund and Chirumbolo, 2017; Granato et al., 2017; Araiza-Calahorra et al., 2018). Dueto the increasing prevalence of lifestyle-related diseases, nutraceuticals are gaining importance globally. The largest nutraceutical market is in Europe, followed by the Asian market, which is growing rapidly (Reque and Brandelli, 2021).

Nutraceuticals are food-derived bioactive molecules that improve human health, and they include ω-3 polyunsaturated fatty acids, linoleic acid, phytosterols, probiotics, carotenoids, and polyphenols (McClements et al., 2009; Abuajah et al., 2015). However, the concept of nutraceuticals is not yet well established, as it is not yet defined whether they belong to food products, supplements, or pharmaceuticals. Some authors consider nutraceuticals as part of dietary supplements. Other authors report that nutraceuticals differ from dietary supplements in showing clinical evidence (Santini et al., 2018).

Nutraceuticals are used to combat chronic diseases associated with aging, such as cardiovascular diseases (CVDs), diabetes mellitus type II, cancers, and neurodegenerative diseases (Chung et al., 2009; Grivennikov et al., 2010). Phytochemical nutraceuticals have antiinflammatory properties that delay aging and maintain health against acute and chronic diseases, thereby promoting longevity and quality of life (Hu et al., 2012). The low solubility, chemical stability, and bioavailability of some nutraceuticals limit their effectiveness (Velikov and Pelan, 2008; McClements et al., 2009; (Huang et al., 2010); Chen and Hu, 2020). Nanoparticles (Reque and Brandelli, 2021), nanoemulsions, encapsulation by electrospinning (Zare et al., 2021), nanoliposomes, and tocosomes as multifunctional nanocarriers (Zarrabi et al., 2020) have all been explored as technologies for the encapsulation of nutraceuticals.

4.1 Encapsulation of nutraceuticals with nanoparticles

Reque and Brandelli (2021) have widely used nanoparticles based on biopolymers such as proteins and polysaccharides to encapsulate nutraceuticals, increasing their biological effectiveness and improving their stability (Reque and Brandelli, 2021). Protein desolvation or carbohydrate precipitation, complexation of two differently surface-charged biopolymers, nanogels of biopolymers, and nanotubes or nanofibrils of whey proteins can all be used to create nanoparticles (Brandelli et al., 2017). Plant-derived nutraceuticals (resveratrol, quercetin, curcumin, genistein, and epigallocatechin gallate) encapsulated in nanoparticles show better solubility, absorption, bioavailability, and anticancer potential compared to nonencapsulated nutraceuticals (Illahi et al., 2019). To date, few studies prove the efficacy of nanoparticles in real food systems (Lopes and Brandelli, 2018). For example, the encapsulation of folic acid with silica particles can be successfully applied in commercial citrus juices, such as apple or orange juices (Ruiz-Rico et al., 2017).

4.2 Encapsulation of nutraceuticals with nanoemulsions

Nanoemulsions are transparent systems formed by two immiscible liquids (oil and water) stabilized by a surfactant, and they are composed of 10–100nm nanodroplets (Shah et al., 2010; Rao and McClements, 2011). Nanoemulsions can enhance the transport of nutraceutical ingredients through biological membranes, thus intensifying their bioavailability and effectiveness (Acosta, 2009; Donsì et al., 2011). In recent years, nanoemulsions have been mainly realized for the encapsulation and release of lipophilic nutraceuticals (Öztürk, 2017) such as carotenoids, xanthophylls, curcumin, resveratrol, and coenzyme Q10 (Choi and McClements, 2020). The encapsulation of carotenoids with nanoemulsions has been widely investigated (Dos Santos et al., 2018), mainly in the optimization of processes for the elaboration of beta carotene nanoemulsions with high-energy methods. For example, the formation, composition, stability, properties, type of emulsifier, type and conditions of homogenization, and concentration of beta carotene in the system have been studied (Jo and Kwon 2014; Mao et al., 2010). Also studied are the conditions for the elaboration of stable beta carotene nanoemulsions with quillaja saponins and whey protein as emulsifiers by microfluidization (Luo et al., 2017). Additional studies have been done on the effect of time and cutting speed on the preparation of beta-carotene nanoemulsions using the high-energy emulsification-evaporation technique (Silva et al., 2011), and the optimization of the conditions for the encapsulation of lycopene by nanoemulsions by homogenization-evaporation (Kim et al., 2014). Some studies have shown that the types of oils used to prepare beta-carotene nanoemulsions do not significantly influence particle size. However, they do affect bioaccessibility. Therefore, long-chain triglycerides are better (Qian et al., 2012; Rao et al., 2013; Yi et al., 2015; Zhang et al., 2016). Currently, few studies on the encapsulation of xanthophylls by nanoemulsions have focused on evaluating the bioaccessibility and bioavailability of xanthophylls (astaxanthin and fucoxanthin) with long-chain triglycerides in a simulated gastrointestinal system (Liu et al., 2018). Regarding the encapsulation of curcumin by nanoemulsions, the effect of the triglyceride oil phase on the bioaccessibility of nanoemulsified curcumin using high pressures has been studied. It was found that long-chain fatty acids promote greater bioaccessibility dueto the generation of small droplets in the system (Ahmed et al., 2012). There was also a study on the bioavailability of nanoemulsified curcumin by sonication using triglycerides and whey protein or Tween 80, which was resistant to digestion but slowly released in the intestine (Sari et al., 2015). In a comparison study of nanoemulsified curcumin and nanoparticulated curcumin, it was determined that the nanoparticulated curcumin prevented degradation dueto environmental stress, and the nanoemulsified curcumin was more effective at increasing shelf life during storage (Chuacharoen and Sabliov, 2019). The use of sodium caseinate in curcumin nanoemulsions has also been reported to have a protective effect against pH, temperature, and ionic strength (Kumar et al., 2016). In this sense, the use of chitosan increases the stability of nanoemulsified curcumin, protecting it from temperature and UV rays (Li et al., 2016). The effect of the proportional amount of oil, emulsifier, and water on the droplet size of curcumin nanoemulsified with black pepper oil by spontaneous emulsification has been studied to improve its dispersion in water (Moghaddasi et al., 2018). The combination of curcumin encapsulation technologies has also been used. For example, nanoemulsions with curcumin have been prepared by spontaneous emulsification and then encapsulated in other polymeric matrices such as hydrogel beads (Zeeb et al., 2015). Another interesting study is the development of multilayer nanoemulsions using a cationic polymer and an anionic polymer to encapsulate curcumin nanoemulsion drops (Abbas et al., 2015). Lately, nanoemulsions are being used to study the encapsulation and release of turmeric extract (Park et al., 2019). Studies to encapsulate resveratrol through nanoemulsions have focused on investigating the effects of emulsifiers (lecithin, sucrose palmitate, Tween 80, and glycerol monooleate) on the formation, stability, effectiveness, and bioavailability of nanoemulsified resveratrol by sonication with homogenization and high pressures, compared to nonnanoemulsified resveratrol (Sessa et al., 2011; Kumar et al., 2017). Nanoemulsions loaded with resveratrol-rich red grape pomace extract have been shown to inhibit lipid oxidation in hazelnut pastes (Spigno et al., 2013). The effect of droplet size on the stability of nanoemulsified resveratrol has also been evaluated using high- and low-energy methods (Davidov-Pardo and McClements, 2015). It is worth mentioning that liquid and solid nanoemulsions loaded with resveratrol obtained with low-energy methods have managed to increase oral bioavailability and intestinal permeability (Mamadou et al., 2017). In recent years, studies have been conducted on the encapsulation, release, and bioavailability of coenzyme Q10 using different biopolymers, emulsifiers, and high-energy methods. For example, oral bioavailability has been evaluated in rats using nanoemulsified coenzyme Q10 at high pressures and stabilized with polyethylene glycol, castor oil, stearic acid esters, and sucrose palmitate, which had a positive effect compared to the nonnanoemulsified coenzyme Q10 (Zhou et al., 2014). Another study indicates that coenzyme Q10-loaded nanoemulsions made from olive oil and Tween 20 exhibit good physical stability and a high degree of encapsulation (Katsouli and Tzia, 2019). It has also been shown that nanoemulsions loaded with coenzyme Q10 prepared with digestible oils present greater oral bioavailability compared to the use of indigestible oils (Cho et al., 2014).

4.3 Encapsulation of nutraceuticals by electrospinning

In the electrospinning technique, the active compound and the carrier polymer are dissolved to forma homogenous spinning solution, where the solution is extruded through the charged spinneret and with sufficient applied voltage, the meniscus deforms into a conical shape. In this, a polymer jet is emitted, which then stretches and reduces in diameter, and the solvent present in the polymer solution evaporates, producing a fibrous solid (Zare et al., 2021). Probiotics are living microorganisms that confer health benefits to the host (Plaza-Diaz et al., 2019), improving the integrity of the intestinal epithelium, regulating the immune system in the gastrointestinal tract, protecting the intestinal barrier, and also inhibiting the growth of pathogenic bacteria (Ait-Belgnaoui et al., 2012; Bajaj et al., 2015). Electrospinning blend technology has been employed to encapsulate probiotics to improve the gastrointestinal system, including *E. coli* K12 MG1655 (Diep and Schiffman, 2021), *Lactobacillus paracasei* KS-199 (Yilmaz et al., 2020), *Bifidobacterium animalis* Bb12 (López-Rubio et al., 2009), *Enterococcus faecium* HKLHS (Heunis et al., 2010), and *Lactobacillus acidophilus* FTDC 8933 (Fung et al., 2011). This promotes improved thermal stability, storage viability, and biocompatibility. This technology has also been used to encapsulate probiotics with other properties, such as *Lactobacillus plantarum* ATCC 8014 toreestablish the balance of the microbiota in the vagina (Škrlec et al., 2019), *Staphylococcus epidermidis* BH1 as a preventive treatment for diabetic foot (Kurecic et al., 2018), *Bacillus* sp. 25.2.M to combat periodontal disease (Zupančič et al., 2018) and *L. acidophilus* to combat bacterial vaginosis (Nagy et al., 2014).

4.4 Encapsulation of nutraceuticals with nanoliposomes and tocosomes

Nanoliposomes consist of a phospholipid bilayer, where the hydrophilic material is encapsulated in an aqueous central core (Khorasani et al., 2018). Tocosomes are carrier and bioactive matrices formed mainly by alpha-tocopherols (Mozafari et al., 2017), in addition to having sterols, proteins, and polymers in their structure (Gianello et al., 2005). The process of making elaborate nanoliposomes and tocosomes consists of placing the oil phase in an aqueous medium and supplying enough energy to establish the thermodynamic equilibrium in the system (Zarrabi et al., 2020). There are two types of processes currently in use: high-energy and low-energy methods. High-energy methods employ high-pressure homogenization, sonication, and microfluidization, and low-energy methods include the Mozafari method and solvent diffusion (Wang et al., 2017). Nanoliposomes have been applied in the food industry mainly to encapsulate flavoring, nutritional, and antimicrobial substances. Currently, some studies indicate the use of tocosomes and nanoliposomes as potential carriers to encapsulate and supply nutraceuticals in food systems (Reque and Brandelli, 2021). It is worth highlighting the use of encapsulated bacterial or fungal proteinases (Kheadr et al., 2020) to reduce the cost and maturation time of cheese (Mozafari et al., 2008) as well as the use of encapsulated flavourzyme produced by *Aspergillus oryzae* for protein hydrolysis (Merz et al., 2015). The use of nanoliposomes to encapsulate nisin and bacteriocin produced by *Bacillus P34* improves the antibacterial activity against *Listeria monocytogenes* in fresh cheese (Da Silva Malheiros et al., 2012). The encapsulation of nisin and garlic extract with nanoliposomes increases the antibacterial activity against pathogenic bacteria such as *E. coli, L. monocytogenes,* and *S. aureus*, especially in Gram-positive bacteria (Pinilla and Brandelli, 2016). Nanoliposomes formulated with soy lecithin have been shown to improve the stability and bactericidal activity of clove oil against *S. aureus* (Cui et al., 2015, 2016). The encapsulation of flavors and aromas through nanoliposomes and tocosomes allows the flavors and aromas soluble in the oily phase to be suspended in the aqueous medium. This alternative has great potential for its application in foods that do not use microwaves and are low in fat (Kaddah et al., 2018). In addition, the fortification of cheese with encapsulated vitamin D is used to benefit cartilage and bone tissue function (Mohammadi et al., 2015). Also, the coencapsulation of vitamin C in the aqueous phase and vitamin E in the oil phase is presented asan alternative to encapsulating two vitamins in an encapsulated food system (Khorasani et al., 2018). The encapsulation of lipophilic antioxidants by tocosomes is a very powerful antioxidant alternative (Mozafari et al., 2017) in addition to the encapsulation of vitamin C and vitamin E to avoid fat oxidation in mayonnaise, spreads, and margarines (Zarrabi et al., 2020). The encapsulation of iron (ferrous sulfate) and antioxidants, such as vitamin E or ascorbic acid, is a common practice to prevent the oxidation of ferrous ions (Xia and Xu, 2005) in dairy products, and thus avoid anemia byproduct consumption (Simiqueli et al., 2019). Another mineral used in dairy is encapsulated magnesium, which is essential to prevent diabetes, hypertension, and cardiovascular disease (Gharibzahedi and Jafari, 2017). The encapsulation and synergistic release of tocopherol and ascorbic acid, or tocopherol and glutathione through nanoliposomes and tocosomes, increases antioxidant activity and stabilizes minerals in beverages (Zarrabi et al., 2020). In addition, the incorporation of polyunsaturated fatty acids encapsulated in nanoliposomes and tocosomes improves antioxidant stability and shelf life in bread and milk (Rasti et al., 2012).

4.5 Encapsulation of nutraceuticals with candelilla wax nanosystems

The encapsulation of nutraceuticals with candelilla wax nanosystems has been little investigated. Recently, the formulation of a nanoemulsion based on candelilla wax, distilled water, gum Arabic, glycerol, Tween 80, and jojoba oil, with the addition of a crude extract of tarbush *Flourensia cernua* as a nutraceutical, has been studied. The nanoemulsion was made using high-shear hot agitation and managed to increase the nutritional quality of apples at both the laboratory and industrial levels (De León-Zapata et al., 2017, 2018). Also, the formulation of a candelilla wax nanoemulsion, distilled water, corn oil, and Tween 80 as a precursor for nanostructured lipid carriers for bioactive release in the human gut using a sonication technique has been reported (Sislioglu et al., 2021).

4.6 Encapsulation of nutraceuticals with candelilla wax microemulsions

Microemulsions are thermodynamically stable systems of water, oil, and surfactant that are transparent or slightly opalescent where microdroplets with a size of 100nm are formed (Hu et al., 2012; McClements, 2012; Rai and Pandey, 2014). They promote Brownian movements in the system avoiding flocculation and sedimentation (Zhu et al., 2015). The main advantages of microemulsions are: (1) simple formulation (shaking or mixing); (2) long service life; and (3) optically opalescent and transparent. The main disadvantages are: (1) formulation with synthetic surfactants; and (2) the surfactant micelle has a relatively low loading capacity for many polyphenols (Haham et al., 2012).

The most relevant works related to the use of candelilla wax to produce encapsulating emulsions of nutraceuticals are mainly focused on the preparation of candelilla wax microemulsions prepared by hot homogenization emulsification to encapsulate bioactive compounds, which have been used as edible coatings to increase the shelf life of fruits and vegetables. For example, microemulsions have been prepared with candelilla wax, distilled water, gum Arabic, and jojoba oil to encapsulate *Aloe vera*, gallic acid, and ellagic acid to improve the antioxidant potential and nutritional quality of fresh-cut apples (Saucedo-Pompa et al., 2007). These formulations have been applied in avocado and apple to increase nutritional quality and reduce damage caused by *Colletotrichum gloeosporioides* (Saucedo-Pompa et al., 2009), *Fusarium oxysporum*, and *Penicillium expansum* (Ochoa et al., 2011). The encapsulation of a fermented extract of polyphenols from tarbush *Fourensia cernua* (De León-Zapata et al., 2015) and purified polyphenols from Creosote bush *Larrea tridentata* (Aguirre-Joya et al., 2017) using the above-mentioned microemulsions has also been studied to improve the quality of the avocado and apple.

5. Organoleptic and sensory determinants of candelilla wax nanoemulsions and bioavailability in human body

In the food industry, the consumer's needs are the most important premise; all the developments or formulations are made to address those needs. For the nanoemulsions of additives for the food industry, such as antioxidants, colors, flavors, emulsifiers, preservatives, and stabilizers, a new approach is in vogue to improve the food products' attributes such as flavor preservation and technological functions while also enhancing their texture or appearance (Tomaska and Brooke-Taylor, 2014). For that reason, the nanoemulsions of food additives are known as organoleptic or sensory determinants. In the previous lines, we talked about antioxidants and colors with polyphenols and carotenoids. The flavor, aroma, emulsifiers, and stabilizers are the next items of content, followed by the interactions of the food additive nanoemulsions inside the human body.

5.1 Flavor and aroma

Flavors are a principal group of organoleptic/sensory determinants because the consumer has a food product memory based on food flavor and/or aroma. Nanoemulsions of food flavors are functional and efficient nanocarriers dueto their stability, bioavailability, and clarity, and the structure–function relationships are usually applied to determine and optimize formulations (Estevinho and Rocha, 2017). In nature, the essential oils obtained from plants, fruits, and vegetables are the main sources of flavor and aroma compounds. These compounds require low concentrations and/or quantities to provide multiple effects, such as antioxidant and antimicrobial, that impact the shelf life, but they can also be used as flavoring and aroma in nanoemulsions, andas a consequence in the applied food matrix. The essential oils of peppermint (Liang et al., 2012), lemon (Rao and McClements, 2011), lemongrass, clove, tea tree, thyme, geranium, marjoram, palmarosa, rosewood, sage (Salvia-Trujillo et al., 2015), oregano, thyme, and mandarin, among others (Guerra-Rosas et al., 2016), are examples of nanoemulsion ingredients as food additives. Besides the multiple applications, there are some limitations to essential oil use. Low water solubility, high volatility, and strong odor are the main properties that prevent the application of essential oils (Fernández-López and Viuda-Martos, 2018). Terpenes, polyphenols, alcohol, or aldehydes can also provide flavor and aroma; several reports on their use in nanoemulsions for food applications can be found (Gupta et al., 2016; Doi et al., 2019; Saifullah et al., 2019; Khan et al., 2020). However, their physicochemical behavior has received less attention than essential oils.

5.2 Emulsifiers and stabilizers

Thickening or gelling agents, typically polysaccharides, can be used in nanoemulsions to adjust textural properties, alter the feel in the mouth, and/or improve physical stability (Zhang et al., 2020). These properties are in vogue because some experiments demonstrate that the presence of hydrocolloids protects the bioactive agents from chemical degradation within foods and beverages during storage but increases their bioavailability after consumption. Furthermore, it can be used to target the delivery ofbioactive agents to specific sites in the gastrointestinal tractor to modulate their release profiles (McClements, 2021). As a result, the digestive process can be controlled or altered (McClements, 2021), and prebiotics can be used to modify the gut microbiota (Chassaing et al., 2017). Besides hydrocolloids, proteins or peptides are also used as thickening or gelling agents (Xiong et al., 2020); this activity can be attributed to the amphiphilic nature and film-forming abilities of the oil/water interface (Jarzębski et al., 2019). Protein/peptide use is dependent on the food matrix because the final cost of production/fabrication increases, so the hydrocolloids allow cheaper processes. Also, phospholipids and monoglycerides can be used as emulsifiers in nanoemulsions dueto their biphasic behavior (Rahemm et al., 2021). Although lecithin is commonly used asan emulsifying agent (Abu-Ali et al., 2021; Castro-Vázquez et al., 2021; Lin et al., 2021; Vernazza et al., 2021), other authors describe the use of rhamnolipids and synthetic agents (Tween 80) (Gonçalves et al., 2021). Although synthetic compounds are nanoemulsion ingredients that differ from other natural molecules or compounds previously mentioned, they exhibit an additional effect on consumer health. Because the surface activity is quickly absorbed onto the oil–water interface, emulsifiers also act as stabilizers; this reduces interfacial tension and generates repulsive interactions between the oil droplets, allowing for improved stability during storage (Li et al., 2021). According to the molecule, the emulsifier/stability activity can be a nanoemulsion with *candelilla wax*. Different molecules can provide this characteristic for nanoemulsion stability. Among them are phospholipids, glycolipids, and saponins (Liu et al., 2019) as well as the proteins and polysaccharides previously mentioned.

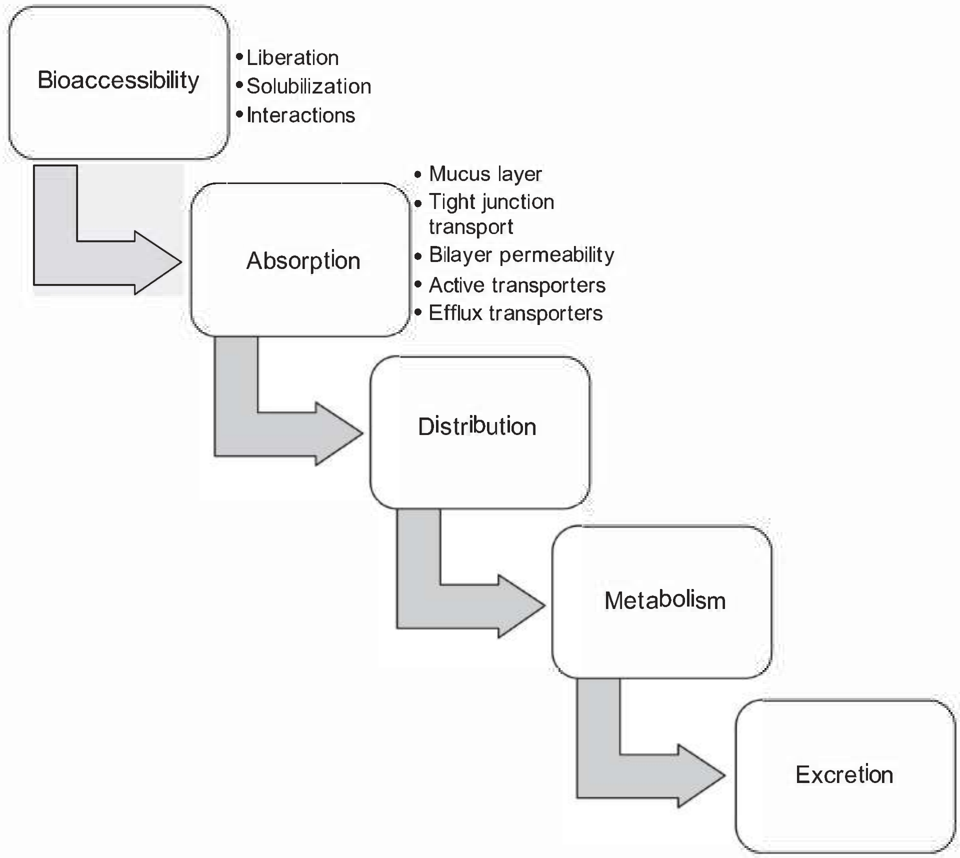


FIG. 5 Bioavailability and possible mechanisms limiting it through nanoemulsions in the human body.

5.3 Bioavailability in human body

Due to the increasing bioavailability compared with emulsions or microemulsions, nanoemulsion bioavailability is an important subject to understand how these mixtures can contribute to human health and wellness. To deliver the active principle of the nanoemulsions into the blood and probe the benefits, it is necessary to complete the digestion process that comprises bioaccessibility, absorption, distribution, metabolism, and excretion. Also, we need to consider the possible mechanisms that limit bioavailability such as liberation, solubility, interactions, bilayer permeability, tight junction transport, active transport, efflux transport, chemical modifications, or metabolism (Fig. 5) (McClements et al., 2015).

Normally, after oral ingestion, the saliva and its enzymes begin the chemical active digestion in the mouth, but with nanoemulsions, this step is not completed because normally it goes through the esophagus into the stomach. Here, powerful enzymes and acids release the principal molecules from the food that moves into the small intestine. At this point, other organs, such as the pancreas and liver, release more enzymes and bile to break down the molecules, and the mucosal layer moves across the gut layer between the epithelium layer and the lymphatic system. Subsequently, anything left in the small intestine moves into the large intestine to residues fermentation and/or synthesis of some vitamins (e.g., Vitamins B and K). Finally the solid waste (faecal material) and liquid waste (urine) are expulsed a few hours later. And the residues or toxic molecules reach the kidney dueto the blood (Sotomayor-Gerding et al., 2016). Although nanoemulsions of food nutraceuticals or additives improve the bioavailability at targeted sites inside the human body and meet pharmacopeia requirements for drug delivery (sterility, isotonicity, nonpyrogenic compounds, nontoxic compounds, biodegradability, and stability) (Abu-Ali et al., 2021), some prejudicial cases must be considered when the nanoemulsions are formulated and/or administered. McClements (2021) reports four situations that concern potential toxicity: (1) greater penetration through biological barriers dueto the droplet size. Digestion is not done at the correct site; otherwise the digestive tract reaches the small or large intestine with the incorrect molecules or the indigestible food matrices are released into the small intestine before being fully digested; (2) increased bioavailability to a toxic level, mainly the compounds that offer an adverse effect in higher quantities (e.g., vitamins, pesticides, or colorants) and mostly hydrophobic compounds; (3) dysregulation of the metabolism or hormonal system. This condition is attributed to lipid digestion time. Nanoemulsions are digested faster than bulk oils or conventional emulsions, causing a spike in blood lipids or other symptoms; and (4) increased toxicity as a result of the ingredients used. Some molecules used as stabilizers for nanoemulsions can alter the gut microbiome or permeability. For that reason, the recommendation is for proteins, phospholipids, or food-grade emulsifiers. Although studies have been conducted for approval and disapproval, the candelilla wax nanoemulsions used as a delivery vehicle for drugs, food additives, antioxidants, and vitamins, among others, are not completely elucidated. More scientific studies are needed on the nanoemulsion effects to define the health and wellness impact. Otherwise, scientific advances in nanoemulsion formulation, fabrication, application, and human metabolism create a milestone in the new trends in human wellness and nutrition with a molecular basis, using plant extracts or plant resources such as candelilla wax as the main compounds of nutraceuticals or food additives.

6. Conclusions

Nanoemulsions have become an outstanding option for several applications in different areas, such as pharmaceutics, cosmetics, food, and agriculture. They can be useful in solving several problems, such as packaging, flavors, pigments, nutraceuticals, antioxidants, shelf life, protection against the growth of spoilage microorganisms, food supplements, pesticide formulations, and more. Nanoemulsions do not form spontaneously, so it is necessary to apply external energy in the formation process. Nanoemulsions are mainly formulated using low-energy methods. High-energy methods produce more stable nanoemulsions but are more expensive than low-energy methods. Scientific advances in nanoemulsion formulation, fabrication, application, and human metabolism have created a milestone in new trends in human wellness and nutrition with a molecular basis, using plant extracts or plant resources such as candelilla wax. Although few studies are focused on the nanoencapsulation of nutraceuticals using candelilla wax-based nanosystems such as nanoemulsions, there is great potential for their use in the elaboration and study of different nanostructures such as nanoparticles, nanoliposomes, tocosomes, and by the technique of electrospinning, among others. As shown in this chapter, a variety of lipophilic nutraceuticals can be encapsulated within nanoemulsions, and this can increase their water dispersibility, stability, and bioavailability. Additionally, these nanodelivery systems can be derived from natural and inexpensive sources, making them suitable for large-scale industrial applications. Moreover, it is necessary to prepare nanosystems without the use of toxic solvents by economic and scalable techniques for the pharmaceutical and food sectors. The nanoemulsions have to be carefully formulated. Despite the advantages, the main challenges they face are their low physical stability, their relatively high sensitivity to temperature and pH variations, and the inopportune release of hydrophilic bioactive compounds under long-term storage conditions. The lipid phase composition, interfacial properties, and particle size have to be controlled through the nanoemulsion composition and homogenization conditions. The current and future perspectives of candelilla wax nanosystems are very promising because they present great advantages in encapsulating, protecting, and delivering nutraceuticals efficiently.

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Bio-Based Nanoemulsions for Agri-Food Applications

Edited by Kamel A. Abd-Elsalam and Kasi Murugan

Provides information on how nanoemulsions are used in the agri-food sector

A volume in the Nanobiotechnology for Plant Protection series

Recent agricultural, food, and pharmaceutical research focuses attention on the development of delivery systems that can encapsulate, protect, and deliver natural compounds. Nanoemulsions are recognized as the best delivery systems for natural-origin nutraceuticals and phytochemicals and have many agri-food applications.

Bio-Based Nanoemulsions for Agri-Food Applications provides information on food-grade nanoemulsions and their applications in agriculture and the food industry. This book covers concepts, techniques, current advances, and challenges in the formulation and application of emerging food-grade nanoemulsions. Particular attention is paid to food-grade nanoemulsion production methods and components used, such as plant/microbial products, biosurfactants, cosurfactants, emulsifiers, ligand targets, and bioactive/functional ingredients. This is an important reference source for materials scientists, engineers, and food scientists who are looking to understand how nanoemulsions are being used in the agri-food sector.

Key Features

- Provides an overview of a range of bio-based nanoemulsions used in the agri-food sector
- Explores how nanotechnology improves the properties of bio-based emulsions
- Assesses the major challenges of manufacturing nanoemulsions at an industrial scale

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