Ultrasonically-prepared biopolymeric multifunctional nanocarriers for encapsulating dietary oils: Recent developments and food applications

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Abstract

Dietary oils (DOs) from various sources are known to be beneficial functional bioactives in medicinal applications. However, DOs are highly susceptible to light, temperature, and oxygen, rendering them chemically unstable and prone to oxidation. As a result, their use in the food and pharmaceutical sectors is constrained. Nanoencapsulation techniques are widely regarded as highly promising tactics for augmenting the inherent properties and therapeutic impacts of DOs. This article is focused on the utilization of ultrasonically produced biopolymeric nanocarriers (UPNs), along with their advantages and disadvantages, which have demonstrated promising potential for encapsulating various DOs. Furthermore, a full discussion has been carried out on the advanced loading techniques of various DOs using UPNs, particularly protein/polysaccharide-coated nanoemulsions and nanoparticles. These nano-vehicles are considered promising candidates for protecting DOs due to their remarkable features and their capability to enable accurate and efficient delivery to targeted sites. The

gastrointestinal fate of protein/polysaccharide-coated nanocarriers is mostly determined by their size, surface characteristics, and physical attributes. UPNs provide a range of desirable properties inherent to biopolymeric nanoparticles, enabling them to provide stability and effective dispersion of DOs in functional food products. Additional research is extremely needed to explore novel possibilities for utilizing DOs-loaded UPNs in the realm of food and beverage applications, with the prospect of eventual commercial viability.

Keywords: Functional oils; Ultrasonication; Biopolymers; Essential oils; Nanoencapsulation; Gastrointestinal fate

1. Introduction

Dietary oils (DOs) are acknowledged as an important part of the human diet because they contain essential fatty acids (FAs) and fat-soluble vitamins, as well as the capacity to improve food palatability. DOs, including seed, essential, and marine oils, together with their bioactives, have garnered the interest of numerous industries such as food, cosmetics, agriculture, and pharmaceuticals (Rehman, Jafari, Tong, Karim, et al., 2020a; Wang et al., 2024). These products are valued for being both natural and safe, making them widely accepted by consumers. Approximately 90% of edible oil is derived from vegetable seeds. The composition of seed oils (SOs) offers detailed information about the oil's melting point and the total energy content of the seeds. The observed trend in the melting point of SOs is attributed to the progressive degradation of FAs (Piravi-vanak et al., 2022). According to the consumption rate of SOs, soybean oil ranked first, followed by palm and rapeseed oils, respectively. Essential oils (EOs) are vaporous liquids composed of complex combinations derived from different organs of plants and have garnered significant popularity due to their therapeutic effects (Rehman, Tong, Korma, et al., 2021). Most of the essential oil compounds are effective in preventing diseases, making them highly valued by the food sector as natural preservatives and flavoring agents. Marine oils (MOs) are predominantly obtained from slender fish species such as cod, as well as small, cold-water fish species (e.g., capelin, sardine, and mackerel). MOs have become significantly more in demand due to the fact that their constituents contain the highest concentrations of ω-3 polyunsaturated FAs (PUFA), which are known to provide substantial health benefits (Popalia & Kumar, 2022; Shehzad et al., 2021).

DOs, as natural bioactives, have been utilized since ancient times and have demonstrated significant potential in the treatment of numerous life-threatening illnesses, including diabetes, cancer, cardiovascular diseases, and psychological disorders. In contrast to commonly utilized allopathic medicine, dietary supplements, and synthetic compounds, medicinal preparations derived from natural DOs contain numerous potent bioactives that may demonstrate a synergistic effect on combating various ailments **(Fig. 1)**, including anti-inflammatory, anti-cancer, anti-arrhythmic, antioxidant, antinociceptive, antihypertension, antidandruff, anti-aging, and antimicrobial effects

(Ganesan et al., 2018; Liu et al., 2019; Prakash et al., 2018). The remarkable capabilities of DOs have significantly captured the interest of scientific research groups. Utilization of DOs has the foremost limitations in the food industry, since they are chemically unstable, easily oxidized during storage, and poorly soluble in water.

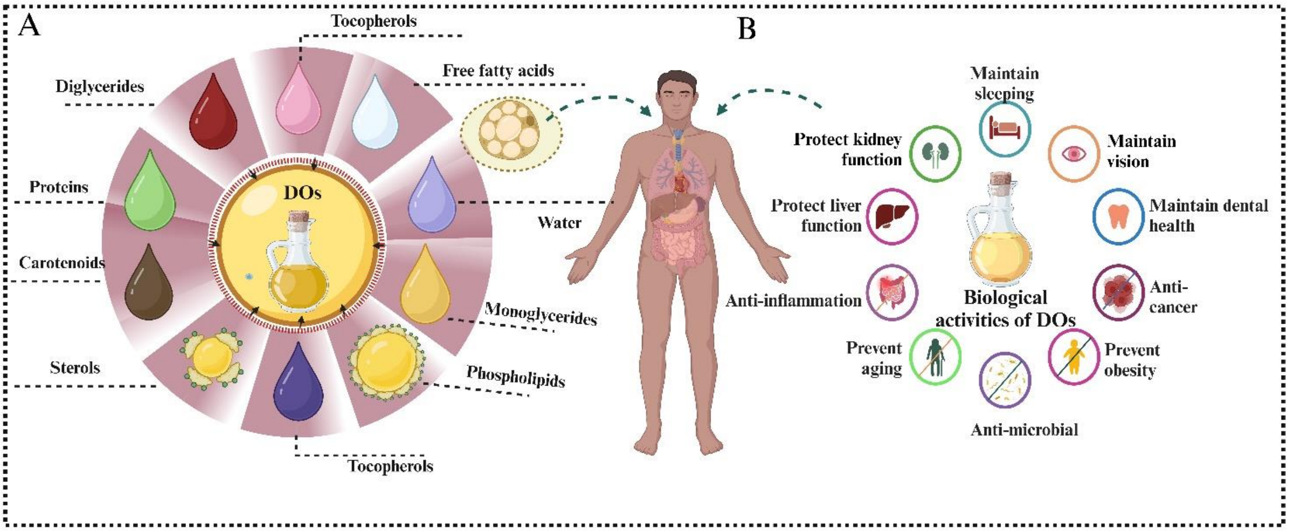

Fig. 1. General composition (A) and numerous biological activities (B) of dietary oils.

Additionally, they can cause deterioration in the food quality due to their unpleasant taste and odor (Rehman, Qunyi, et al., 2021). The aforementioned limitations could significantly impact the sensory characteristics, shelf life, and general desirability of the produced commodities. In order to develop enriched food products comprising SOs, EOs, and MOs, encapsulation technology is considered a versatile approach for protecting their physiochemical and biological properties (Rehman, Jafari, Tong, Karim, et al., 2020b; Sánchez-Juárez et al., 2019). Encapsulation is a fast-growing endeavor for the delivery of DOs based on coating or entrapping them inside a carrier to transport, protect, and control the releasing mechanism of DOs (Karim et al., 2022). The process of encapsulating DOs at the nanoscale is known as "nanoencapsulation," and it is a subject that is increasingly attracting the attention of researchers. Although several nanoencapsulated delivery systems, including nanoparticles (NPs), nano-liposomes and nanoemulsions (NEs), have been employed for the oral administration of DOs, their efficacy has been somewhat restricted (Rasheed et al., 2024). The efficacy of an oil delivery system and its integration into functional foods is dependent on a multitude of factors, including carrier stability, release mechanism, wall material, dispersion medium, mass transfer, carrier size, and fabrication technique (Bakry et al., 2016).

To date, a comprehensive review article has not been published to specifically examine all categories of ultrasonically-produced nanocarriers (UPNs) utilized for the encapsulation of DOs. For decades, ultrasonication (ULS) has gained more popularity and is being used for the fabrication of DOs-loaded nanocarriers because it can produce tiny-sized carriers at great energy efficiency and is relatively known for its low-cost approach. UPNs are fabricated using a ULS probe in batch or continuous systems (Rehman, Jafari, Tong, Karim, et al., 2020a). The batch ULS is mostly applicable in research labs. In this regard, an ultrasonic probe is immersed in a vessel containing both water and oil phases. High-intensity ultrasonic waves are then produced to create disturbance between the two phases, resulting in the production of small droplets. In contrast, the continuous method consists of a glass tube filled with pressurized water that is inserted within a steel jacket and vibrates the jacket using a piezoelectric transducer to transport the sonicated liquid. Owing to the efficient outcomes displayed by both systems (batch or continuous), ULS can improve the bioavailability and precise release of DOs on the target sites inside the body (Walia et al., 2017a). Particularly, nanocarriers having diameters < 100 nm offer a greater surface area, which may enhance the dissolution rate. It has been well proven in previous literature that UPNs, including nano-liposomes (NLPs), solid lipid nanoparticles (SLNs), nano-hydrogels, NEs, and nanostructured lipid carriers (NLCs), may provide more protection to DOs as well as smooth delivery to the targeted sites (Rehman, Jafari, Tong, Karim, et al., 2020b; Suganya & Anuradha, 2017; Valencia-Sullca et al., 2016).

The encapsulating materials for UPNs typically consist of proteins, carbohydrates, and lipids and must be classified as generally recognized as safe (GRAS). There are many benefits associated with biopolymeric (carbohydrates and proteins)-based nanocarriers (Pereira et al., 2020), because they are recognized as environmentally friendly and they can perform several nutritious and operational purposes inside the human body; therefore, they have extraordinary demands for the manufacturing of foodstuffs (Jafari et al., 2020; Rehman, Tong, Shehzad, et al., 2020). In fact, biomaterials could be used as encapsulants due to their physiochemical properties (i.e., plenteous, non-toxic, cheap, biodegradable, and biocompatible) and superior targeted and controlled release features, endowing them as powerful carriers (Rehman, Tong, et al., 2019). Conversely, there is a rising research focus on the enhanced production and use of lipid-based UPNs encompassing DOs. This is primarily due to their non-toxic nature, which allows for the complete protection of the functional properties of DOs. Similarly, these nanocarriers possess several advantages, including better solubility of DOs, easy production through natural ingredients, and targetability in the human body (Saravana et al., 2019b). In addition, the releasing rate of these nanocarriers can be easily identified through *in vivo* evaluations using either passive or active methods. Additionally, by contributing effective protection via ULS, these nanocarriers may improve the biostability and bioavailability of DOs during the processing of foods and medications. In this article, we have offered comprehensive insights into the following topics: (i) a concise overview of different DOs in terms of sources, classification, and their health-promoting effects; (ii) a summary of the ULS technique applied for the fabrication of DOs-loaded nanocarriers; (iii) a brief illustration of nanocarriers such as NEs, NLPs, nanohydrogels, and NPs; and (iv) the gastrointestinal fate (GF) of UPNs and their use in food products.

2. Sources of dietary oils; a brief overview

The demand for DOs has increased due to alterations in dietary behaviors followed by the transition from the hunting regime to agricultural practices. DOs are a wide array of natural bioactives mainly derived from three origins, i.e., plant seeds, phenolic-rich plants, and marine organisms. Table 1 offers a brief summary of different DOs, detailing their origins, diverse range of bioactive compounds, and potent therapeutic advantages, which are further discussed in the following sections.

2.1. Plant-derived dietary oils

Seeds are valuable sources of DOs that can be easily extracted and utilized in various applications, including perfumes and medical uses. The functions and biological activities of SOs depend on their fatty acid profile, leading to variations in their use in dietary, industrial, and pharmaceutical goods (Rehman, Tong, Jafari, et al., 2021). This alteration is due to various plant species and the conditions under which they are grown and harvested. Certain seeds, such as rapeseed, soybean, pomegranate seeds, grape seeds, and annatto seeds, are known for their use in producing vegetable oils (Davidov-Pardo & McClements, 2015; Goula et al., 2012; Sicaire et al., 2016). Significant fatty acids and bioactive compounds found in sunflower oils utilized in various products are palmitic acid, linoleic acid, vanillic acid, syringic acid, gallic acid, protocatechuic acid, p-coumaric acid, and ferulic acid. Grape seeds, a by-product of the wine industry, include health-promoting unsaturated oils and polyphenols such as condensed tannins and flavon-3-ols. Also, they consist of unsaturated fatty acids, the majority of which are essential fatty acids.

Table 1: Different dietary oil categories with their sources, major bioactive compounds and potent therapeutic actions.

Oil sources	Species	Sources of oil extraction	Major bioactive compounds	Significant biological actions	Reference
Tuna	*Euthynnus affinis*	Head and skin	DHA and EPA	Anti-cardiovascular, Anti-cancer,	(Garofalo et al., 2023)
Cod liver	*Gadus morhua*	Liver		Anti-tumor, anti-inflammatory, anti-cardiovascular	(Pycia et al., 2023)
Krill	Euphausia superba	krill meal		Cholesterol controlling	(Sun et al., 2023)
Salmon	*Atlantic salmon*	Viscera, heads and skins		Anti-obesity, anti-cardiovascular	(Liu et al., 2020)

Mackerel	*Chub mackerel*	Ground skin		Anti-dementia, anti-cardiovascular, anti-obesity	(Ahmmed et al., 2021)
Sardine	*Sardinella longiceps*	Fatty tissues of sardines		Anti-cardiovascular, anti-obesity	(Santos et al., 2023)
Cuttlefish	*Todarodes pacificus*	Viscera	EPA, DHA and peptides	Anti-microbial, anti-mutagenic, anti-cancer,	(Moovendhan et al., 2019)
Bonito	*Euthynnus pelamis*	Muscle and liver	EPA and DHA	Anti-cardiovascular, anti-dementia	(Guénard et al., 2019)
Sunflower oil	*Helianthus annuus*	Seeds	Oleic acid, stearic acid, linoleic acid	Anticancer, antioxidant, skin-protective, anti-inflammatory	(Romanić et al., 2021)
Flaxseed oil	*Linum usitatissimum*	Seeds	*α*-linolenic	Anti-inflammatory, anti-carcinogenic	(Zhu et al., 2020)
Olive oil	*Olea europaea*	Whole fruit	Oleic, linoleic and palmitic acid	Anti-cancer, anti-inflammatory	(Lu et al., 2023)
Soybean oil	*Glycine max*	Seeds	Linoleic, linolenic and oleic acids	Anti-microbial, anti-cancer	(Ferreira et al., 2022)
Mint EO	*Mentha Piperita*	Flowering parts and leaves	Geranial, Thymol, *α*-Terpineol, *β*-Cubebene, Camphor	Anti-cancer, anti-oxidant	(Rehman, Tong, Korma, et al., 2021)
Clove EO	*Eugenia aromatica and Eugenia caryophyllata*	Flower buds	Eugenol, Eugenyl acetate, 4-Allylanisole, *β* -Cadinene, α-Pinene	Anti-oxidant, anti-fungicidal, anti-carcinogenic	(Kaur et al., 2019)
Rose EO	*Rosa damascena*	Petals	Eugenol,Methyl eugenol, Phenyl alcohol, Rose oxide, Citronellyl acetate	Laxative, anti-microbial, anti-cancer and anti-oxidant	(Yi et al., 2019)
Basil EO	Ocimum Basilicum	Leaves	*β*-Limonene, Methyl-eugenol, *γ* –Terpinene, endo-5,5,6-Trimethyl-2-norbornanone	Larvical, anti-bacterial, anti-oxidant	(Sundararajan et al., 2018)

Cinnamon EO	Cinnamomum zeylanicum	Inner bark of the shoots	Cinnamyl alcohol, Benzenemethanol, Acetaldehyde, Benzaldehyde, Ethyl alcohol	Aesthetic, analgesic, antiulcerogenic, Antiallergic	(Xu et al., 2020)
Oregano EO	*Origanum vulgare*	Leaves	*β*-Caryophyllene, Sabinene, Thymol, *α*-Terpinene	Antimicrobial	(He et al., 2023)
Lavender EO	*Lavandula angustifolia*	Flower heads	Linalool, Cuminaldehyde, *α*-Terpinol 1, Lavandulol, Cuminaldehyde	Cytotoxic, antibiotic, anti-inflammatory, antiseptic	(Rashed et al., 2017)
Black cumin seed oil	*Nigella sativa*	Seeds	*α*-Pinene, Limonene, *β*-Caryophyllene, Thymol, Sabinene,	Anti-inflammatory, anti-microbial, anti-elastase, Anti-mutagenic, α-Pinene, Limonene, β-Caryophyllene, Thymol, Sabinene	(Rostaei et al., 2018)
Pomegranate EO	*Puncia granatum*	Fruit seeds	Stearic, punicic, oleic, palmitic and linolenic acid	Antiallergic, anti-inflammatory and Anti-oxidant,	(Kawhena et al., 2021)
Lemongrass EO	*Cymbopogon citratus*	Leaves	Geraniol, citronella, myrcene, borneol, citral, limonene, neryl acetate, and Z-caryophyllene	Antimicrobial, anticancer, antidiarrheal, antiseptic, insecticidal, analgesic, aesthetic, anti-inflammatory and antioxidant,	(Perdana et al., 2021)

Abbreviations: DHA, Docosahexaenoic acid; EPA, Eicosapentaenoic acid.

In this sense, grape seed oils are the richest source of natural antioxidant agents, including tocopherol and phytosterol; thereby, they have gained in popularity not only as pharmaceuticals and nutraceuticals but also as bioactives delivering beneficial effects on human health like antioxidants, anticarcinogens, antiobese, and cardioprotective effects (Piravi-vanak et al., 2022). Another supportive example of SOs is the oils extracted from annatto seeds, which hold bioactives like tocotrienols and geranylgeraniol diterpenes. Due to its anti-cancer and anti-inflammatory properties, annatto seed oil has the potential to be utilized in the pharmaceutical and culinary industries.

EOs, which are secondary metabolites obtained from aromatic plants and herbs, have attracted considerable interest in recent times because of their diverse biological characteristics (Al-Maqtari et al., 2021). EOs are a diverse mixture of different types of compounds, known for their ability to dissolve in fats. They are divided into various categories, such as carotenoids, alkaloids, phenolic acids, flavonoids, monoterpenes, isoflavones, and aldehydes. Additionally, EOs, which are volatile and aromatic, are derived primarily from plants belonging to particular botanical families, including *Asteraceae*, *Rutaceae*, *Myrtaceae*, *Lamiaceae*, and *Zingiberaceae* (El Asbahani et al., 2015). EOs are apparently extracted from a variety of plant organs, including but not limited to the buds (e.g., clove), leaves (e.g., thyme, eucalyptus, and salvia), fruits (e.g., anis and star anise), seeds (e.g., cardamom), bark (e.g., cinnamon), zest (e.g., citrus), wood (e.g., sandal), and roots (e.g., ginger). Dry distillation, steam distillation, and cold pressing are among the techniques employed to extract EOs from these organs (El Asbahani et al., 2015; Yang et al., 2023).

Interestingly, EOs have been widely utilized in nutraceutical and functional food products to capitalize on their broad spectrum of health benefits, including antimicrobial, antifungal, anticancer, anti-inflammatory, antiallergic, and antioxidant properties (Mutlu-Ingok et al., 2021; Tariq et al., 2019). For example, cinnamon essential oil is commonly utilized in traditional Chinese medicine. It has notable biological characteristics, including antibacterial, diabetic, and antioxidant effects. It is widely utilized in the food and beverage sector and for managing inflammatory illnesses, including arthritis and gastritis. In the food industry, clove EO (CEO) has long been recognized for its flavor and antimicrobial properties. The major compound of CEO is eugenol, which is a phenolic compound exhibiting superior antimicrobial and biological properties. It can denature proteins and inhibit both Gram-positive and Gram-negative bacteria. The food and pharmaceutical industries are currently utilizing CEO as a biodegradable antimicrobial agent (Shahavi et al., 2016). The pomegranate seed is a significant source of essential oils, yielding an average of 37-143 g/kg of fruit. The composition of pomegranate seed oil (PSO) consists of 65-80% conjugated fatty acids. The scientific literature provides ample evidence to support the assertion that PSO exhibits characteristics of lipoperoxidation, immune function, lipid metabolism, and antioxidant activity. PSO is of interest due to its pharmacological and nutraceutical properties, as well its significant annual production as a by-product of the juice extraction process (Cheng et al., 2023).

2.2. Marine animal-derived dietary oils

MOs are predominantly obtained from a wide variety of marine animals, which are accredited to be the richest and copious sources of PUFAs, including ω-3, ecosapentaenoic acid (EPA), and decosahexaenoic acid (DHA) (Du et al., 2022). The functionalities and bioactivities of MOs are influenced by their FAs profiles, leading to variations in food and pharmaceutical products. Various organism species, growing environments, and living conditions are all factors that are responsible for this variation. Primarily, various species such as microalgae, bacteria, sponges, plants, and macroalgae are known for producing MOs that are rich in EPA and DHA (Otero et al., 2021). One of the primary sources for extracting MOs includes fish, algae, and other seafood, particularly fatty fish like salmon, mackerel, herring, and menhaden, along with the blubber of whales, seals, and the liver of halibut. As an example, the blubber of seals contains significant levels of EPA (5.4–6.4%) and DHA (7.6–7.9%) (Pateiro et al., 2021). In the same vein, menhaden oil contains approximately 10.4–13.2% EPA and 10.1–11.5% DHA. Recently, krill oil was highlighted as an excellent source of PUFAs, with approximately 23.7–28.1% of EPA and 16.7–21.0% of DHA (Fuller et al., 2020). In several clinical investigations, it has been revealed that consumption of PUFAs obtained from MOs can reduce the risk of cancer, improve brain function, and prevent several disorders and diseases, including ulcerative colitis, immune response disorders, and Crohn's disease (Lu et al., 2019). But in many societies, the consumption of MOs is very limited due to the low availability of their sources (fish). However, incorporation of MOs-loaded carriers into foods seems to be an interesting approach for elevating the nutritional level of PUFAs intake (Linke et al., 2020).

3. Extraction of dietary oils (DOs)

The extraction process is crucial for achieving maximum efficiency and effectiveness in the manufacture of DOs, including both the quantity and quality aspects. Common methods employed to extract edible DOs include solvent extraction, soxhlet extraction, cold pressing, distillation, heat pressing, and maceration, among others. These processes typically involve lengthy extraction durations and lead to the deterioration of thermally sensitive bioactive compounds (Riaz et al., 2023). The researchers were motivated to explore innovative extraction methodologies due to the challenges encountered in this area. Recent studies have focused on investigating innovative ways for extracting techniques, including supercritical fluid extraction, as well as preliminary processing methods, including enzyme-assisted extraction, ultrasound-assisted extraction, microwave-assisted extraction, and pulsed electric field-assisted extraction (Nde & Foncha, 2020). During the initial stage of obtaining SOs, the seeds are acquired as a byproduct of the fruit juice manufacturing sector. Before the extraction process, the seeds go through several preparatory steps, which include cleaning, drying, and pulverization. It is crucial to use appropriate handling and protection methods for seeds and the extraction of oil to prevent the formation of mycotoxins and the occurrence of oxidative reactions that can cause deterioration (Kalinowska et al., 2022). The SOs products that are commonly found on the market are typically cold-expressed oils. As an example, Khoddami and colleagues conducted a study that revealed that cold-pressed oils possess a higher beneficial fatty acid composition. Furthermore, these oils had favorable physicochemical characteristics, such as a minimum peroxide value, maximum phenolic content, and an exceptional fragrance profile (Khoddami et al., 2014). These findings are consistent with prior studies undertaken on the subject. Nevertheless, it is crucial to acknowledge that cold-pressed oil often has a lower yield and may pose challenges in ensuring consistent product standards (Çakaloğlu et al., 2018).

The soxhlet extraction method is commonly utilized globally in research labs for extracting DOs. Extraction purposes typically involve the use of organic and nonpolar solvents. The most commonly employed method for obtaining DOs is extraction using hexane as a solvent (Chemat et al., 2019). According to a study conducted in 2018, it was found that extracting pomegranate seed oil using hexane at a temperature of 28–30 °C for a period of 8 hours resulted in a yield of 39%. In contrast, previous studies have indicated that the oil yield attained by utilizing hexane as the solvent falls within the range of 20–28% (Aruna et al., 2018). In the latest investigation undertaken by Kaseke and his colleagues, it was observed that the application of blanching to pomegranate seeds at a temperature of 90 °C for a time of 3 minutes induced notable alterations in the structural composition of the parenchymal cells. The blanching procedure resulted in a notable 35% augmentation in oil yield, along with enhancements in various functional attributes. Despite its reduced extraction efficiency and substantial solvent requirement, the soxhlet extraction technique continues to serve as the predominant standard for enhanced oil extraction methodologies (Kaseke et al., 2020). Furthermore, the utilization of hazardous solvents on a significant industrial scale leads to the exacerbation of atmospheric contamination, thereby impeding the implementation of solvent extraction techniques (Cheng et al., 2016). Similarly, it was noted that the implementation of pre-treatment strategies resulted in a notable reduction in the operational costs associated with aqueous extraction. The researchers conducting a techno-economic analysis of the production of soybean oil have emphasized that a substantial increase in production capacity can effectively mitigate operational costs (Cheng et al., 2019).

The supercritical fluid extraction (SFE) technique has become highly significant due to its ability to quickly, selectively, and effectively extract substances. Furthermore, this approach is considered environmentally safe since it does not produce any destructive residues in the obtained oil (Ruslan et al., 2021). Prior studies on the SFE (CO_2) technique used for the extraction of DOs have documented increased oil output, punicic acid, and tocopherol levels (Bañares et al., 2023). In another research, Abbasi and his co-workers discovered that the SFE method produced more phenolic content in DOs than other extraction methods like mixing, microwave, soxhlet, and ultrasonic extractions. Nevertheless, the elevated capital and investment expenses impede the marketing of SFE. The effectiveness of SFE is contingent upon the selection of solvent, the material preparation, and the extraction parameters (Abbasi et al., 2008). The temperature and pressure employed in SFE are crucial variables that fluctuate based on the need for increased yield of extraction or the specificity of particular substances. The findings indicated that higher levels of antioxidants, along with increased pressure and temperature, led to an increase in oil output (Da Silva et al., 2016).

Mechanical extraction (ME) has been employed as one of the earliest techniques for extracting DOs. However, ME is frequently utilized in rural regions because of its reduced initial investment expense and the absence of a need for extensively educated individuals to operate the machinery (Yate et al., 2020). The employment of this extraction method presents various benefits, including the generation of superior-quality oil and the possibility of utilizing its cake, distinguishing it from solvent-based extraction methods. Usually, the seeds are positioned between barriers, which effectively limits the volume that the seed can occupy. Usually, the quality of the oil is evaluated based on the acid value, phosphorus content, water content, and iodine value of the oil obtained using this procedure (Rani et al., 2021). Mechanical presses are widely used for oil extraction, with two common types being hydraulic presses and motor-driven screw presses. While mechanical pressing is known for its efficiency, it often leads to a significantly low oil yield. The screw press offers several advantages compared to the hydraulic press. It provides a little enhanced yield and can be easily modified for uninterrupted processing (Subroto et al., 2015). For instance, Heriawan and co-workers examined four distinct screw types (transport, onward, standby, and idle screws) and two distinct barrel filter types for oil extraction from Nyamplung seeds (*Calophyllum inophyllum* L.). They found that the configuration of mechanical extractors should be tailored to the specific seed material being utilized, as it might have a substantial impact on the amount produced (Heriawan et al., 2018).

Microwave-assisted extraction (MAE) is a modern and appealing approach for extracting oil that has gained attention recently. Microwave treatment causes denaturation of the protein material, resulting in enhanced extraction (Hasni et al., 2023). The microwave's ability to rapidly heat and destroy the structure of biological cells guarantees efficient extraction in a short period with minimal solvent usage, resulting in the production of high-quality oil. Another significant benefit of this procedure is its reduced energy demand, resulting in less environmental impact and financial expenses (Isopencu et al., 2019). The phenomenon of MAE occurs through the migration of ions and the revolving of dipoles, which occurs due to the impact of microwaves on the molecules of the processed material. The rise in temperature of the extraction medium is a result of ionic conduction, which arises from the movement of ions caused by a current electromagnetic field, leading to electrophoretic migration and dipole rotation (Isopencu et al., 2019). The soluble nature of the compounds in the solvent, mass diffusivity, partition coefficient, and the dielectric properties of the feedstock and solvent exert a substantial influence on MAE (Yılmaz et al., 2021). Mgudu and co-workers examined the effect of microwave treatment on the oil production and quality derived from castor beans. An optimal yield of 44.34% was achieved by applying a microwave power of 280 W for a duration of 120 s (Mgudu et al., 2012). In another work, authors found that the MAE technique resulted in a higher-quality palm oil with a reduced amount of unsaturated fatty acids but yielded less compared to the expeller press and solid-liquid extraction methods (Mosquera et al., 2013). In another interesting piece of research, the authors exhibited that the yield of MAE was 32.6%, whereas the yield from soxhlet extraction was 34.7%. The extraction times for MAE and soxhlet extraction were 3.5 minutes and 16 hours, respectively (Taghvaei et al., 2014). MAE is not recommended for PUFA extraction due to oxidation and degradation at high temperatures; however, it has demonstrated effectiveness in the extraction of advantageous phytochemicals (Yousuf et al., 2018).

Ultrasound-assisted extraction (UAE) refers to a distinct form of sound wave that falls outside the range of human auditory perception and is often characterized by frequencies spanning from 20 to 100 MHz. The UAE offers several benefits, such as reduced extraction duration, minimal energy requirements, and superior extraction effectiveness (Thilakarathna et al., 2023). The major cause of the UAE is mostly ascribed to the occurrence of cavitation, which entails the creation and expansion of bubbles followed by their sudden collapse. The collapse leads to physicochemical and mechanical reactions that cause the material matrix to break, making it easier for extractable compounds to be released and allowing the solvent to penetrate the sample (Liang et al., 2023). This ultimately enhances the discharge of target chemicals from the matrix into the solvent. Despite the emergence of alternative extraction methods like microwaves, some researchers still prefer the UAE due to its extraordinary efficiency and time-saving characteristics (Lin et al., 2021). For instance, authors have established that augmenting the ultrasonic power results in a corresponding rise in oil production. However, researchers observed a significant decline in this rise once the ultrasonic power exceeded 90 W, which is considered the optimal level. Increasing ultrasonic power enhanced the dissolution of seed oil by increasing the frequency of solvent and oil oscillations (Wang & Wei, 2015). Based on the investigation's findings, the utilization of UAE extraction resulted in a 10% improvement in chia seed oil production. However, soxhlet extraction exhibited a significantly higher yield increase of 69.2%. Furthermore, the researchers found that the highest quantity of the desired component was obtained after 60 minutes of UAE extraction, while it took 90 minutes of solvent extraction to achieve the same quantity, leading to a shorter overall extraction time (Rosas-Mendoza et al., 2017). In order to extract sea buckthorn oil, Isopencu and his team optimized temperature, duration, and ultrasonic intensity (UI). Operational parameters for an optimum extraction were 40 °C, 13.77 W/cm2 UI, and 10 min extraction time for UAE. These outcomes were contrasted with the microwave power, time, and solid/liquid ratio MAE parameters. For an extraction period of 20 minutes, a solid/liquid ratio of 15 mL/g, and a microwave power of 225 W were the perfect factors requisite to get a production of 87.4% ± 0.44%. Based on the results, it was possible to achieve extreme production for the UAE in half the time compared to MAE (Isopencu et al., 2019).

4. Factors affecting the bioavailability of DOs

There are several obstacles that must be confronted prior to effectively integrating DOs into the commercial market for nutritional foods and supplementation. DOs are composed of either small-chain triacylglycerols or long-chain triacylglycerols, both of which have low water solubility due to their hydrophobicity (Du et al., 2022). Consequently, the solubility of these substances in water is limited, necessitating their conversion into colloidal states prior to their integration into water-based food and beverage systems. DOs are more susceptible to accelerated lipid oxidation due to the abundance of double bonds (-C=C-) that are present within omega-3 polyunsaturated fatty acids (PUFAs) (Rehman, Tong, Jafari, et al., 2021). Specific environmental elements, including heat, illumination, the presence of oxygen, transition metals, and specific enzymes, can enhance the ratio and quantity of lipid oxidation. The oxidation of DOs leads to the formation of reaction products that possess unfavorable sensory attributes, such as rancidity, rendering them unappealing to consumers. The oxidation rate of DOs during storage significantly impacts their longevity (Shehzad et al., 2021). The factors influencing the bioavailability of DOs are extensively highlighted in **Fig. 2**.

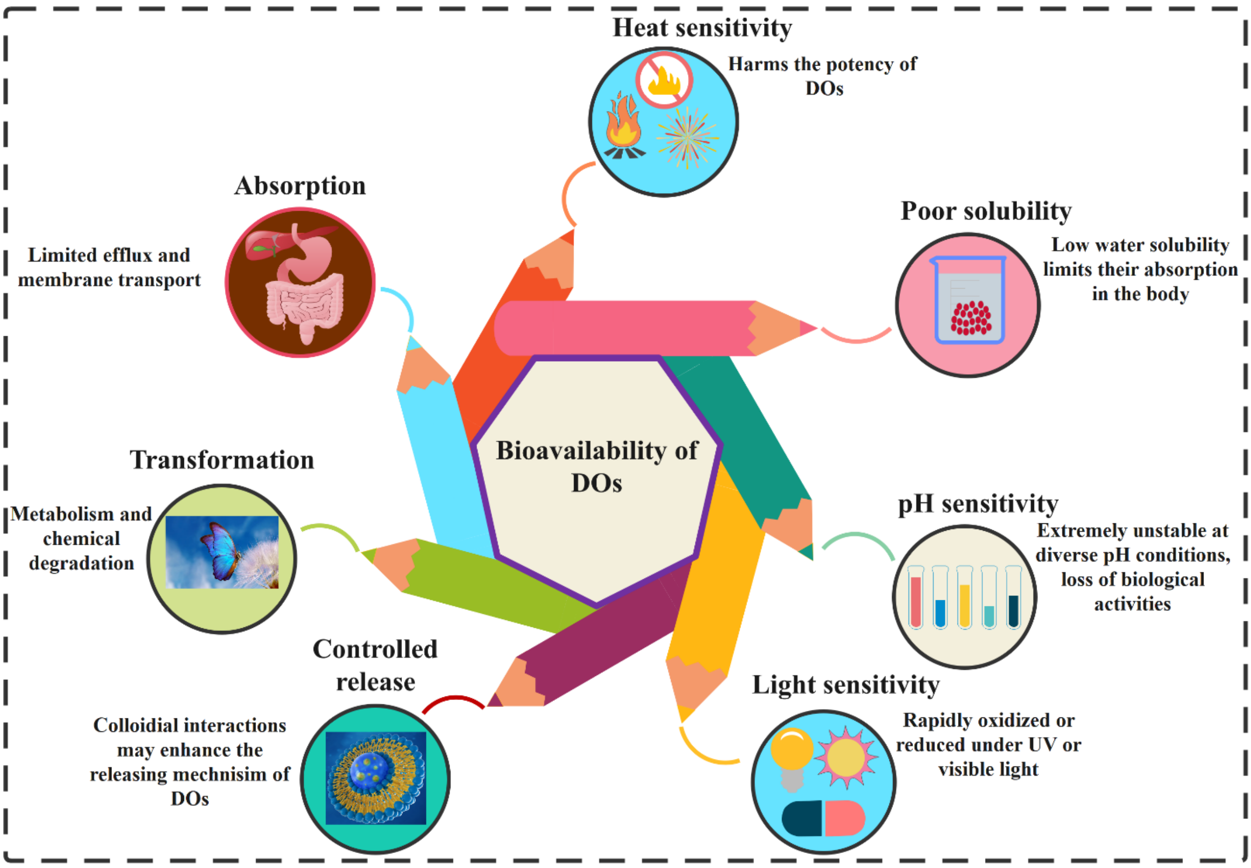

Fig. 2. Factor affecting bioavailability of DOs.

Moreover, it has been found that specific byproducts formed during the oxidation of lipids have harmful properties, which could lead to negative health consequences if oxidized DOs are consumed frequently (Grootveld et al., 2020). Thus, it is imperative to implement efficient protocols to reduce the oxidation of DOs in food items and dietary supplements. There are various methods to accomplish this goal, encompassing the regulation of storage conditions, the utilization of packaging, and the incorporation of antioxidants and chelating agents (Zhao et al., 2022). Additionally, the utilization of sophisticated encapsulating carriers is also discussed in Section 6. The molecular structure of omega-3 fatty acids and the composition of the surrounding food matrix can impact the oral bioavailability of certain DO's formulations, making it difficult to achieve consistent results. This phenomenon is primarily influenced by the challenges posed by the solubility of omega-3 oils in the gastrointestinal fluids and their vulnerability to oxidation during transit through the gut (Walia et al., 2017a). Orally consumption of DOs results in their passage through the mouth, esophagus, stomach, and small intestine, where they may be absorbed. They come into contact with a range of gastrointestinal system elements, including mineral ions, bile salts, pH levels, mechanical forces, flow patterns, and digestive enzymes (Rehman, Jafari, Aadil, et al., 2020).

Emulsified oils are colloidal by nature prior to ingestion, whereas bulk DOs undergo a process of conversion in the mouth and stomach, where they transform into more substantial oil-in-water emulsions (Rehman et al., 2024). Free fatty acids (FFAs) and monoacylglycerols are produced from triacylglycerols (TAGs) during lipid metabolism. The initiation of this process is facilitated by gastric and pancreatic lipases, which exhibit binding affinity towards the surfaces of lipid droplets that contain TAGs (Otero et al., 2021). The interaction between endogenous bile salts and phospholipids and digestive products such as FFAs and TAGs results in the formation of mixed micelles. The transportation of lipids from the mucin layer to the epithelial cell surfaces is facilitated by these mixed micelles. Research has indicated that bioavailability is enhanced when omega-3 oils are consumed in emulsified form instead of free form (Boerekamp et al., 2019). This can be explained by the fact that lipases can adsorb on a larger surface area in emulsified systems.

It is possible to significantly alter the bioavailability profiles of DOs by adjusting the surface characteristics, size, and content of the colloidal particles that encapsulate these oils in their early phases. Additionally, absorption enhancers, which raise the permeability of the epithelial cells, can be added to supplement formulations to boost the bioavailability of DOs (Wei et al., 2018). Advanced nanoencapsulation strategies commonly address the restricted water solubility, poor chemical stability, and low or variable bioavailability of DOs.

5. Role of ultrasonication in the development of nanocarriers

In the arena of nanoencapsulation, the nutraceutical and food bioactive industries encounter numerous difficulties when trying to find ways to develop cutting-edge nanocarriers that are safe for the environment and work well for bioactive applications. The challenges manifest themselves as a result of the inherent risks associated with the fabrication and utilization of nanomaterials. The use of high-intensity ULS has proven to be highly effective in fabricating various organic nanocarriers (Liang et al., 2023). This approach has emerged as a prominent choice among various nanoencapsulated techniques because of its many advantages, including enhanced safety measures, simplified operational procedures, greater energy efficiency, the potential for scalability, and the capability to exert control over dimensions and morphological characteristics (Rehman, Jafari, Tong, Karim, et al., 2020a). Ultrasound refers to a collection of sound waves that possess frequencies exceeding the upper limit of human auditory perception, specifically > 16 kHz. These waves can be categorized based on their frequency and intensity characteristics. High-frequency ultrasound with low intensity has the capacity to pass through a substance without causing any harmful physical or chemical changes (Li et al., 2024). Despite the utilization of high frequencies within the range of 1–10 MHz, the power intensity associated with low-intensity ultrasound is insufficient, measuring < 1 W/cm^2, to induce any discernible alterations in the material (Walia et al., 2017a).

On the contrary, high-power ultrasound, distinguished by its low frequency and high intensity, showcases power intensities spanning from 10 to 1000 W/cm^2 and frequencies between 16 and 100 kHz. As a result, the use of low-intensity ultrasound is commonly employed within the realm of medical imaging, specifically in the domain of sonography, with the objective of discerning and diagnosing various conditions (Xu et al., 2021). Conversely, the utilization of high-power ULS is increasingly being employed in disintegration and disassembly, such as depolymerization of macromolecules, reduction of particle dimensions to the nanoscale, generation of emulsions via homogenization, dispersion of droplets, and extraction of bioactives from diverse matrices. This phenomenon is notably prominent in lab environments and within the domain of the food industries. The process of converting acoustically generated power into a chemically usable form is accomplished through a well-known phenomenon called acoustic cavitation (Yao et al., 2022). This is because molecules are unable to directly absorb acoustic energy. Acoustic waves, also known as pressure waves, are a combination of expanding and compressing waves that move through a liquid media (Taha et al., 2018).

Expansion waves can generate pressure that disrupts the cohesion of a fluid medium, resulting in the formation of a microbubble, also known as a microcavity. The compression wave travels through the cavity, causing it to compress (Chavan et al., 2022). This is then followed by an expansion wave that restores the cavity to its original size. Afterward, an oscillatory bubble forms and displays a repetitive motion occurring at a frequency of 20 kHz. The process involves the accumulation of heat in the oscillating bubbles, which results from the ultrasonic energy. These bubbles continue to grow until they reach a specific size, usually in the range of tens of micrometers. At lower levels of ultrasound intensity, bubbles exhibit a phenomenon known as "stable cavitation," wherein they undergo repetitive oscillations without undergoing collapse. The behavior of bubbles changes from linear oscillation to nonlinear oscillation as ULS intensity rises, followed by implosive collapse (L. Li et al., 2021). This collapse results in the rapid release of the stored energy within the bubble, which occurs over a short period of time. The occurrence of "collapse," "transient," or "inertial" cavitation leads to the manifestation of elevated localized temperatures, increased pressures, the presence of free radicals, and the generation of shock waves. These phenomena collectively serve as the main mechanism for inducing sono-chemical impacts. The significance of acoustic cavitation in the synthesis of nanomaterials is well recognized. However, current research is focused on identifying the underlying mechanisms that drive the formation of NPs when a mixture of reacting substances is exposed to ULS (Yao et al., 2022).

ULS, either used independently or in association with various nanoencapsulation techniques, is employed to disrupt particle aggregates and polymeric structures, resulting in a reduction of their dimensions to the nanometer range. Considering the energy input provided by cavitation, which ranges from 10 to 100 kJ/mol, it can be inferred that only hydrogen bonds are susceptible to being affected by this particular method. An additional mechanical clarification can be attributed to its role in the development of colloidal nanocarriers, including Janus particles, vesicles, emulsion droplets, and other similar entities (Zhao et al., 2022). The colloidal structures present in the suspension exhibit aggregation tendencies due to intriguing forces from the surface or particle incarceration, while being subject to random Brownian motion. Nevertheless, the newly formed structures that arise from self-assembly exhibit a predominantly distorted morphology, and lack the interior dynamics necessary to accurately replicate the intended shapes (Y. Li et al., 2021). Hence, the occurrence of increased random movements resulting from alterations in pressure, temperature, or volume is crucial for the reorganization of these entities. Conversely, the unassociated colloidal particles exhibit translational motion through the absorption of energy from the surrounding medium. Additionally, the deliberate movement of colloids can be induced by acoustic waves.

The significance of equipment settings is paramount in both contexts, since they have a substantial influence on the functioning and optimization of ULS. An extensive range of commercially available specialized equipment has been established to support sono-chemical processes, such as direct-immersion ultrasonic horns, ultrasonic cleaning baths, and flow reactors designed for continuous operations. A standard ultrasonic device typically includes three main components: (i) an electrical generator that creates an electrical current with a specific power rating; (ii) piezoelectric transducers that transform electrical energy into mechanical vibrations at ultrasonic frequencies, producing sound waves; and (iii) an emitter, often in the form of titanium horns or baths, that helps transmit the sonication waves from the transducer into the nearby medium (Zhang et al., 2020). The application of ultrasonic probes, also known as ultrasound horns **(Fig. 3A)** and ultrasonic cleaning baths **(Fig. 3B),** is widespread in research labs. Flow reactors have the capability to generate significant ultrasonic intensities suitable for large-scale and industrial irradiation processes as well.

High-intensity ultrasonic horns are predominantly applied at 20 or 40 kHz, with the latter being commonly employed for cleaning baths. There exist various ultrasound configurations that possess the capacity to operate within frequency ranges spanning from a few hundred kHz to a few MHz. Prior research has demonstrated that the phenomenon of cavitation heating resulting from the collapse of bubbles can occur across a wide frequency range (Chavan et al., 2022). On the other hand, lower frequencies mainly lead to physical effects caused by ultrasound, such as emulsification processes or the creation of nanomaterials.

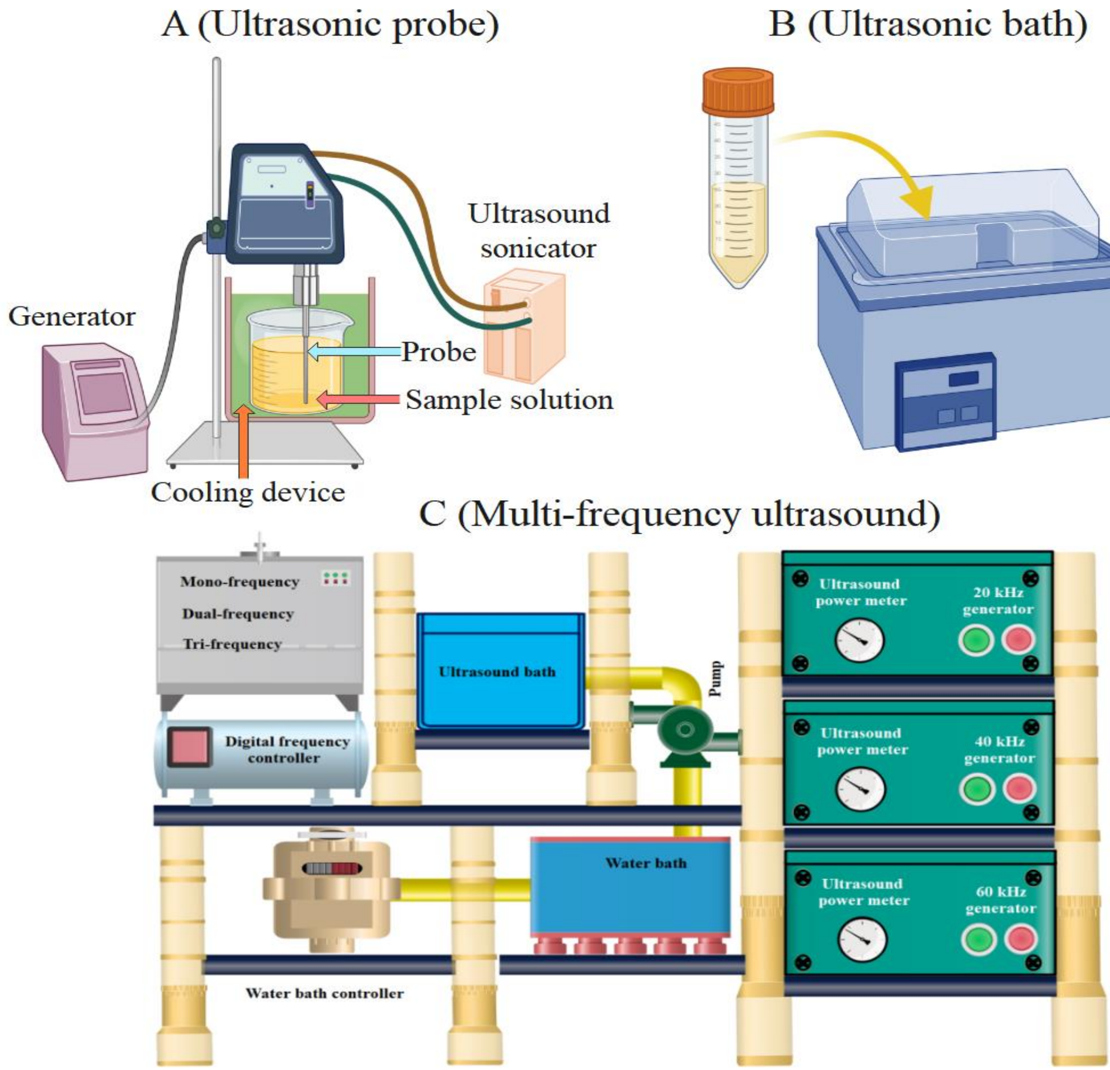

Fig. 3. A schematic illustration of probe (A), cleaning bath (B), and multi-frequency ultrasonic devices, respectively.

Ultrasonic cleaning baths are commonly employed in the food and dietary supplement industries for various applications, including freezing or thawing, extraction of bioactives, and modifications in food structures because of their affordability and early accessibility (Zhou et al., 2023). However, the existence of specific limitations in their functionality, such as a gradual decline in power, inconsistent ultrasound transmission, inflexible power configurations, and difficulties in maintaining accurate temperature regulation within the bath, has led to reduced reproducibility of results (Song et al., 2021). It has been observed that the cleaning baths lack the necessary level of intensity to generate nanostructured compounds. On the other hand, probe-based sonicators are commonly employed and offer a reliable approach for adjusting ULS parameters such as power, frequency, and duration to meet specific requirements. It is crucial to highlight that the utilization of high-power sonication horns may produce significant heat and shear forces (Liu, Song, Zhou, Yuan, Wang, Yuan, Li, Yuan, et al., 2023). This has the potential to degrade delicate and unstable bioactives through thermal degradation or the formation of free radicals (Antes et al., 2017). To effectively control temperature elevation, a cooling jacket can be implemented in a cyclical manner, thereby reducing the duration of ULS (Wang et al., 2023).

In order to address the issue of inadequate ultrasonic effectiveness and reduced cavitation occurrences due to an uneven distribution of the acoustic field, our research team has developed a multi-mode, multi-frequency power ULS array (Xu et al., 2021). The methodologies mentioned comprise a diverse array of techniques, which consist of sweeping and fixed-frequency ULS, pulse and continuous ULS, single-mode ULS, and a multitude of multi-mode and multi-frequency power ULS devices that have been independently designed **(Fig. 3C)**. These devices have been extensively utilized in diverse domains of food processing, encompassing extraction, cryogenic preservation, maturation, desiccation, degradation, blanching, sterilization, enzymatic breakdown, including enzymatic conversion, modification of substrate materials, and management of enzymatic hydrolysis procedures (Chen et al., 2022). Furthermore, these devices find application in various washing methodologies, wherein their primary purpose is to eradicate harmful pesticides, diminish microbial presence, and uphold the overall standard of excellence (Liu, Song, Zhou, Yuan, Wang, Yuan, Li, He, et al., 2023). The careful consideration and development of an appropriate methodology for the fabrication of nanocarriers hold great importance in the field of nanoencapsulation (Ma et al., 2023). The observed phenomenon can be explained by the complex interaction between the physical, chemical, and biological characteristics of both the encapsulated and encapsulating components. The aforementioned characteristics are notably impacted by the techniques employed in the preparation phase as well as the critical variables that govern the conditions of the process.

6. Production of dietary oil-loaded nanocarriers by ultrasonication

As previously mentioned, there are primarily two kinds of nanocarriers, encompassing biopolymeric and lipid-based nanocarriers. Both are highly recommended as carriers for delivering DOs, as they can enhance the performance of DOs by improving their bioaccessibility, solubility, and bioavailability (Frosi et al., 2022). For example, non-polar lipids like triacylglycerol and cholesterol, along with polar lipids such as phospholipids and monoglycerides, are commonly used as encapsulating candidates or wall materials due to their non-toxic nature and their significant role in the emulsification process (Đorđević et al., 2016). Moreover, they behave efficiently during transferring DOs in the gastrointestinal tract (GIT) by forming blended micelles, enhancing the solubilization process (de Souza et al., 2022). Thus far, polar lipids, especially phospholipids, are widely acknowledged for their biocompatibility, remarkable surface-active properties, and their effectiveness in ensuring excellent preservation, protection, and accurate transportation of oils. As a result, lipid-based nanocarriers (**Fig. 4**) are being highly regarded due to their excellent encapsulation efficiency (EE) and minimal toxicity in comparison to biopolymeric nanocarriers.

On the other hand, proteins including whey protein, gelatin, soy protein, and pulse proteins, together with polysaccharides like chitosan, alginate, gums, cellulose, pectin, and starches, have been effectively employed for the creation of DOs-loaded nanocarriers (Sharif et al., 2017; Taban et al., 2020). These biopolymers are widely distributed in nature, and their cost-effectiveness, exceptional biodegradability, biocompatibility, and non-reactive and non-toxic qualities make them extremely valuable (Shehzad et al., 2020). The physiochemical properties of NPs and nanohydrogels allow for their effective formulation in assembly, facilitating successful delivery and smooth handling during chemical reactions as needed (Rehman, Tong, et al., 2019). Furthermore, biopolymers that occur naturally possess the ability to be identified and adhere to their designated targets. In addition, these biopolymers have the capacity to stick to and move across mucosal surfaces, demonstrate targeted release, and undergo enzymatic breakdown at specific sites in response to environmental stimuli (Wang et al., 2022).

These biopolymeric and lipid-based DOs-loaded UPNs essentially require energy due to their non-equilibrium character, which can be obtained from the chemical potential of substances or specialized mechanical equipment (Rehman, Jafari, Tong, Karim, et al., 2020a). High-speed agitators and high-pressure homogenizers have certain drawbacks, including high energy consumption and limited control over the stability and particle size distribution of nanoemulsions (Rehman, Qunyi, et al., 2021). Ultrasound-assisted emulsification, on the other hand, is a high-energy, low-complexity, non-toxic, repeatable, eco-friendly, and low-complexity method for making nanoemulsions that can break the oil-water interface and reduce emulsion droplets to nanometric size (Rehman, Tong, Jafari, et al., 2020). It is thought that ultrasonic emulsification occurs in two stages through various mechanisms. Firstly, the stability of the oil-water interface is upset by mechanical vibrations resulting from sound waves passing through the medium (a phenomenon known as Rayleigh-Taylor instability), which causes the oil phase to separate into the aqueous phase as droplets (Wang & Wei, 2015). Secondly, the dispersed droplets break up into smaller ones to form a stable emulsion with the desired droplet size as a result of the shockwaves caused by the bursting of cavitation bubbles (Zhang et al., 2020). The following discussion focuses on biopolymeric and lipid-based oil-loaded UPNs, including their ULS characteristics and their significant potential for precise and regulated release of DOs.

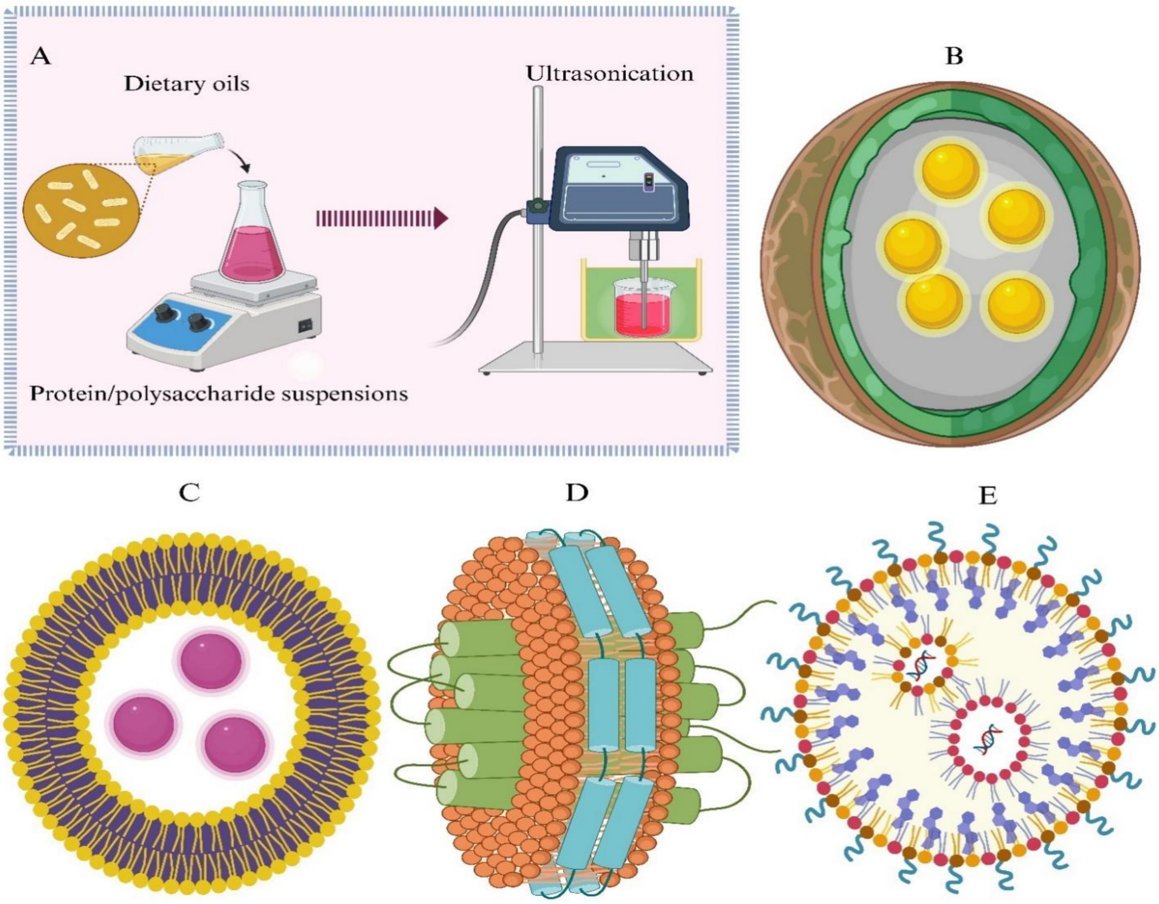

Fig. 4. Schematic illustration of different ultrasonically assisted oil-loaded nanocarriers: (A) biopolymeric nanocarriers. (B) Oil/Water nanoemulsions; (C) Nano-liposomes; (D) Solid lipid nanoparticles; and (E) Nanostructured lipid carriers.

6.1. Ultrasonically embedded lipid-based nanocarriers

Lipid-based nanocarriers are rapidly expanding as excellent carriers and have successfully been used to enhance the efficacy of bioactives (e.g., DOs) by improving their solubility and bioavailability through the GIT pathway and oral administration (Rehman, Tong, Jafari, et al., 2020). In addition, these kinds of nanocarriers can easily target the desired site of action inside the human body through different transportation systems, such as active transport systems (e.g., entrapping antibodies) or passive transport systems (depending on particle diameters). In addition, these compounds possess distinctive features, including the protection of loaded substances from denaturation while preserving the sensory properties and prolonging the shelf life of food items (Kaliamurthi et al., 2019). Most significantly, lipid-based nanocarriers can be efficiently fabricated through different types of equipment now commonly available in food science labs as well as in industries such as microfluidization, high-pressure homogenization, and ULS. Mainly, four types of nanocarriers, including, NEs, NLPs, SLNs, and NLCs, are composed of lipid-based molecules that are discussed in this section. **Table 2** further elaborates on the case study description of lipid-based UPNs entrapping different kinds of DOs.

6.1.1. Dietary oil-loaded nanoemulsions

Ultrasound has higher control over the quality and characteristics of NEs, and it can successfully enhance the stability and size distribution of NEs **(Fig. 4B)**. Besides, ultrasonically assisted NEs are more appropriate for the entrapment and delivery of bioactives. In our recent study, we successfully established ultrasonically assisted borage seed oil (BSO)-loaded NEs stabilized by the purity gum ultra (a modified starch), where diverse proportions of the peppermint EO (PEO) were used to explore the oxidation stability and antioxidant activity of NEs. In order to achieve a particle size of 132.3 nm, the emulsion underwent ULS using a 20 mm probe diameter and 1200 W maximum power at 20 kHz for 13 min. The impact of various concentrations of BSO and PEO on the oxidative stability, antioxidant activity, and capacity of NEs stored at 4, 25, and 40 °C for 30 days was found to be significant. It was demonstrated that the best formulation, consisting of 5% (v/v) PEO and 5% (v/v) BSO, showed a slight increase in size and oxidative stability under all storage conditions when compared to other samples. The study found that PEO may act as a natural antioxidant, improving the oxidative stability, antioxidant activity, and capacity of NE delivery systems (Rehman, Jafari, Tong, Karim, et al., 2020b). Another study was conducted to produce NEs containing mustard oil, which were stabilized by Tween 80 (T80) and Span 80 (S80). The emulsions were created using ULS and had a minimum droplet size of 87.38 nm. Various operating conditions were employed, including a ULS time of 30 min, a frequency of 20 kHz, and a power set at 40%. An increase in the ultrasonic power resulted in lower size of NEs. Furthermore, the oil structure was not affected by the ultrasonic cavitational effects. Additionally, the mustard oil NEs made by ULS were more stable as compared to control sample for three months without experiencing any changes in droplet size or phase separation (Carpenter & Saharan, 2017).

NEs containing sunflower oil were prepared by utilizing S80, T80, and sodium dodecyl sulphate. The resulting NEs exhibited an average droplet size of approximately 40 nm following ULS for 1.0 min. The droplet size decreased significantly with an increase in overpressure. A droplet size of 40 nm was attained through the application of an overpressure of 160 J/mL. The stability of the oil was maintained, potentially attributed to the generation of free FAs, mono- and di-glycerides, which were ascribed to ULS (Leong et al., 2009). Interestingly, it has been documented that SOs (e.g., basil oil) can be used as antimicrobial agents in nanoencapsulated systems. In this regard, a stable NE containing the basil oil was created using ULS and T80, a non-ionic surfactant. The process involved subjecting a coarse emulsion to ULS for 15 min using a 20 kHz sonicator with a maximum power output of 750 W. The resulting emulsion had a size of 29.3 nm and was highly stable. Additionally, these NEs were effective in reducing bacterial cells by six logs within 1.0 min. Also, the antibacterial properties of NEs were evaluated by conducting kinetics killing experiments against *E. coli*. The results showed that even after being diluted with water, NEs still demonstrated significant antibacterial activity against *E. coli*. The stability and size of NEs were significantly affected by the mixing proportion of surfactant, concentration of surfactant and oil, and ULS time (Ghosh, Mukherjee, et al., 2013a). Similarly, Shanmugam & Ashokkumar (2014) developed flaxseed oil (FSO)-loaded NEs stabilized with a protein surfactant by subjecting coarse emulsion to ULS at 20 kHz for 1–8 min and an acoustic power of 176 W. They concluded that the processing time (3 min) at 176 W was enough to achieve a fine droplet size (0.64 nm), and an emulsion processed for 3 min was found to be more stable after 9 days kept at 4 ° C. Also, emulsions displayed a surface charge (–30 mV) owing to adsorbed proteins that contributed to their stability due to electrostatic repulsion. As ULS time increased, the droplet size decreased, and the emulsion droplet provided excellent stability while partially denaturing the whey proteins (< 20 nm) (Shanmugam & Ashokkumar, 2014).

As discussed earlier, EOs comprise diverse bioactives able to contribute to antioxidant and antimicrobial potential, thus, they can be used in NEs-based systems to enhance their physiochemical characteristics and stability. It is well documented that, as an EO, the nettle oil can be used as a natural antimicrobial agent. For this purpose, NEs were produced comprising nettle EO (NEO) stabilized with T40 by subjecting coarse emulsion to ULS to reduce the particle size by a 20 kHz ULS equipped with a 13 mm probe for 3.5 min. This study depicted that NEO could be potentially useful as an antimicrobial agent to enhance the physiochemical characteristics of emulsion-based beverages (Gharibzahedi et al., 2015). In another study, an ultrasonically fabricated cinnamon NE was prepared by T80 with ULS time of 30 min, which produced a stable 65 nm droplet size, due to which this NE showed the highest bactericidal activities even after dilutions (Ghosh, Saranya, Mukherjee, & Chandrasekaran, 2013). In another interesting investigation, Shahavi et al. (2016) claimed that CEO had good antibacterial activities, and they successfully incorporated CEO into NEs to enhance its stability and solubility by ULS, as well as to access its antibacterial potential against *E. coli* and *B. cereus*. After subjecting coarse emulsion to ultrasonic emulsification three times using the 70 W ULS at 20 kHz equipped with a 3 mm-diameter probe, about 50 nm droplets of CEO-loaded NEs mediated by T80 and S80 surfactants were obtained. It was reported that CEO-loaded NEs exhibited minimum inhibitory concentrations (MIC) of 32 and 16 μg/mL against *B. cereus* and *E. coli*, respectively (Shahavi et al., 2016).

Table 2. A summary of lipid-based nanocarriers entrapping different dietary oils fabricated by ultrasonication.

Lipid based nanocarriers	Surfactants	Entrapped oils	Processing conditions	Particle size (nm)	Zeta potential (mV)	Encapsulation efficiency (EE, %)	Conclusive remarks	References
Nanoemulsions (NEs)	Tween 80 (T80), sodium dodecyl sulfate (SDS), and cetylpyridinium chloride (CP)	Thyme EO (TEO)	20 kHz, different power (350, 450, 550 W) and time (5, 10, 15 min)	100	+48 to -65	NM	All studied nanoemulsions had varying storage stability and antibacterial mechanisms. TEO-NEs stabilized by T80 had good storage stability but poor antibacterial activity due to its regulated in vitro release, while TEO-NEs-CPC had great antibacterial activity due to its cationic emulsifier electrostatic contact effect.	(Yang et al., 2022)
	Bitter almond gum, sodium caseinate (SC)	Fish oil	40 kHz 130 W, 5 min	450	-55	NM	The findings indicate that the concurrent utilization of SBAG and its conjugate may serve as a suitable approach for enhancing the oxidative and physical stability of lipophilic substances in functional foods.	(Rahimi et al., 2021)
	T80 and span 80 (S80)	Mustard oil	20 kHz, 750 W, 30 min	109.6	NM	NM	ULS increased the stability and had no effects on oil structure	(Carpenter & Saharan, 2017)
	Purity gum ultra (PUG)	Borage seed oil (BSO) and peppermint oil (PO)	20 kHz, 1200 W 400 W, 13 min	186-364	-30.5 to -42.3	70.30 to 96.50	The study found that varying PO concentrations affect the physicochemical properties of BSO-loaded nanoemulsions.	(Rehman, Jafari, Tong, Karim, et al., 2020a)
	T80	Cinnamon EO	20 kHz, 750 W, 30 min	65	NM	NM	Droplet size is affected by surfactant concentration, emulsification time and oil-surfactant mixing ratio. These oil NEs have the potential as an effective antimicrobial agent.	(Ghosh, Saranya, Mukherjee, Chandrasekaran, et al., 2013)

Sodium octenyl succinic anhydride modified starch and chitosan	Oregano essential oil and sunflower oil	20 kHz, 80 W, 7 min	180-265	−42 to +35	97.11	ULS boosted the stability of triple-layered NEs, and in vitro stomach and intestinal circumstances demonstrated that each polymeric layer affects OEO bioaccessibility, resulting in a greater value with the three-layer system.	(Espinosa-Sandoval et al., 2021)
T80	Basil EO	20 kHz, 750 W, 15 min,	29.3	-3.70	NM	Ultrasonic emulsification gives minimum droplet size with high physical stability. The prepared NEs has potential against microbial spoilage of food.	(Ghosh, Mukherjee, et al., 2013b)
Whey protein, Sodium alginate and T80	Flaxseed oil	24 kHz, 14mm probe diameter, 10 min	1000	-45.5	70	The flaxseed NEs stabilized by whey protein and sodium alginate showed resistance in gastric digestion while rapidly digested in intestinal environment.	(Shanmugam et al., 2015)
T80	Lemon EO and fish by-product oil	100 W, 42 min	44.40	−5.02		When compared to ascorbic acid, the antioxidant activity of ULS equipped NEs performed better than lemon oil. Additionally, the outcomes demonstrated that NE-FLO had antibacterial activity against every strain of bacteria that was examined during the investigation.	(Azmi et al., 2022)
T80	Orange peel EO	20 kHz, 138 s	12.68	NM	NM	The ultrasonically prepared NEs can remains stable over 3 months. The EOs with long stability can be used in food and pharmaceuticals.	(Hashtjin & Abbasi, 2015)
T40 and jujuble	Nettle oil	24 kHz, 250 W, 2.5 min	86.75	NM	NM	Nettle oil NEs have lower oxidative stability and have enhanced antimicrobial and antioxidant properties	(Gharibzahedi et al., 2015)

	polysaccharides							
	T80	Lemongrass EO	24 kHz, 400 W, 180 s	4.31	-40.0	NM	The viscosity of ultrasonically prepared NEs is decreased with the increased in time and amplitude. ULS is the helpful technique to produce highly translucent emulsion.	(Salvia-Trujillo et al., 2013)
	T80	Eucalyptus EO	30 min	3.8	NM	NM	By increasing the sonicating time, the stability and transparency of emulsion is increased as compared to hand blender emulsion.	(Sugumar et al., 2014)
	T20 and S80	Fish oil	200 W, 30 min	94.20	NM	NM	Lipids were better absorbed when ultrasonic emulsification was used, and absorption efficiency was affected by droplet diameter.	(kumar Dey et al., 2012)
	Whey protein isolate	Fish oil	200 W, 20 min	84	−37.5	NM	Storage temperature has no discernible effect on NE particle size.	(Nejadmansouri et al., 2016)
Nano-liposomes (NLs)	Sunflower oil and lecithin	Fish oil	7 min, 200 UPS probe	339.2	NM	90.12	Liposomes have a positive impact on particle size and EE. The physical and oxidative stability of liposomes have been enhanced by inhibiting oxidation.	(Ojagh & Hasani, 2018)
	Lecithin and cholesterol	Ginger essential oil	24 kHz, 90% power, 30 s	154.40	−18.17	66.24	GEO-loaded NLs released nearly 90% of the nutraceutical in oral, gastric, and intestinal circumstances. Finally, nano-liposomes increased antioxidant, UV stability, and cytotoxicity on HT-29 and HUVEC cell lines.	(Ekrami et al., 2023)
	Lecithin and sunflower oil	Fish oil	20 kHz, 200 UPS probe, 7 min	633	NM	92	The stability of FO has been enhanced, and syneresis, peroxide value, and acidity have decreased due to nano-liposome encapsulation.	(Ghorbanzade et al., 2017)

	Egg yolk lecithin and cholesterol	Tee tree oil (TTO)	24 kHz, 10 min	227.8	−14.8	80.31	The MIC test showed that nano-liposomes increased TTO's antibacterial effectiveness against E. coli strains. In vitro TTO-NLs exposure damaged E. coli structurally to varying degrees. TTO-NLs oral treatment reduced clinical symptoms and intestinal lesion in E. coli-challenged hens.	(Bo et al., 2023)
	Lecithin	Eugenol and cinnamon EO	20 kHz, 10 min	90.6	NM	NM	Encapsulation of volatile compounds in liposomes gives good antimicrobial films with EOs.	(Valencia-Sullca et al., 2016)
	Lecithin and cholesterol	*Zhumeria majdae* EO (ZMEO)	24 kHz, 30 s, 90% power	50 to 300	−34.33 to −21.37	67.48 to 92.33	The generated nanoparticles demonstrated enhanced cytotoxicity and efficacy against various cell lines, in addition to a high degree of encapsulation efficiency. In fact, the potent antitumor activity of NLs-ZMEO was demonstrated in this study, suggesting that it may represent a novel treatment option for lung cancer in humans.	(Ekrami et al., 2022)
Solid-lipid nano carriers	T80 and poloxamer	*Eugenia caryophyllata*	Probe sonicator, 30 s	506.4	-21.7	70	These liposomes are used to kill pathogens and has 70% EE.	(Fazly Bazzaz et al., 2018)
Nano structured lipid carrier	T80 and lecithin	Bees wax, propois wax and Pomegranate seed oil	Probe sonicator, power 250 W, 8 min	366	-18.3	96	These NLCs has good physical stability and high distribution of oil throughout the lipid carrier.	(Soleimanian et al., 2018)
	T80 and Soy lecithin	*Zingibar zerumbet*	Probe sonicator, 20 min	96. 59	-39.88	90	The EE increased 80% as well as stability is also enhanced.	(Rosli et al., 2015)

	T20, 60 and 80, lecithin, and poloxamer	ω-3 Fish oil	400 W, 10 min	119	-1.05	30	The stability of NLCs was improved. *ω*- 3 fish oil in demonstrated a more effective reduction of primary oxidative byproducts compared to secondary byproducts.	(Shahparast et al., 2019)
	T80	Cardamom EO	24 kHz, 200 W, 50°C	150	-30	90	These NLCs have small size and high EE and loading capacity.	(Nahr et al., 2018)

NM: Not Mentioned

Plant-based EOs like the eucalyptus EO (EEO), which has antimicrobial properties against foodborne pathogens, were used to fabricate NEs embedded with T80, where the coarse emulsion was exposed for 0 to 30 min to ULS. The most stable EEO-loaded emulsion was only achieved after 30 min of ULS, with the droplet size of 3.8 nm. Also, the antibacterial analysis of the EEO-loaded emulsion indicated a complete loss of *S. aureus* viability during the interaction period (15 min). In addition, an *in vivo* treatment with the EEO-loaded emulsion reported faster wound healing in Wister rats compared to the control and neomycin-treated rats (Sugumar et al., 2014). As clearly outlined in Section 2, MOs like fish oil (FO) serve as an excellent ω-3 FAs source. However, they may not always be appreciated by consumers because of their undesirable fishy odor. In addressing this issue, Kumar and his colleagues (2012) succeeded in producing NEs and traditional emulsions containing FO emulsified with T80 and S80 via ULS at 200 W for 30 min. Following the ultrasonic liquid processing, the droplet size ranged from 78.96 to 94.20 nm. The absorption level of lipids in the small intestines of the rats was significantly enhanced by FO-loaded NEs. This discovery is quite intriguing, indicating that the uptake of lipid NEs or nanocarriers could be a powerful tool in developing lipid-based enteral diet therapy for individuals experiencing lipid malnutrition (kumar Dey et al., 2012).

On the other hand, biopolymers such as whey protein isolate (WPI) and gum Arabic (GA) have been extensively used in many investigations as emulsifying and stabilizing agents for the encapsulation of different bioactives. For instance, Campelo et al. (2017) produced GA and WPI-based emulsions to encapsulate lime EO (LEO) by using an ultrasonic homogenizer in order to explore the kinetic stability of LEO-loaded emulsions. It was proven that the droplet size increased with the increasing lipid phase level in the emulsions. Furthermore, the emulsion stabilized by WPI presented greater zeta potential values, promoting its electrosteric stabilization behavior, which is highly appealing, depicting that biopolymers can be used as excellent stabilizers for the fabrication of oil-loaded emulsions (Campelo et al., 2017). Similarly, NEs encapsulating FO embedded by WPI were prepared by ULS homogenization (200 W, amplitude at 80, and cycle of 0.7), resulting in an average size of around 84 nm. The physiochemical properties and storage stability of NEs were affected by increasing the concentration of WPI, pH, weight ratio, and storage temperature. Also, a declining trend for refractive index, surface tension, and viscosity and an increasing trend for droplet size and optical density were observed as the pH and concentration of WPI increased. The final size of NEs was due to the concentration and aggregation of depolymerized fractions. The authors also found a significant degradation in the unsaturated FAs profile existing in FO-loaded NEs that might be due to the storage temperature (Nejadmansouri et al., 2016). The food industry has recognized the significance of orange peel EO (OPEO) due to its distinct aroma and cost effectiveness. However, the solubility and stability of OPEO are low, which poses challenges during processing and storage. Therefore, to enhance its solubility, the OPEO-loaded NEs were fabricated with T80 combining with

GA and tragacanthin gum by subjecting them to ULS (time= 138 s, amplitude= 98%, and temperature= 37 °C). The obtained OPEO-loaded NEs exhibited droplet sizes around 12.68 nm. Moreover, it was found that a very minute concentration of tragacanthin gum had a noteworthy effect on the size, stability, and rheology of OPEO-loaded NEs (Hashtjin & Abbasi, 2015).

6.1.2. Dietary oil-loaded nano-liposomes

NLPs are one of the most suggested nanocarriers for the encapsulation of DOs. NLPs can be defined as carriers artificially constructed with phospholipids (Karim et al., 2022). These vesicular particles composed of one or more bilayer membranes with a spherical shape **(Fig. 4C)** and have a size ranging from nanometers to micrometers (Rehman, Tong, et al., 2019). For instance, Ojagh and his co-workers described the influences of entrapped FO in NLPs thru ULS. The production of NLPs involved subjecting the liposome suspension to a ULS for 7 min using a probe while maintaining the temperature of the system in an ice bath until the suspension achieved clarity. NLPs containing FO were rendered stable through the combination of lecithin and sunflower oils. NLPs had a size of 339.0 nm and an EE of 90.12%, respectively. Furthermore, in comparison to free FO, nanoencapsulated FO showed better oxidative stability in response to lipid oxidation (Ojagh & Hasani, 2018). Similarly, Ghorbanzade et al. (2017) prepared FO-loaded NLPs via ULS stabilized with lecithin and sunflower oils. The liposomal dispersions were subjected to ULS for 7 min at 25 °C using a probe sonicator set at 80% of its maximum power. The study demonstrated that NLPs loaded with FO had higher levels of DHA and EPA compared to free FO. Furthermore, NLPs loaded with FO demonstrated a decrease in peroxide value, syneresis, and acidity, along with an elevation in DHA and EPA levels. In addition, the sensory features of the yoghurt supplemented with NLPs did not exhibit any significant changes after storing for 21 days (Ghorbanzade et al., 2017). In another work, Valencia-Sullca et al. (2016) prepared eugenol and cinnamon EO-loaded NLPs stabilized with lecithin by ULS at 20 kHz and 10 min. These NLPs were further incorporated into the chitosan-based films, which provided fine and micro-structured films due to nano-sized liposomes. The study established that the microstructure improved the flexibility of the films while decreasing their hardness. By introducing NLPs, the optical characteristics of the films were modified (Valencia-Sullca et al., 2016).

6.1.3. Dietary oil-loaded SLNs

SLNs can be defined as carriers made by physiological lipids dispersed in water and consist of a size range between 50 and 1000 nm. SLNs are spherical-shaped particles **(Fig. 4D)**, able to increase the stability and bioavailability of entrapped DOs as well as improve their stability. In addition, there is no specific solvent needed for their fabrication and modification. ULS has been referred to as an emerging approach for manufacturing SLNs. It has been proposed that EO-loaded SLNs can be used to eradicate pathogens. In one study, Fazly Bazzaz et al. (2018) prepared T80 and Poloxamer 188-based SLNs with ULS and high-shear homogenization (HSH) approaches, comprising *E. caryophyllata* EO. SLNs were first produced by HSH, and then passed through ULS by a probe sonicator in order to obtain the fine size of 397.1 nm. Probe sonication was accomplished over 9 cycles with 30 s ULS. TEM images confirmed the spherical shape of SLNs, proposing an EE= 70%. Additionally, the MIC and MBC values of SLNs loaded with EOs were lower compared to those of the oil without SLNs. Moreover, the time-kill studies showed that the EO-loaded SLNs were either as effective as or superior to EOs (Fazly Bazzaz et al., 2018).

6.1.4. Dietary oil-loaded NLCs

NLCs are mediated through a mixture of aqueous fluid and solid lipids, which serve as the innermost layers, along with emulsifiers in water that make up the external layers (Rehman, Jafari, Aadil, et al., 2020). Generally, they are recognized as the modified version of SLNs. However, the primary distinction between the two lies in the fact that NLCs contain an aqueous fluid, which replaces 5−40% of the solid segment. The main aim of manufacturing NLCs (**Fig. 4E**) is to enhance loading proficiency as well as the controlled release of entrapped bioactives to targeted sites. Furthermore, NLCs are known for their high EE, minimum changes in particle sizes, and higher colloidal stability (Mitrea & Meghea, 2013). As an example, ω-3 FAs-loaded NLCs, stabilized by Poloxamer 407 (a non-ionic surfactant), were sonicated at 100–400 W for 10 min at 85°C. The acquired NLCs exhibited a size < 100 nm, improved stability, and demonstrated an enhanced ability to withstand the oxidation of lipid particles. The study revealed that EE of FO in NLCs exhibited greater efficacy in hindering primary and secondary oxidative products (Shahparast et al., 2019). Another study conducted by Mitrea and Meghea (2013) revealed that NLCs containing a blend of soybean lecithin, Poloxamer 407, and T80 as the primary components were able to encapsulate FO with the aid of HSH and ULS. The resulting NLCs exhibited superior stability and the smallest particle size. The process of melting emulsification was executed through HSH; subsequently, the aqueous dispersions of NLCs underwent ULS for 9 min, with particle size analysis being conducted after every 3 min of ULS. The results indicated a reduction in the average particle diameter from 271 to 231 nm (Mitrea & Meghea, 2013).

Cardamom EO (CAEO)-loaded NLCs were also produced with the help of cocoa butter as an emulsifier through HSH and ULS. For preparing an emulsion, after HSH process, ULS was performed with T80 emulsifier. For this purpose, the operating conditions of ULS were set at 70% amplitude, 200 W power, and 24 kHz at 50°C for 10 cycles with a one-minute interval. The structure and size of NLCs was depending on their composition, e.g., the composition of lipid, emulsifier, and type of lipid, as well as their preparation procedure, e.g., emulsification method, cooling rate, and ULS procedure. The CAEO-loaded NLCs showed fine sizes (<150 nm), good loading capacity (> 25%), and high EE (>90%). This work permitted the use of CAEO-loaded NLCs in aqueous-based foods, i.e., beverages (Nahr et al., 2018). In another study, NLCs were prepared from beeswax, propolis wax, and PSO, stabilized by a mixture of stabilizers (T80 and lecithin), and subjected to ULS. When the primary emulsion was ready by the melt emulsification method, it was directly treated by a probe sonicator for 8 min. The prepared emulsion was cooled in an ice bath for 30 min to recrystallize the lipids in order to produce NLCs. This method offered better physical stability and provided spherical-shaped NLCs (71−350 nm). The propolis wax and a mixture of beeswax and glycerol behenate, encompassing 10% oil and 6% surfactant was reported as optimum formulation in this study (Soleimanian et al., 2018). Zhu and colleagues (2015) successfully developed krill oil-loaded NLCs to explore their further application in functional drinks. NLCs had a spherical structure with the smallest size of 150 nm and a high EE= 96%, as well as being significantly protected from photo-oxidation when exposed to ultraviolet irradiations. It was proposed that NLCs could be used for the fortification of milk powders as well as for the preparation of functional foods (Zhu et al., 2015).

6.2. Ultrasonically embedded DO-loaded biopolymeric nanocarriers

The utilization of biopolymeric nanocarriers as delivery systems has yielded positive outcomes. There exists a wide variety of biopolymers that offer distinct advantages, including but not limited to, high loading capacity, facile engineering of targeted carriers, highly modifiable surfaces, and easy preparation. These biopolymers can be utilized for coating, entrapping, or encapsulating functional bioactives, such as DOs. One of the primary considerations when choosing a biopolymer to serve as a wall material for the encapsulation of DOs is its status as GRAS (Rehman, Jafari, Tong, Riaz, et al., 2020). Biopolymeric nanocarriers may be produced using either single biopolymers or through the combination of two distinct biopolymers, such as protein and polysaccharide nanocomplexes (Rehman, Qunyi, et al., 2021). **Table 3** provides an overview of recently published research on biopolymeric UPNs for encapsulating various DOs.

Table 3: Brief description of ultrasonically fabricated biopolymeric nanocarriers encapsulating dietary oils.

Encapsulating material	Nanocarrier	Entrapped oil	Processing conditions	Particle size (nm)	Zeta potential (mV)	Encapsulation efficiency (%)	Conclusive outcomes	Ref.
Soy protein isolate	Nanoparticles	*Llitsea cubeba* EO	500 W, 5 min	243.15	−25.12	81.76	The lentinan film with nanoparticles had the highest break elongation (196%) and lowest oxygen permeability (12 meq/kg). It has good tensile strength, water vapor barrier,	(Cui et al., 2023)

							antimicrobial activity, oxidation resistance, and thermal stability.	
Chitosan	Nano particles	Cardamom EO	35 k Hz	100	50	90	The cardamom EO loaded with chitosan had excellent antibacterial properties as well as it showed non-cytotoxic behavior on human corneal epithelial cells	(Jamil et al., 2016)
GA	Nanoparticles	Fish oil	24 kHz, 120 s	36.67	NM	87.17	GA-enriched fish oil was utilized to fortify milk and exhibited a high level of probiotic microorganisms. The enriched milk contained significant levels of EPA and DHA.	(Moghadam et al., 2019b)
Whey protein concentrate (WPC) and pectin	Nanocomplex	Rose essential oil (REO)	20 kHz with a 12 mm probe, 350 W 10 min,	6.96 to 21.80	-15.7	96.97	REO-loaded nanocomplexes were found to be stable at pH 3, with the highest porosity and solubility of 0.912 and 52%, respectively.	(Heydari et al., 2021)
Chitosan (CS) and sodium alginate (AL)	Nanoparticles	Sacha inchi oil	24 kHz, 300 W, 3 min	320-340	−22 to +35	30-35	The sacha inchi oil-loaded nanoparticles demonstrated the highest antioxidant activity and phase stability throughout time. Sacha inchi oil encapsulated in AL-CS nanoparticles showed potential for controlled drug release due to its stability.	(Elgegren et al., 2019)

Sodium dodecyl sulphate	Nano hydro gel	Sunflower oil	20 kHz, 300 W, 30 min	171	NM	NM	The viscosity and storage modulus had increased and droplet size decreased. The nano gels were formed at 40 wt % oil content.	(Nejatian et al., 2018)
Sodium caseinate and GA	Nano complex	Fish oil	55 amplitude, 2 min	232. 3	NM	78.88	The fruit juice supplemented with FO-loaded sodium caseinate and GA complex contained no saturated FAs but was rich in unsaturated FAs.	(Ilyasoglu et al., 2014)

6.2.1. Biopolymeric dietary oil-loaded nanoparticles

Nanoparticles (NPs), which are defined as particles smaller than one micron (**Fig. 5A**), are used for the encapsulation of a wide range of bioactive compounds. Two fundamental techniques are employed in the fabrication of polymeric nanoparticles. One approach pertains to natural molecules, whereas the other entails the process of dispersing and solubilizing polymers (Rashidinejad et al., 2022). As efficient carriers, NP-based biopolymers loaded with DOs are frequently suggested as an attractive alternative for improving the solubility and stability of a variety of DOs. For example, chitosan nanoparticles loaded with CAEO were synthesized via ionic gelation solutions and ULS. The obtained NPs ranged in diameter from 50 to 100 nm and possessed an EE of 90%. Regarding both human corneal epithelial cells and HepG2 cell lines, the cytotoxicity analysis revealed that no cytotoxic or hemolytic effects were detected. The antimicrobial properties of NPs against *E. coli* and *S. aureus* were found to be remarkable in this study (Jamil et al., 2016). Moghadam et al. (2019) conducted an additional study wherein they synthesized an emulsion of FO stabilized with GA by means of sonication at 24 kHz for 120 sec. Subsequently, NPs with the highest EE (87.17%) were produced by passing the emulsion through a freeze-dryer (Moghadam et al., 2019a). Based on the findings of these studies, it appears that the incorporation of oil-loaded biopolymeric NPs into food items, including bread, could enhance their nutritional content and strengthen human immunity.

6.2.2. Biopolymeric dietary oil-loaded nanohydrogels

Hydrogels are composed of 3D solid-like structures made physically or chemically via cross-linked hydrophilic polymeric assemblies that are able to hold up the maximum quantity of biological liquids or water inside their network. Molecular interaction of polymer and liquid, osmosis, and capillary forces are those leading aspects that make the hydrogels able to engage the liquids and may employ vital effects on the dimension and assembly of the gels. However, hydrogels can be developed in different physical states, including coatings, films, microparticles, and NPs (Gul et al., 2022). Moreover, hydrogel particles can develop at the nanoscale; examples of these are the nanogels, or nanohydrogels, shown in **Fig. 5B** (Abaee et al., 2017; Rehman, Ahmad, et al., 2019). Recently, ULS has shown potential to produce nanogels holding a large amount of the sunflower oil, emulsified by sodium dodecyl sulphate as an emulsifier. The nanohydrogels (comprising 40, 50, and 60% of the total oil) were sonicated for 3, 9, and 30 min, and then concentrated emulsions were made by mixing a higher fraction of the oil with an aqueous phase. In this study, ULS of the nanohydrogel for 9 min was found to be more stable, with an average size of 158–171 nm at a low surfactant/oil ratio of 0.7:10. Therefore, on the basis of fine particle size and textural modifications, such nanohydrogels are useful for manufacturing reduced-fat gel-like products (Nejatian et al., 2018).

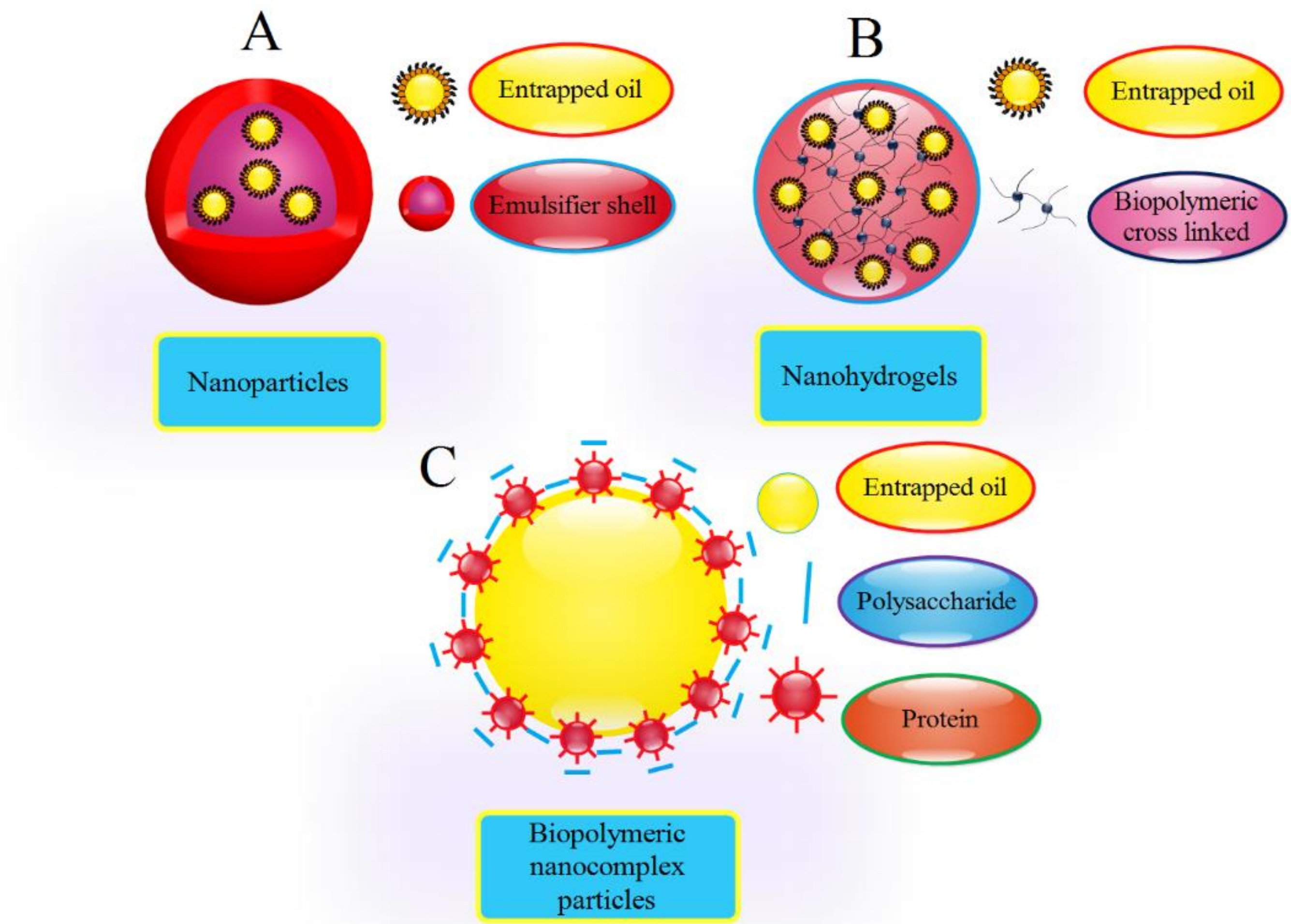

Fig. 5. Illustration of different ultrasonically prepared oil-loaded biopolymeric nanocarriers. (A) Nanoparticles; (B) Nanohydrogels; (C) nanocomplexes.

6.2.3. Biopolymeric dietary oil-loaded nanocomplexes

Biopolymeric complexes have a wide range of beneficial qualities due to the synergistic interactions between various functional groups of several biopolymers, such as amino and carboxyl groups (Rehman, Tong, Korma, et al., 2021). Various biopolymeric complexes are used as encapsulants for encapsulating DOs, as shown in **Fig. 5C**. Recently, many bioactive compounds have been enclosed and safeguarded by nanocomplexes composed of polysaccharides, proteins, or a combination of both (Hosseini et al., 2017). As an example, sodium caseinate (SC) and GA-based complexes encapsulating the FO exhibited robust electrostatic interactions. The mixture of SC-GA complexes and FO was first homogenized using a high-speed homogenizer (HSH) and then subjected to ULS with the parameters of 55 amplitude for 2 min while being kept cold with ice. The particle size obtained was 232.3 nm, with an encapsulation efficiency of 78.88%. *In vitro* investigations showed that the bioaccessibility of EPA + DHA, EPA, and DHA were 47.37%, 56.16%, and 36.25%, respectively. Protein-polysaccharide complexes containing hydrophobic compounds such as EPA and DHA may be a more efficient method for enhancing beverages (Ilyasoglu et al., 2014).

7. Application of ultrasonically produced dietary oil-loaded nanocarriers in food products

Nanocarriers, particularly lipid-based ones, are recommended to fortify food items with encapsulated bioactives, such as DOs, that may have a vital role in boosting the immune system (Khorasani et al., 2018; Rashidinejad et al., 2022). Oil-loaded nanocarriers have a stable consistency that makes them able to be utilized in the food sector to fortify products based on liquid-like beverages, such as nectar, containing water-insoluble antioxidants. Ultimately, oil-loaded nanocarriers cause no changes, specifically in the viscosity, quality, or other physiochemical characteristics of food (Shanmugam & Ashokkumar, 2015). **Table 4** contains numerous case studies covering diverse applications of oil-loaded UPNs in functional foods.

Table 4. Different applications of ultrasonically fabricated nanocarriers in food products.

Oils	Ultrasonically prepared nanocarriers	Applications	Potential outcomes	References
Fish oil	Nanocomplexes	Functional yogurt	Encapsulating fish oil with BCD boosted EPA and DHA but decreased yogurt's acidity, peroxide value, and syneresis. The results showed that yoghurt enriched with encapsulated fish oil possesses sensory attributes more in line with the control sample.	(Ghorbanzade et al., 2022)
Flaxseed oil (FSO)	Nanoemulsion	Dairy emulsion	The milk proteins helped to stabilize the emulsion. The minimum process of 3 min was recommended to produce the stable emulsion of 7% FSO and milk	(Shanmugam & Ashokkumar, 2014)
		Carrot juice emulsion	The sonication process allowed the production of stable emulsion of FSO in carrot juice. The	

			sonication had increased the carotenoid content to about 1.5 mg/100 mL of juice.	
Cinnamon EO		Bactericidal activity in minimally processed food	The cinnamon EO nano emulsion showed significant bactericidal activity against *B. cereus*. This antibacterial activity is due to the important bioactive component of cinnamon i.e., eugenol	(Ghosh, Saranya, Mukherjee, & Chandrasekaran, 2013)
Eucalyptus EO		Antibacterial and wound healing activity	Eucalyptus nano emulsion worked against *Staphylococcus aureus*. It damaged the bacterial cell membrane. The wound healing property was also observed in Wistarn rats.	(Sugumar et al., 2014)
Wheat germ oil		Functional Yoghurt	The authors observed that treating yogurt with wheat germ oil nanoemulsions increased all texture profile analytical measures, decreased syneresis, and reinforced pH and acidity throughout storage.	(Abu-El Khair et al., 2023)
Fish oil	Nano-liposomes	Functional bread	Bread enriched with nano liposomal fish oil had high loaf volume and no negative effect on textural and sensory properties of fish oil.	(Ojagh & Hasani, 2018)
		Fortification of yogurt	The yogurt fortified with the fish oil had high EPA and DHA contents as well as good sensory properties than yogurt containing free fish oil	(Ghorbanzade et al., 2017)
Cardamom EO	Nanostructured lipid carriers	Antibacterial activity, used as food supplements	The nano structured lipid carriers provided the protection to antibacterial activities of cardamom EO.	(Nahr et al., 2018)
Fish oil		Enrichment of food stuffs in particular clear beverages	ω-3 fish oil showed high oxidative stability and decreased the primary oxidative products. That is why it used to fortify the food stuff.	(Shahparast et al., 2019)
Zingiber zerumbet oil		Used for transdermal delivery system	Ultrasonically prepared nano structured lipid carrier of *Zingiber zerumbet* used as transdermal delivery system due to its size and stability. It enhanced the penetration to deeper layer.	(Rosli et al., 2015)
Bees wax, propolis wax, pomegranate seed oil		Antioxidant and anti-bacterial capacity	The functional nano carriers provided different health promoting properties due to complex composition of different lipid carriers	(Soleimanian et al., 2018)
Eugenia caryophyllata	Solid lipid nanocarriers	Antibacterial activity against	The ultrasonically prepared nano carriers of *Eugenia caryophyllatus* showed the antibacterial activity against the *Salmonella typhi*,	(Fazly Bazzaz et al., 2018)

		human pathogens	*Pseudomonas aeruginosa*, *S. aureus* and *Candida albicans*

As an example, an ultrasonically fabricated FSO-loaded emulsion stabilized with protein surfactant was added to the pasteurized homogenized skim milk that remained stable for 9 days at 4 °C. This stable dairy emulsion production was due to the ultrasound cavitation mechanism; it was proposed that FSO (the richest source of ω-3 FAs) can be used as a substitute for FO (Shanmugam & Ashokkumar, 2014). Another study covered the development of a pectin-based stable emulsion containing FSO in carrot juice using ULS at 20 kHz with 176 W power for 4 min. Pectin successfully provided stability to emulsions by creating electrostatic repulsion between emulsion droplets. The cavitation phenomenon owing to ULS offered the smallest droplet size as well as increased the carotenoid contents (approximately 1.5 mg/100 mL) in the juice. Also, the inherent properties of juice remained unaffected by ULS, and upon storage, the viscosity of the emulsion remained stable even after ULS for up to 8 min (Shanmugam & Ashokkumar, 2015). In another study, the effect of FO-loaded NLPs produced by ULS on the technological and sensory qualities of the fortified bread was examined. The nano-liposomal FO-enriched bread showed a higher bread loaf than others as well as improved the nutritional value of the bread. Furthermore, the enrichment of FO-loaded NLPs into the bread had no negative effects on the quality or sensory acceptability of the bread (Ojagh & Hasani, 2018). Moghadam et al. (2019) produced an ultrasonically fabricated emulsion encompassing FO stabilized with GA that was passed through a freeze-dryer to obtain NPs. The addition of FO-loaded NPs to fermented milk significantly increased the viability of *L. plantarum* as well as the enrichment of EPA and DHA contents (Moghadam et al., 2019b).

So far, various case studies have successfully investigated the role of oil-loaded UPNs in different food products that offer inspiring consequences in terms of nutritional worth. At the moment, there is still a need for factual understanding regarding the influence of diverse mixtures of emulsifiers used for nanocarriers as well as their stability, and this could be an important direction for future investigation. Particularly, researchers should focus on the combinations of natural emulsifiers, including phospholipids, proteins, polysaccharides, and saponins. Subsequently, there is a growing appeal provoked by consumers in order to acquire clean and safe products.

8. Safety and gastrointestinal fate of ultrasonically produced dietary oil-loaded nanocarriers

UPNs present a promising approach for improving the bioavailability and bioaccessibility of poorly soluble bioactives, such as DOs (Rehman, Jafari, Tong, Riaz, et al., 2020). This is achieved without any chemical interaction during handling and transportation to the intended sites within the body. Therefore, there is widespread utilization of UPNs in the field of drug delivery systems. Regardless, both the food industry and consumers have consistently expressed concerns regarding the safety and possible toxicity of nanocarriers owing to their diminutive particle dimensions (Lamch et al., 2018). Because variation in the particle size may enforce nanocarriers to behave alternatively on the effects of absorption, metabolism, and excretion within the human body, they may generate possible toxicity. Physiochemical properties such as dimensions, configurations, interfacial properties, and physical compositions are the main factors on which the biological fate of the nanocarriers and their alternation properties depend while passing through the GIT. **Fig. 6** depicts the mechanism designed to facilitate the GF of DOs from nanocarriers within the GIT. Bioavailability refers to the quantity of DOs assimilated from the intestinal contents after consumption. The process of bioavailability encompasses several stages, including absorption, release from the food matrix, metabolism, tissue distribution, and elimination. Alternatively, bioaccessibility can be defined as the maximum amount of encapsulated bioactives that can be released from nanocarriers within GIT environments and made readily available for absorption. The bioavailability evaluation of entrapped DOs can be conducted through *in vivo* or *in vitro* models (Rehman, Jafari, Tong, Riaz, et al., 2020). This involves administering an acute or chronic dose of an isolated constituent. On the other hand, the estimation of bioaccessibility is typically achieved through simulating gastric and small intestinal digestion using *in vitro* digestion protocols. Additionally, absorption can be assessed with the assistance of Caco-2 cells (Saravana et al., 2019a).

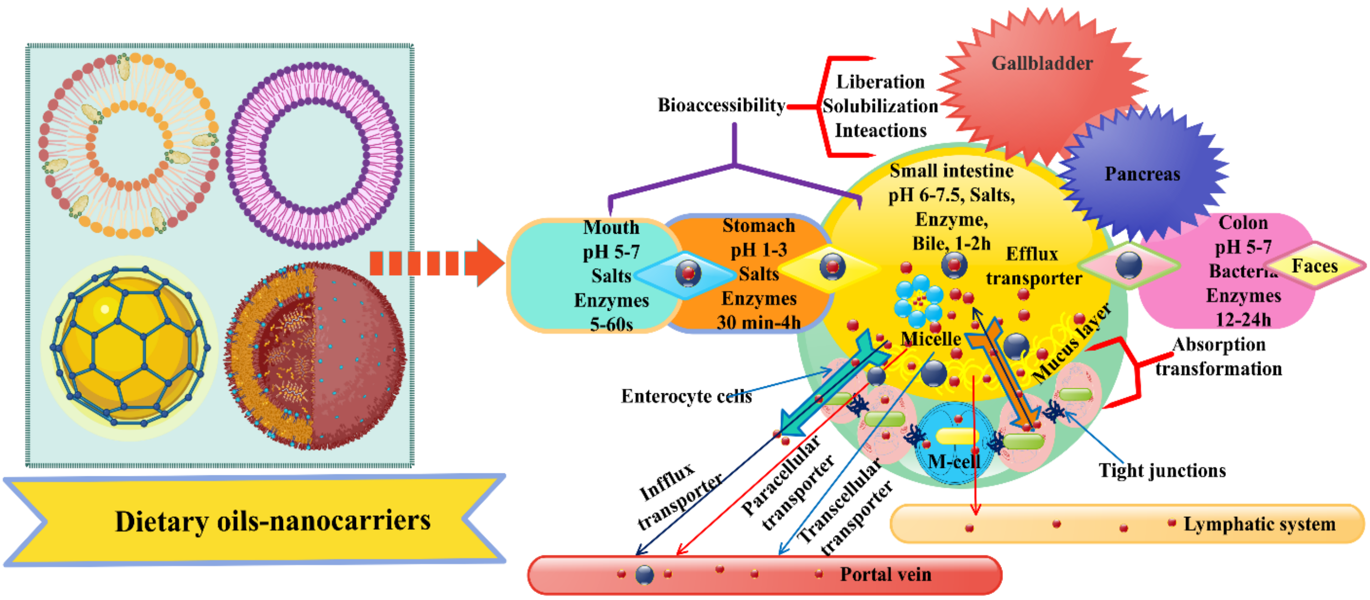

Fig. 6. The gastrointestinal fate of different dietary oil-loaded nanocarriers.

UPNs, on the other hand, are strongly advocated to boost bioavailability by illuminating surface-to-volume proportion and, in turn, to raise muco-adhesive prospects in the small intestine by improving the feasibility of intermixing with enzymes. Due to their ability to diffuse through the cell wall, these nanocarriers may make their way to their intended cells and release their cargo of DOs once they arrive (Rehman, Jafari, Aadil, et al., 2020). Numerous oil-loaded nanocarriers, some of which were developed with ULS, have proven to be resistant to the harsh physiological conditions found in the GIT. For instance, vitamin D was encapsulated into the FO-loaded T20-based NEs fabricated via ULS, which showed higher oral availability. These fabricated NEs showed a regular distribution with a size of 350–450 nm and EE= 95.7–98.2%, having a shelf life > 90 days. Also, vitamin D encapsulated in FO-based NEs showed higher gastrointestinal bioavailability compared to a non-encapsulated vitamin. This was due to the fact that, if a NE contained a high oil concentration, a thick layer of oil particles covered the vitamin molecule, showing a significant amount of mechanical strength against acidic conditions. Thus, the degradation of vitamin was decreased, and its bioavailability was enhanced under the simulated mouth and gastric phases. After the stomach phase, the free vitamin was degraded because of its exposure to acidic conditions (Walia et al., 2017b).

Another *in vitro* study on FSO-loaded alginate-whey protein NEs fabricated by ULS was conducted, in which particle sizes < 1000 nm with a spherical shape and uniform distribution were obtained. *In vitro* release profiles revealed great resistance to gastric digestion but increased release of the fatty compound during intestinal digestion. Also, FAs contents in FSO, especially ω-3 FAs, increased in thigh and breast meat. Moreover, the bioactives, due to their smallest particle size, had a large surface area, which allowed rapid penetration through the intestinal wall (Abbasi et al., 2019). Since the seaweed oil has antioxidant properties that contribute to the protection of the immune system from oxidative injury, K-carrageenan-based NEs were used to encapsulate the seaweed using ULS. This study explored whether K-carrageenan coating appreciably enhanced the bioaccessibility of fucoxanthin-rich oils in simulated digestion as well as showing positive results against different cancer cell lines (Saravana et al., 2019b).

The physical state, either solid or liquid, is an important feature on which the influence of lipid NPs depends when passing through GIT. Body temperature alters the composition very rapidly. For example, if a frozen product with a lipid portion passes through GIT, its lipid phase may melt due to body temperature, and if the lipid phase is present in hot food, it may crystallize. Food products that have dissolved bioactives in a crystalline phase precipitate when ingested, and bioactives are released into gastrointestinal juices (Li, Kim, et al., 2012). On the other hand, if an initially crystallized bioactive-based food product is ingested, it is then directly released into the gastrointestinal juices. So the initial composition of the lipid NPs is the cause, which tells about their biological fate, safety, and toxicity during their metabolism (Li, Zheng, et al., 2012). In another interesting study, Periasamy et al. (2016) prepared *N. sative* EO (NSEO)-loaded NEs by ULS and stabilized them with polysorbate 80 and water. This NSEO-loaded NE significantly minimized cell viability and changed the nuclear morphology in a dose-dependent manner. The findings indicated that NSEO-loaded NEs encouraged the apoptosis phenomenon inside the MCF-7 cancer cells (Periasamy et al., 2016).

There are a number of environmental factors that can affect the targeted and controlled release of oil-loaded UPNs within GIT surroundings. For instance, when any food or food product composed of oil-loaded UPNs is ingested, the first environment it faces is the mouth or oral cavity. When food products containing oil-loaded UPNs are ingested, they may experience conformational alternations and changes in structure; as a result, they are mixed with saliva, dissolved, and diluted. Within the GIT environment, changes in pH and temperature are the major factors that cause digestive enzymes to act. Food is further entered into the gastric cavity, or stomach, after passing through the esophagus. In the stomach, lipid-NP-based ingested food is susceptible to varying physical changes like pH changes between 1 and 3 due to the action of a strong acid, proteases and lipases (enzyme activity), the incorporation of sodium and calcium salts (ionic strength), and the act of proteins and phospholipids (surface-active compounds) (Karim et al., 2022). The gastric phase causes strong physiochemical variations in the lipid-based NPs. After the action of gastric situations, chyme gush (food material leaving the stomach) is passed through the pylorous sphincter (small muscular valve), which is responsible for the action of the small intestine and capable of controlling the amount of food entering the small intestine (Karamanidou et al., 2016).

Chyme mixed with different fluids and a material having an alkaline nature, for instance, pancreatic lipase, bile salts, bicarbonates, and other salts, may ultimately increase the pH to neutral. This mixing towards the alkaline path helps to digest different macronutrients so that they are easily absorbed by the epithelium. Within the conversion that takes place in the small intestine, colloidal structures are formed, which help in the digestion of micro- and macronutrients within the small intestine. The gastric system consumed a substantial quantity of sustenance and subsequently processed it, with a significant portion progressing towards the colonic region. If lipid NPs with a high number of fabricated components are ingested, then it may be the single component that goes towards digestion in the stomach and then the small intestine. Some microbes present within the colon or intestine help to digest, absorb, or utilize the components of ingested food (McClements, 2013). After digestion, absorption of lipid-based NPs takes place in lumen epithelium cells on the surface. Then it may be transported to the circulation system of the body through varying processes. The biological fate of lipid-based nanocarriers completely depends on the initial concentration and conformation of their structure. It provides the stability and bioavailability of bioactives within the body, but at the same time, different health issues occur due to its formation strategies and digestion parameters. Lipid nanocarriers require a large surface area to digest, which sometimes causes a partial effect on health concerns. Above all, the importance of lipid- or oil-loaded nanocarriers in the food industry with potential benefits for the body is never neglected.

9. Limitations, challenges, and regulatory concerns of dietary oil-loaded nanocarriers

There may be potential safety risks associated with smaller droplet sizes of ultrasonically prepared DOs-loaded nanocarriers due to alterations in the functionality of the GIT. However, their biological fate in the GIT should be taken into account, depending on the kind of DOs-loaded nanocarriers or nanodroplets utilized in the food systems. The nano-sized droplets of DOs-loaded nanocarriers have a high surface area, leading to rapid digestion by the enzymes in the GIT. This effectively minimizes the risk of toxicity that may result from their accumulation in the cells of the gastrointestinal organs (McClements & Xiao, 2017). Scientific reports mostly focus on accumulations or alterations in gastrointestinal functionality related to inorganic and metallic nanocarriers made of indigestible materials such as mineral oils, hydrocarbons, and dietary fibers. This occurs when nanodroplets quickly diffuse into the mucus layer of the gastrointestinal tract, allowing them to stay intact (Singh et al., 2021).

Additionally, the fabricating materials utilized in the composition of DOs-loaded nanocarriers may display hazardous properties at higher concentrations. Recent research indicates that using materials such as solvents, which can be harmful if not completely evaporated, is essential. Reducing the size of droplets in nanocarriers requires a greater amount of biopolymer to cover the larger surface area of the smaller droplets. This indicates that in order to fulfil the required daily intake of the compounds being used, a higher quantity of biopolymer is required (Rehman, Tong, Jafari, et al., 2020). Generally speaking, orally administered DOs-loaded nanocarriers composed of digestible components may have some intact nanodroplets that can enter epithelial cells (Karim et al., 2022). However, the potential toxicity of this absorption is not well understood and requires further investigation. There is a scarcity of research on the interactions between DOs-loaded nanocarriers and biological systems, but the available literature offers insights into the interactions of DOs-loaded nanocarriers *in vivo* (Wani et al., 2018). There is a noticeable gap in the existing research and literature on the antibacterial properties of DOs-loaded nanocarriers. Evaluating the timing of the release and the features of these nanocarriers is essential, considering the potential impact of the active compounds on the microbial flora or epithelial cells of the GIT.

Natural DOs (consisting of SOs, EOs, and MOs) that are categorized as food additives are primarily supervised by the Food and Drug Administration (FDA) of the United States, the European Food Safety Authority (EFSA), and the China Food Additives and Ingredients Association (Donsì & Ferrari, 2016). At present, there is no international regulatory organization monitoring nanocarriers; despite this, regional regulations in the field of food nanotechnology have been implemented by the European Union and Switzerland. The regulation of food nanotechnology falls under the authority of the European Parliament and Council as novel food additives and novel food components. Regarding regulations pertaining to nanotechnology products, the FDA has issued industry recommendations (Amenta et al., 2015; Wani et al., 2018).

10. Concluding remarks and perspectives

The focus of this article is on the significance and effects of ULS on DOs-loaded nanocarriers. Oils derived from various plants and animals serve numerous biological purposes. Therefore, many studies have effectively entrapped oils within various nanocarriers to achieve the required results. It is worth noting that UPNs, such as NEs and NLPs, are more suitable for precisely transporting and encapsulating DOs. Through the use of ultrasonic technology, the droplet size was reduced, leading to an improvement in the encapsulation efficiency of the compounds. In conclusion, ULS has demonstrated beneficial effects on the dimensions of lipid and biopolymeric nanocarriers incorporating certain oils. Both the food and pharmaceutical sectors can reap the advantages of utilizing DOs in a diverse range of applications due to the potential of nanoencapsulation. The digestion and absorption of lipid-based UPNs are heavily influenced by their composition, which can be modified by various factors like changes in pH and temperature, both of which can be controlled through specific compositional adjustments.

ULS provides substantial advantages in the design and performance of nanocarriers, as previously discussed. It has the ability to enhance bioavailability, control, and accurately release drugs at specific target sites within the body. This article offers a thorough examination of recent research that has made notable progress in understanding the effectiveness and controlled release mechanism of DOs-loaded UPNs. The study's findings suggest that UPNs have distinct characteristics related to their adaptability in structure and function. These characteristics could have important implications for the development of various technological applications. However, further investigations are required to apply these proof-of-concept models to real-world scenarios. The following suggestions are proposed for future research endeavors: (1) The analysis of the attributes of biopolymeric nanocarriers loaded with DOs in the context of pharmaceutical, health, and cosmetic applications can be undertaken considering their appealing taste and fragrance, along with the noteworthy properties demonstrated by these DOs in enhancing human welfare. (2) The impact of various storage circumstances, including temperature, duration of time, relative humidity, and type of packaging, on the physicochemical and microbiological properties of functional food enriched with DOs-loaded biopolymeric nanocarriers needs to be further studied. We hope that this comprehensive evaluation will inspire researchers from various fields, including biochemistry, food science, bioscience, and materials science, to continue their groundbreaking research efforts in developing DOs-loaded biopolymeric nanoencapsulated functional foods with exceptional performance.

Author contribution

Abdur Rehman: Conceptualization, Investigation, Writing – review & editing. **Seid Mahdi Jafari:** Conceptualization, Visualization Writing-review & editing. **Aiman Karim:** Writing. **Hafiz Abdul Rasheed:** Writing. **Elham Assadpour:** Editing. **Muhammad Safiullah Virk:** Writing. **Qiufang Liang:** Writing. **Hafiz Ansar Rasul Suleria:** Writing – review & editing. **Renyou Gan:** Supervision. **Xiaofeng Ren:** Supervision, Project administration, Investigation, Writing-review & editing, Funding acquisition. All authors equally contributed to the study conception and design. All authors read and approved the final manuscript.

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Data Availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

Declarations

Ethics Approval

This review article does not include any human or animal studies performed by any author.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Conflict of Interest

The authors declare no competing interests

Abbreviations

Borage seed oil	BSO
Clove essential oil	CEO
Decosahexaenoic acid	DHA
Ecosapentaenoic acid	EPA
Essential oils	EOs
Eucalyptus essential oil	EEO
Fish oil	FO
Flaxseed oil	FSO

Gastrointestinal fate	GF
Gastrointestinal tract	GIT
Generally recognized as safe	GRAS
Gum Arabic	GA
Marine oils	MOs
Minimum inhibitory concentrations	MIC
Nanostructured lipid carriers	NLCs
Nettle essential oil	NEO
Orange peel essential oil	OPEO
Peppermint essential oil	PEO
Polyunsaturated fatty acids	PUFA
Seed oils	SOs
Solid lipid nanoparticles	SLNs
Whey protein isolate	WPI

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