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Recent trends in the encapsulation of functional lipids: comprehensive review

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Recently, the demand for natural foods with promising health benefits has increased daily. Functional lipids such as omega 3 fatty acids, omega 6 fatty acids, linoleic acid, conjugated linoleic acid, carotenoids, and other functional compounds have many beneficial effects on human health, such as cardiovascular diseases, mental disorders, and metabolic disorders such as diabetes. The application of such substances in food matrices is often hindered by their poor solubility in water, unpleasant flavor, low oral bioavailability and low stability during storage and gastrointestinal interactions. Several encapsulation techniques have been used to address these issues and make these compounds bioaccessible and bioavailable. In the present review, the current knowledge of encapsulation delivery systems with suitable wall materials for functional lipids and their production techniques and the mechanism and behavior of the wall and core matrix are discussed. Additionally, the impact of such encapsulation delivery systems on the stability of encapsulated functional lipids in storage as well as the gastrointestinal environment has been discussed. Furthermore, this review highlights the impact of encapsulated functional lipids on the fortification of staple foods in terms of enhanced physicochemical, functional and nutritional profiles. Finally, the review article concludes with the factors affecting the commercialization of these encapsulated functional lipids.

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Sustainability spotlight

In this extensive review, the current knowledge of encapsulation delivery systems with suitable wall materials for functional lipids and their production techniques and the mechanism and behavior of the wall and core matrix are discussed. Additionally, the impact of such encapsulation delivery systems on the stability of encapsulated functional lipids in storage as well as the gastrointestinal environment has been discussed. This work is related to UN's Sustainable Development, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round as encapsulations have the following advantages: address formulation issues related to restricted chemical or physical stability of active ingredients overcome the incompatibility of active component and food matrix, regulate the release of a sensory active compound, help or enhance nutrition absorption.

1. Introduction

The increasing demand for safe and sustained nutrition, supported by the rapid growth in nutraceuticals, superfoods, and functional foods, has significantly spurred interest in encapsulation technology.[1] The controlled release of functional compounds over time is often preferred by researchers and industry professionals in the nutraceutical field, as it can increase the bioavailability and efficacy of these compounds. This method is particularly beneficial in contexts where sustained delivery is needed to maintain optimal therapeutic levels in the body over an extended period, reducing the need for frequent dosing and improving patient compliance. From a technological perspective, an efficient delivery system should incorporate functional ingredients into food systems with greater physicochemical stability and minimal impact on the sensory attributes of food products.[2,3] Moreover, encapsulation techniques should maximize the uptake of encapsulated compounds upon consumption and ensure controlled release in response to specific biological conditions.[4] Functional compounds, which are often hydrophobic, tend to degrade during processing or within the body and have rapid clearance rates, leading to poor bioavailability.[5] The encapsulation of

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Table 1 Selected commercially available functional lipid supplements: sources, lipid types, and delivery systems[a]

Product name	Source	Functional lipids	Delivery system	Reference
Mar in Oil®	Salmon oil	EPA/DHA	Soft gels	23
Nature's Bounty®	Herring, anchovy, mackerel, sardine oils	EPA/DHA	Gummies, capsules	24
Jamieson®	Wild salmon fish oil complex	EPA/DHA	Gummies	25
CLA One®	—	CLA	Capsules	23
Nutra Vege®	Algal oil	DHA	Soft gels	29
Nordic Naturals®	Plant based oil	ALA, ARA, LA	Soft gels	27
Rx Omega3®	Flaxseed oil	LA, ALA	Soft gels	28
Neptune Krill 1000®	Krill oil	EPA/DHA	Soft gels	30
Source Naturals® Phytosterol complex	Plant based oil	β-Sterols and phytosterol complex	Tablets	31
Clear Muscle®	—	ARA	Liquid caps	32
Pometane®	Pomegranate oil	Punicic acid	Soft gels	33
Deep blue®	Shark liver oil	Squalene	Capsules	34
NOW® by Abbot Pharmaceuticals	Evening prime rose oil	ω-6 fatty acids	Soft gels	35
Jarrow Formulas, Borage®	—	GLA	Soft gels	36
NOW foods, astaxanthin	Fish and shellfish	Astaxanthin	Soft gels	35
Fucothin®	Seaweed	Fucoxanthin	Capsules	37

[a] This table provides a selection of commercially available functional lipid supplements from various regions. It highlights key examples rather than offering an exhaustive list of all products available on the market. LA-linoleic acid, ALA-α-linoleic acid, EPA-eicosapentaenoic acid, DHA-docosahexaenoic acid, CLA-conjugated linoleic acid, GLA-γ-linoleic acid, ARA-arachidonic acid.

these compounds is crucial for efficient delivery. Researchers have focused on increasing bioavailability through novel encapsulation techniques.[5–7] Among these functional compounds, functional lipids stand out because of their numerous health benefits.

Functional lipids such as omega 3 fatty acids, omega 6 fatty acids, linoleic acid, conjugated linoleic acid, carotenoids, and other functional compounds have many beneficial effects on human health, such as cardiovascular diseases, mental disorders, and metabolic disorders such as diabetes.[8] These compounds are available in a wide range of natural sources, such as vegetables, seeds, meat, fish, algae and microbes, and have tended to constitute an integral part of the human diet for many years.[9] However, several researchers have reported that the direct consumption of such functional lipids still does not satisfy the minimum dietary intake level, which can be a consequence of improper dietary patterns, the geographical distribution of sources, and the limited availability of sources.[10–13]

Over the last few decades, researchers have developed various techniques and formulations to make functional lipids more accessible and convenient for consumers.[14–16] Among these, oils rich in functional lipids have become one of the most widely available and commonly used products. Oils extracted from plant sources such as walnut, linseed, canola and flaxseed are rich in α-linoleic acid.[8,17–19] Fish oils are rich sources of ω-3 fatty acids (O3FAs), especially eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), and have been used to make dietary supplements.[20–22] Various types of nonencapsulated delivery systems are available for the convenient supply of functional lipids as dietary supplements.[23] The most commonly used dietary supplements of functional lipids are O3FAs and ω-6 fatty acids (O6FAs). Fish oils entrapped by soft gels, flavored gummies and capsules are the most preferred options for the oral delivery of O3FA, which can mask the odd flavor and odor of the fish oil.[24,25] Plant-based oils, including flaxseed oil, primrose oil and pomegranate oils, are also entrapped in soft gels and provide a dietary supply of arachidonic acid (ARA), linoleic acid (LA), α-linoleic acid (ALA), γ-linoleic acid[26] and conjugated linoleic acid (CLA).[27,28] Recently, several manufacturers have targeted algal oils as sustainable sources of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA).[29] Table 1 summarizes the commercially available functional lipid supplements and their nonencapsulated delivery systems.

Generally, marketed functional lipids are entrapped in gelatin-based capsules and soft gels and thus have poor GI stability and a shorter shelf life.[38–40] Moreover, functional lipids are unsaturated and hydrophobic in nature, so bioavailability and bioaccessibility can be major obstacles for oral delivery or food fortification.[4,5] Furthermore, commercially available dietary supplements contain synthetic antioxidants such as butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT) to prevent the oxidation of functional lipids, which are associated with certain adverse health concerns.[41] In addition to these disadvantages, the "burp effect" is inconvenient for the user. Encapsulation techniques are thus designed to protect functional lipids from adverse environmental conditions in foods, enhance water dispersibility, improve food matrix compatibility, reduce unpleasant sensory attributes, and increase GI stability and bioavailability.[42–44] This review aims to provide a comprehensive overview of the current state of encapsulation technology for functional lipids by selecting and discussing seminal papers, key studies, and recent developments that have significantly impacted the field. Through this focused selection, we aim to

highlight the most relevant and influential research, offering insights into the latest advancements, challenges, and future directions in the encapsulation of functional lipids. By doing so, we intend to support further innovation and application in this promising area of nutraceuticals and functional foods.

2. Conventional encapsulation strategies for functional lipids

During the past few decades, researchers have developed various encapsulation technologies for improving the bioaccessibility of functional lipids.[45,46] Various types of wall materials and encapsulation strategies have been developed to ensure the increased oxidative stability of functional lipids either incorporated in food or consumed orally.[47,48] The most common encapsulation techniques used for the majority of nutraceutical compounds are drying-based delivery systems for functional compounds.[49] Spray drying and freeze drying are the most common drying methods for encapsulating functional lipids.

Spray drying is one of the most commonly used encapsulation processes because of its low cost, simplicity, and flexibility. It yields high-quality powders and can preserve various vegetable and animal oils against oxidation as well as external deterioration influences such as humidity, light, and temperature. The processing time is only a few seconds, which is sufficient to preserve heat-sensitive components such as fatty acids.[50] Another benefit of encapsulation by spray drying is the capacity to decrease the amount of oil at the particle surface (nonencapsulated oil) and thus increase the encapsulation efficiency (EE).

Spray drying facilitates the preparation of the final product in powder form for better storage and transportation. The aqueous solution or dispersed lipids with wall materials are injected into the spray dryer in the form of sprayed particles, where the water is removed by the hot air in a fraction of time to obtain the powder form of the encapsulated particles. Spray drying provides a wide range of encapsulated functional lipids, including omega 3 fatty acids, EPA-rich oils, ALA-rich oils, and squalene.[51,52] Although spray drying is one of the most common methods for the encapsulation of functional lipids, some drawbacks have been linked to this process. For example, a major disadvantage is the use of hot air at high inlet temperatures, which can promote the volatilization and oxidation of some functional lipids. Several authors Encina *et al.*[51] have reported improvements in the oxidative stability of fish oil by spray drying with methanol (MeOH); Goyal *et al.*[53] reported the highest encapsulation efficiency and lowest peroxide values of flaxseed oil encapsulated *via* the spray drying process.

Recent advances in the encapsulation of essential fatty acids and other functional lipids through spray drying have been extensively reviewed. These reviews discuss challenges such as optimizing wall materials and process conditions to improve encapsulation efficiency and stability.[54] The detailed analysis of spray drying parameters highlights the impact of the inlet air temperature, total solids concentration, and wall materials on the encapsulation efficiency of oils.[52] Conventional and nanospray-drying technologies emphasize processing variables and their influence on powder characteristics, discussing advantages such as large yields in conventional spray drying and better preservation of active ingredients in nanospray drying.[55] Additionally, the encapsulation of various lipids, including essential oils, polyunsaturated fatty acids, and structured lipids, focuses on the selection of suitable encapsulating agents and the increasing trend of combining spray drying with other techniques to increase stability and bioavailability.[54]

Encapsulation by freeze-drying is achieved by drying an aqueous solution or dispersion containing functional lipids as core and wall materials. This causes the two components to colyophilize, usually resulting in a porous, nonshrunken, complex structure. Minimizing thermal degradation reactions has been shown to be a highly suitable method for drying heat-sensitive substances. Rezvankhah *et al.*[56] and Hasani *et al.*[57] thoroughly reviewed the encapsulation of functional lipids, especially omega 3 fatty acid-rich fish oils, by means of freeze drying. However, the porous structure within the freeze-dried matrix may increase the exposure of the encapsulated core matrix to air if the final product is not packed under vacuum or an inert atmosphere. The major disadvantages of this technology are the high consumption of energy, the long time required for processing, and the higher costs than those of other encapsulation techniques.

3. Recent advancements in delivery systems for the encapsulation of functional lipids

Over the past few decades, research has shifted toward the development of various delivery systems to increase the physiochemical and functional properties of encapsulates for better bioaccessibility and bioavailability of delivered drugs or functional compounds. The delivery systems have been modified by different encapsulation techniques along with food-grade carrier matrices to increase the feasibility of food fortification. Recent advances in delivery systems for the encapsulation of functional lipids are summarized in Table 2.

3.1. Biopolymer-based delivery systems

Currently, biopolymers, such as chitosan, alginate, whey proteins, gelatins, gum arabic, and zein, have attracted the interest of the scientific community as carrier matrices or wall materials for the encapsulation, immobilization, and controlled release of numerous functional lipids by various delivery systems, such as antisolvent precipitation, complex coacervation, inclusion complexes and solvent evaporation.

3.1.1. Antisolvent precipitation. Antisolvent precipitation has been achieved *via* phase transition methods, *i.e.*, mechanical stirring and ultrasonication, where the functional compounds are immobilized in a solution containing the biopolymer wall material (Fig. 1). Solvent molecule diffusion

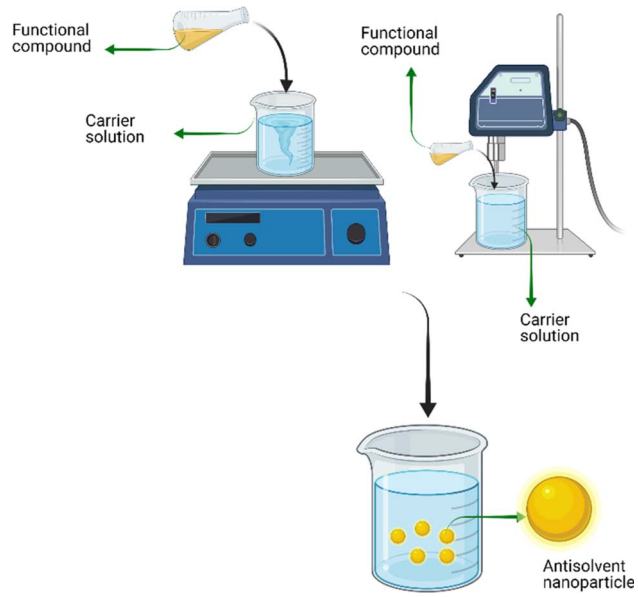

Fig. 1 Antisolvent precipitation.

results in the entrapment of functional lipids in the nanoparticles of the carriers.[85]

Fucoxanthin, a functional lipid-soluble algal pigment, was entrapped in the zein and casein wall matrix by mechanical stirring to obtain nanoparticles with a 100–130 nm particle size.[86] They reported that static quenching between fucoxanthin and the wall material increased the encapsulation efficiency, *i.e.*, >85%, and increased the heat and storage stability (Table 2).[59] developed a nanoencapsulated egg yolk pigment, lutein, *via* a similar technique with >80% encapsulation efficiency and a 140–200 nm particle size. They reported that the zein–lutein complexes formed noncovalent interactions *via* mechanical stirring, which increased the storage stability and release profile in gastric fluid (Table 2). Recently, the sonication method replaced mechanical stirring for phase transition, which provides a uniform distribution of encapsulants and increases the encapsulation efficiency of drug delivery systems. Sonication improved the zeta potential of the encapsulated particles, which might increase the stability of the zein–stigmasterol complex.[60]

The application of nanoparticles in food products is subject to stringent regulations, especially in Europe, where they are classified as novel foods. According to the European Food Safety Authority,[87] novel foods must undergo rigorous safety assessments that include evaluations of potential toxicity, absorption, distribution, metabolism, and excretion.[87] Products containing nanoparticles must be clearly labeled to inform consumers of their presence.[88] The authorization process requires companies to submit a detailed dossier with scientific evidence demonstrating the safety of the nanoparticle for its intended use, as reviewed by the EFSA.[89] Additionally, authorized novel foods are subject to ongoing monitoring to ensure safety and traceability, and environmental impact assessments must also be considered.[90] This regulatory framework ensures that the nanoparticles used in food products are safe for consumption and that consumers are well informed about their presence.

4.1.1.1 Emulsification solvent evaporation. Emulsification followed by solvent evaporation is a technique frequently used for the development of biopolymer-based nanospheres. Encapsulates containing functional compounds have been obtained by homogenizing an organic polymer solution with an aqueous phase, followed by solvent evaporation, which causes the polymer molecules to precipitate and form nanospheres (Fig. 2). Generally, high-pressure homogenization or ultrasonication techniques have been used for nanoparticles. In the case of functional lipids, O/W emulsions are most common when the aqueous phase is water, which acts as an antisolvent and provides more sustainability to the process.[91]

Recently, scientific research has explored the interaction between functional lipids and biopolymer composites such as zein and carboxy methyl cellulose (CMC) for the production of nanoparticles. For example, zein and fish oil-derived nanocomposites (100–120 nm) have higher encapsulation efficiency (98.8%), and high-pressure homogenization and solvent evaporation methods have been used to develop highly stable nanoparticles with better GI stability.[62] Furthermore, Soltani *et al.*[61] reported a reduction in oxidative gelation for zein-fish oil nanocomposites (73–265 nm). Similarly, carotenoids from red palm oil have been immobilized by CMC by high-pressure homogenization followed by freeze drying to achieve higher encapsulation efficiency (83–96%), better storage stability, enhanced GI stability and targeted drug delivery in the intestinal environment (Table 2).

3.1.2. Coacervation technique and ionic gelation. Coacervation is another simple, accepted, and one of the most practical techniques in micro- and nanoencapsulation. This technique employs two natural biodegradable polymers of

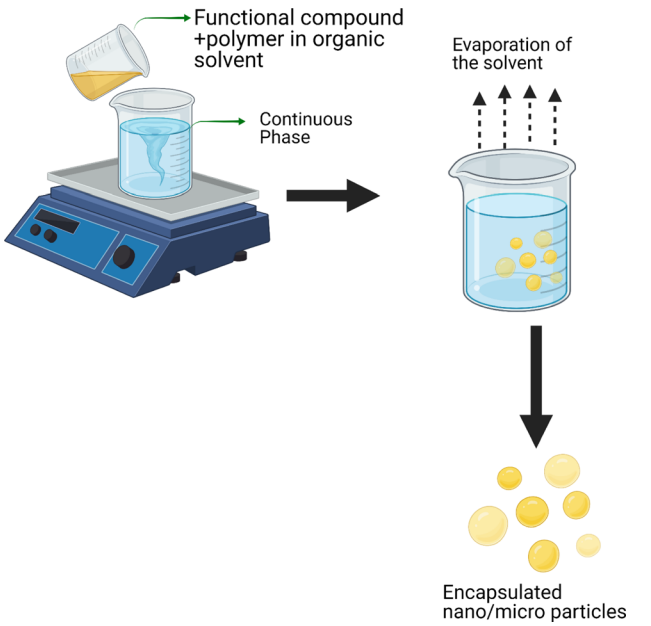

Fig. 2 Emulsification solvent evaporation.

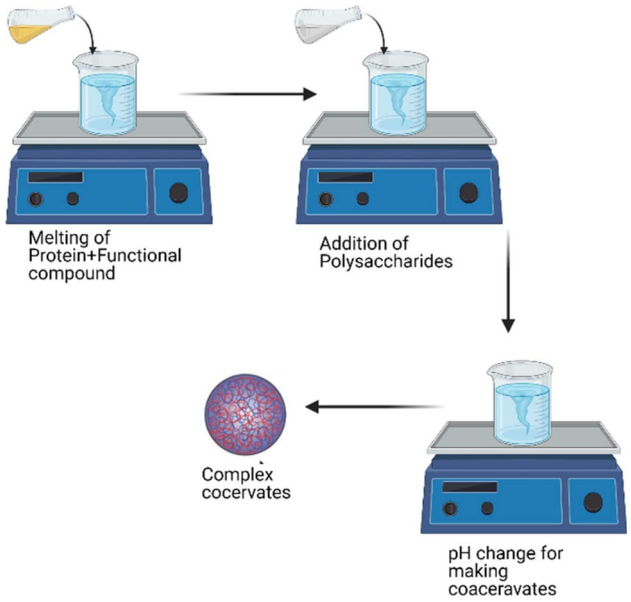

Fig. 3 Coacervation method (ionic gelation).

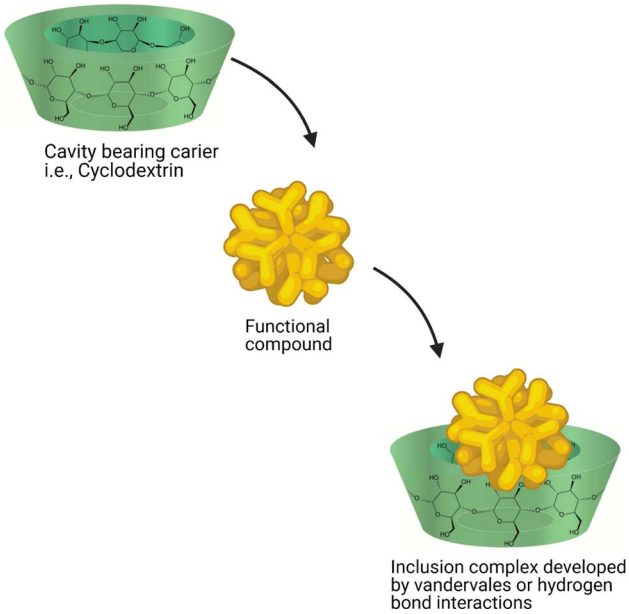

Fig. 4 Inclusion complex.

opposite charge. The most commonly used biopolymers are proteins and polysaccharides, and the pH shifting method is used to change the ionic potential of proteins to form ionic gels between two oppositely charged molecules. Controlled slow release of functional compounds without degeneration is the most promising advantage of complex coacervation. The functional or active compounds are slowly dissolved in the protein solution and may become entrapped in the coacervate during ionic gelation (Fig. 3). Table 2 summarizes the different nanoparticles consisting of functional lipids developed by complex coacervation.

Comunian *et al.*[64] reported that gelatin- and gum Arabic-based coacervation entrapped echium oil with high storage stability and 87% encapsulation efficiency.

The ovalbumin and sodium alginate microcapsule of sachainchi oil protected the acyl group in the omega-3 units, which ultimately reduced the rate of release of functional compounds in the GI tract and provided targeted drug delivery[65]. Rios-Mera *et al.*[66] developed a stable emulsion (94% encapsulation efficiency) consisting of cod liver oil by the complex coacervation of inulin and soy protein isolates, where they reported increased heat and GI stability at a simulated pH (Table 2). The complex coacervation provided minimum isomerization of pomegranate seed oil in microcapsules (8.36–10.96 μm) developed by using whey protein and gum Arabic as the wall matrix.[68]

3.1.3. Inclusion complex. The inclusion complex is based on well-known host–guest chemistry, where one chemical compound has a cavity, *i.e.*, a host, which can accommodate the functional compound, *i.e.*, a guest by Vander vales or hydrogen bond interactions (Fig. 4). Cyclodextrin[92] is the most popular host compound used as a carrier material for various functional lipids.

The perilla oil was more thermostable when it was included in the cavity of γ-CD than when it was placed in interspaces between pseudo rotaxane-type complexes.[69] However, the chemical affinity of functional compounds influences the encapsulation potential of inclusion complexes. For example, PUFA glycerides from anchovy oil are poorly encapsulated[93] in β-cyclodextrin under controlled crystallization conditions, whereas monounsaturated and especially saturated fatty acid glycerides are more appropriate for molecular encapsulation (99% EE). In addition to CDs, chemically modified biopolymers are also used as host compounds for inclusion complexes. Park *et al.*[71] developed a host compound by dextrinization by maize starch, which is used as a wall matrix for fish oil, where dextrinization improved the dispersion stability of the complex particles (Table 2).

3.1.4. Supercritical CO_2 process ($ScCO_2$). The supercritical CO_2 ($ScCO_2$) process is considered a sustainable and green delivery system for the micro- or nanoencapsulation of drugs for efficient drug delivery. The solvent used in this particular process is nontoxic, adjustable in terms of polarity, easy to remove and requires very little temperature, which makes this process more efficient for heat-labile functional compounds. As the solvent possesses a quadrupole moment, strongly polar compounds cannot be dissolved, making this process more feasible for hydrophobic functional compounds such as functional lipids.

This technology has been applied to various functional lipids to form micro- or nanoencapsulations by using different biopolymers as wall materials. Santos *et al.*[74] applied $ScCO_2$ to encapsulate lycopene pigments with *n*-octenyl succinic anhydride[94]-modified starch and reported that a supercritical extraction emulsion provided stable lycopene in aqueous media. The importance of supercritical CO_2 encapsulation techniques was highlighted by Tirado *et al.*[73] for the emulsification of shrimp oil, where *in vitro* release profiles in simulated intestinal fluid (SIF) at pH 7.2 and 310 K revealed 70% release of

the total encapsulated astaxanthin within 10 hours. Prieto *et al.*[95] successfully developed fish oil nanoparticles 6–73 nm in size from $ScCO_2$ with polycaprolactone as a wall matrix.

3.2. Electrohydrodynamic processing of encapsulation

Electrohydrodynamic processing of encapsulation refers to the development of nano- or microstructured particles by subjecting a polymeric fluid to a high-voltage electric field.[96] Generally, fluid is pumped through a conductive capillary where a voltage is applied. Owing to the higher surface/volume ratio and electric repulsion, the solvent in the fluid evaporates, and the dry material is deposited on the collector. The molecular cohesion of the polymer chains in the polymer fluid determines the final size and shape of the nanomaterial.[97] In addition, the functionality of the nanostructures produced by electrohydrodynamic processes can be achieved through the use of blends, coaxial electrospinning (resulting in core–shell structures), the inclusion of other functional molecules, and the adsorption of functional components to the surfaces of the nanomicrostructures.

3.2.1. Electrospinning. The electrospinning process is applied when the molecular cohesion between the polymeric chains in the polymer fluid is high enough, so the generated jet is elongated because of the balance of forces applied on it, and ultrathin fibers are produced upon drying.[97] As shown in Fig. 5, a homogeneous solution of a functional compound and polymer is subjected to an electric field to produce ultrathin fibers. In the case of core–shell electrospinning, the functional molecules can be precisely encapsulated in the core of the fibers. However, in monoaxial electrospinning, the distribution of the bioactive compound within the fibers is influenced by the properties of the solution and the polymer, and the functional molecules may not be uniformly encapsulated in the core but rather distributed throughout the fiber matrix.[98]

Moomand *et al.*[75] reported the distribution of fish oil in electrospun zein fibers, revealing that the lipid phase tended to concentrate at the core of the fibers and beads. They reported that the applied technique developed spun nanofibers (190 nm) with an increased encapsulation efficiency of O3FA of up to 91% (Table 2).

3.2.2. Electrospraying. Electrohydrodynamic atomization is based on the formation of small and uniform droplets by applying an electric field to a polymer solution that can pass through a small nozzle, termed electrospraying.[99] In the process of electrospinning, the molecular cohesion between the polymer chains of the polymer fluid decreases, so the generated jet is destabilized due to varicose instability, which results in the formation of fine highly charged droplets that are partially or fully solidified through solvent evaporation or cooling, and an electrically charged particle remains, which can be directed or accelerated by electrical forces and then collected.[100] As shown in Fig. 6, the functional compounds are dissolved in the organic solvent or water and electro sprayed at high voltage with a polymer solution, which can act as a core or shell for the functional compounds, followed by evaporation of the solvent.

Hu *et al.*[76] encapsulated (95% EE) ARA with a zein biopolymer *via* a coaxial spray technique, which produced natural and edible microcapsules (1–7 μm) with core–shell structures and reduced the unpleasant flavor. The electrospray technique provides low-temperature and fast evaporation characteristics and successfully stabilizes fish oil in zein microcapsules (2–3 μm) with an 84% EE of DHA.[72] Kafirin-based nanoencapsulated capsules (552–861 nm) loaded with fish oil (94% EE) obtained by electrospinning present a high surface-to-volume ratio, which is desirable for better release of the encapsulated bioactive compound.[77]

3.3. Lipid-based delivery system for functional lipids

Lipid-based delivery systems are wide-ranging designs for formulations containing active or functional compounds in dissolved or suspended forms in lipidic cores.[101] The melting range, solubilizing capacity and miscibility properties of the wall material depend on the fatty acid chain length and degree of unsaturation.[102] Lipid-based delivery systems can be developed as simple oils for more complex formulations, such as spontaneous emulsification in aqueous media, and are most suitable for lipid-soluble bioactive compounds and functional lipids.[43] Lipid-based delivery systems can be liquid, semisolid, or solid at room temperature; hence, a variety of product formulations are possible, *e.g.*, drinking solutions, filled soft gel capsules and tablets.[103] Additionally, they are more desirable for

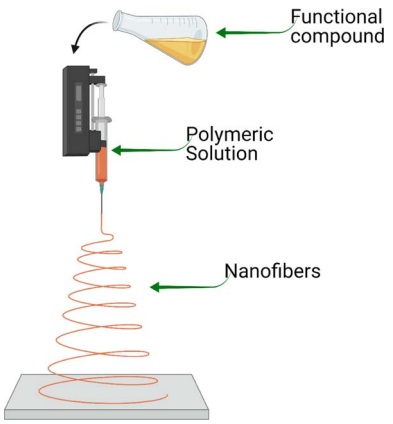

Fig. 5 Electrohydrodynamic processing of encapsulation by electrospinning.

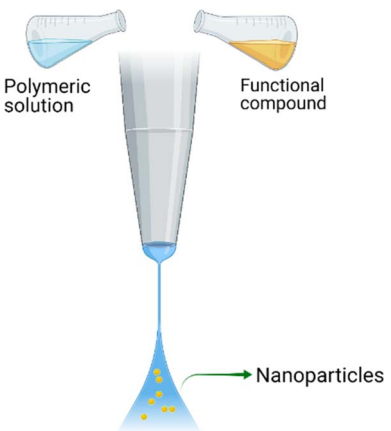

Fig. 6 Electrostatic encapsulation by electrosprying.

Table 2 Recent encapsulation techniques for functional lipids: core materials, methods, and stability assessment

Techniques of encapsulation	Method used	Core material	Functional lipophilic compound	Carrier material/ wall matrix	Encapsulation efficiency (%)	Particle size	*In vitro* digestion study	Heat stability study	Storage stability study	Remarks	Reference
Antisolvent precipitation	Mechanical stirring at	Wakame algae oil	Fucoxanthin	Zein/casein	>85	100–130 nm	29.02% oil release in simulated gastric fluid for 6 h	100% stability after heating at 75 °C for 60 min	72.32% retention after 16 days of storage at 25 °C	Static quenching, corresponding to the formation of complexes between fucoxanthin and casein or zein	58
	Mechanical stirring	Egg yolk	Lutein	Zein/soy protein	>80	14–200 nm	33.94% oil release in simulated gastric fluid for 6 h	—	96.27% retention after 15 days of storage at 25 °C	Zein–lutein complexes can be formed with the help of noncovalent interaction forces	59
	Sonication from 200–800 W	—	Stigmasterol	Zein	95.95	336.74 nm	—	—	—	Sonication improved the zeta potential of the encapsulated particles which might increase the stability of zein-stigmasterol complex	60
Emulsification solvent evaporation	Homogenization at 700 rpm for 15 min at 25 °C	Fish oil	O3FA	Zein	—	73–265 nm	—	—	—	Oxidative gelation rate is reduced	61
	—	Fish oil	DHA	Zein	98.8	150–200 nm	3.3% DHA released in Phosphate buffered saline and with 2% Tween 80 as surfactant	—	—	Lower *in vitro* release proved that the zein and fish oil encapsulation has higher oxidative stability against the GI environment	62
	Homogenization at 10 000 rpm for 5 min followed by freeze drying to evaporate the solvent	Red palm oil	Carotenoids	Carboxy methyl cellulose	83–96	600–2200 μm	>90% oil retained in the GI environment and >20% oil retained in the intestinal digestion	The oil loaded beads have shown lower weight loss up to 150 °C, after with increase in temperature the wight loss is increased	Lowest peroxide value of 25 meq. of O_2 per kg of oil was found after 6 days of storage at 25 °C	Freeze-drying had diminished the migration of oil on to the surface of the beads as freezing temperature might have solidified the palm oil	63

Table 2 (*Contd.*)

Techniques of encapsulation	Method used	Core material	Functional lipophilic compound	Carrier material/ wall matrix	Encapsulation efficiency (%)	Particle size	*In vitro* digestion study	Heat stability study	Storage stability study	Remarks	Reference
Coacervation technique &ionic gelation	Emulsion obtained by mechanical stirring at 10 000 rpm for 3 min at 40 °C and pH was shifted to 4 for making coacervation	Echium oil	Stearidonic acid and phytosterols	Protein–gelatin Poly saccharide–gum arabica	87	—	—	—	96% oil retention after 30 days storage at 37 °C	Gelatin and gum Arabic based coacervation entrapped the echium oil with higher storage stability and less oxidative degradation	64
	Emulsion obtained by mechanical stirring at 13 000 rpm for 3 min followed by pH shifting to 3.8 for coacervation	Sacha inchi oil	PUFA	Protein–ovalbumin Polysaccharide–sodium alginate	99.54	—	14.6% of oil release in simulated gastric digestion at pH 2.8 with the presence of pepsin enzyme	—	—	The reduced release under gastric conditions (low pH and presence of proteolytic enzymes) indicates that the ovalbumin and sodium alginate microcapsule protected the acyl in the omega-3 units	65
	Emulsion was made by mechanical stirring at 400 rpm at 40 °C and coacervation was made by pH shifting to 4	Cod liver oil	PUFA: EPA and DHA	Protein–soy protein isolates Polysaccharide–inulin	94	—	80.54% oil stability at pH 5.5	—	72.24% oil retention at 90 ° C for 30 min	Stable emulsion was carried out by the complex coacervation of inulin and soy protein isolates	66
	Emulsion was obtained by stirring at 600 rpm at room temperature and coacervation complex was created by pH shifting at 3	Algal oil	PUFA: O3FA and O6FA	Protein–soy protein isolates Polysaccharide–chitosan	90.57	—	—	—	—	The hexanal peak area is 23.34 which indicated the lowest oxidation	67
	Emulsion was prepared by mechanical	Pomegranate seed oil	Punicic acid (omega 7 fatty acid)	Protein–whey protein	67.40	8.36–10.96 μm	—	—	—	The complex coacervation provided minimum	68

Table 2 (*Contd.*)

Techniques of encapsulation	Method used	Core material	Functional lipophilic compound	Carrier material/ wall matrix	Encapsulation efficiency (%)	Particle size	*In vitro* digestion study	Heat stability study	Storage stability study	Remarks	Reference
	stirring at 16 000 rpm for 5 min at room temperature followed by coacervation at 3.75 pH			Polysaccharide–gum arabica						isomerization of pomegranate seed oil	
Inclusion complex	Mixing followed by lyophilization	Perilla oil	ALA	γ-Cyclodextrin	—	—	—	63.3% ALA retention after heating at 60 °C after 4 days	—	The perilla oil was more thermostable when included in the cavity of γ-CD than when placed at interspaces between pseudo rotaxane-type complexes	69
	Kneading method and crystallization method	Anchovy oil	EPA and DHA	β-Cyclodextrin	74–99	—	—	—	—	PUFA glycerides from the anchovy oil is poor encapsulated in β-cyclodextrin in controlled crystallization conditions, while the monounsaturated and especially saturated fatty acid glycerides were more appropriate for molecular encapsulation	70
	Dextrinization method	Fish oil	O3FA	Amylose (maize starch)	71.22	—	—	—	—	Dextrinization improved dispersion stability of the complex particles	71
Supercritical fluid technique	CO_2 pressure-8 M.Pa Temperature of extractor 263 K	Fish oil	EPA and DHA	Polycaprolactone	38–43	6–73 nm	—	—	—	Supercritical fluid extraction successfully developed the nanoparticle s from liquid lipophilic compounds like fish oil	72

Table 2 (*Contd.*)

Techniques of encapsulation	Method used	Core material	Functional lipophilic compound	Carrier material/ wall matrix	Encapsulation efficiency (%)	Particle size	*In vitro* digestion study	Heat stability study	Storage stability study	Remarks	Reference
	CO_2 pressure- 80 bar Temperature of the extractor-38 °C.	Shrimp oil	Astaxanthin	Ethyle cellulose	84	363–370 nm	Almost 70% release of astaxanthin after 10 h in simulated intestinal fluid	—	—	The emulsified shrimp oil gets easily ionized in simulated intestinal fluid showed higher release of astaxanthin in intestinal tissues	73
	CO_2 pressure- 9 M.Pa Temperature- 353.15 K	—	Lycopene	*n*-Octenyl succinic anhydride (OSA)-modified starch	64–89	345–366 nm	—	—	—	Supercritical extraction emulsion provided the stability of lycopene in aqueous media	74
Electrostatic nanoencapsulation	Electrospinning	Fish oil	O3FA	Zein fibers	91	190 nm	—	—	Peroxide value of encapsulated complex remains below 200 μmol L^{-1} for 14 days of storage at 25 °C	The distribution of fish oil in the electrospun materials, revealing that the lipid phase tended to concentrate at the core of the fibers and beads	75
	Coaxial electrospray	—	ARA	Zein	77–95	1–7 μm	—	—	Peroxide value of encapsulated ARA is approximately 8.0 meq. per kg after 30 days of storage at room temperature	Coaxial electrospray technique to produce natural and edible microcapsules with core–shell structures and reduce the unpleasant flavor	76
	Electro spraying assisted by pressurized gas	Fish oil	DHA	Zein	84	2–3 μm			Peroxide value was 20 meq/kg oil after 30 days of storage at 23 °C	DHA was successfully stabilized in the zein microcapsules due to the low temperature and fast evaporation characteristics of electro spraying technique used	72

Table 2 (*Contd.*)

Techniques of encapsulation	Method used	Core material	Functional lipophilic compound	Carrier material/ wall matrix	Encapsulation efficiency (%)	Particle size	*In vitro* digestion study	Heat stability study	Storage stability study	Remarks	Reference
	Electro spraying at 20–25 kV voltage with flow rates ranging from 0.5 to 1 mL h^{-1}	Fish oil	O3FA	Kafirin	94	552–861 nm	—	—	—	The kafirin nano capsules loaded with fish oil obtained in this study (average diameter <1 μm) present a high surface-to-volume ratio which is desired for a better release of the encapsulated bioactive compound	77
Liposomes	Sonication of liposome suspension at 25 °C for 7 min (1 s on and 1 s off) with nominal frequency of 20 kHz at 80% of full power	Fish oil	EPA & DHA	Soybean lecithin	73.5	<200 nm	—	—	The TBA reactivity substance was 0.015 μmol MA equivalent after 90 days of storage in dark at 4 °C	The surface charge, physical stability and oxidative stability of liposomal PUFAs increased as the size of the liposomes decreased	78
	Ultrasonication (10 min; 1 s on and off pulse) at 25 °C using an ultrasonic processor at 80% amplitude	Shrimp oil	EPA & DHA, astaxanthin	Soybean lecithin	93.64	40–284 nm	—	—	The peroxide value was approximately 5 meq. peroxide per kg of oil and TBARS approximately 50 malonaldehyde equivalent after 8 weeks of storage at 30 °C	Nanoliposomes produced using ultrasonication method were more stable, smaller in size and showed better nanoencapsulation efficiency	79
	Thin film drying prior to ultrasonication for 10 min at 180 W in an ice-cold water bath with a cycle of 2 s sonication and 2 s standing	—	Astaxanthin	Egg yolk lecithin and lactoferrin	71.92	190 nm	—	The rate of thermal degradation rate was approximately 0.7045 during the study from 0–70 °C	—	The lowest rate of thermal degradation was the result of antioxidant effect of lactoferrin coated with the liposomes	80

Table 2 (*Contd.*)

Techniques of encapsulation	Method used	Core material	Functional lipophilic compound	Carrier material/ wall matrix	Encapsulation efficiency (%)	Particle size	*In vitro* digestion study	Heat stability study	Storage stability study	Remarks	Reference
	Thin film drying prior to sonication using a frequency of 20 kHz at 90%	Perilla oil	ALA and LA	Soybean lecithin and biopolymers	ALA-79.3 to 89.9, LA-72.6 to 85.6	120–300 nm	~10% release in simulated gastrointestinal conditions	—	The peroxide value was ~40 meq peroxides/ kg of oil after 30 days of storage at 45 °C	Liposomes crosslinked with biopolymers have more physical as well as gastrointestinal stability	81
Solid lipid micro/ nanoparticles (SLNs)	Resveratrol-stearate and PUFA mixture were melted at 65 °C followed by cold homogenization at 8000 rpm for 15 min	Fish oil	ALA and DHA	Resveratrol	ALA-77, DHA-100	ALA-842 nm, DHA-1000 nm	—	—	—	SLNs with resveratrol and PUFA omega-3 acted as anti-tumor for colon cancer and reduce the cell proliferation	82
	Oil phase (lipid careers and echium oil) and water phase (WPI solution) were homogenized at 15 000 rpm for 3 min to prepare oil in water microemulsion	Echium oil	O3FA	Lauric acid, palmitic acid and stearic acid	78–85	~200 nm	—	—	Sample stabilized by lauric acid have less TBARS values after 21 days of storge as compare to other lipid careers	Different lipid carriers with different chain lengths affected the physicochemical properties of encapsulated echium oil	83
	Supercritical carbon dioxide with 200 bar expansion pressure, 57 °C, and 50 μm nozzle diameters	Fish oil	O3FA	Fully hydrogenated soybean oil	97.5	5–18 μm	—	—	Anisidine value for the particles with fish oil started to increase on day 9 and reached its maximum on day 15 (2840) while stored at 40 °C	The initial loading concentration of the fish oil have directly proportional to the thermal as well as storage stability of lipid particles	84

incorporation into fat-based food products such as cheese, butter, mayonnaise, and emulsified meats.[104,105]

3.3.1. Liposomes. A liposome is a closed, continuous, spherical vesicle composed of one or more phospholipid bilayers. The amphipathic behavior of phospholipids results in a spherical bilayer with lipidic compounds when mixed in an aqueous environment under controlled conditions.[106] Liposomes are desirable for the encapsulation of lipophilic functional compounds.[5] Researchers have developed various techniques to fabricate liposomes, but the most widely accepted technique is thin film hydration, in which organic phospholipids are dried by solvent evaporation and rehydrated in an aqueous medium.[85] However, this particular method produces heterogeneous liposomes with irregular shapes and sizes; hence, it can be combined with microfluidization or sonication (Fig. 7) to achieve homogeneous sizes and shapes and facilitate large-scale production of liposomes.[5] Table 2 summarizes the techniques and conditions used for the preparation of liposomes as delivery vehicles for functional lipids.

Rasti *et al.*[78] developed soybean lecithin-based liposomes containing fish oil by combining thin film hydration and ultrasonication and reported that ultrasonication reduced the size (<200 nm) of the liposomes and made them homogenous, which increased the stability of the nanoliposomes. Gulzar *et al.*[79] studied the impact of ultrasonication and microfluidization on the physicochemical properties of nanoliposomes containing shrimp oil and reported a greater encapsulation efficiency (93.64%) and smaller particle size (40 nm) of the nanoliposomes obtained *via* ultrasonication than *via* microfluidization.

3.3.2. Solid lipid nano/micro particles. Solid lipid nano/microparticles are composed of a solidified lipid core coated with a layer of emulsifier molecules.[107] Generally, solid lipid nano/micro particles are developed by homogenizing the lipid phase, functional groups and emulsifiers at controlled temperatures beyond the melting point of lipids.[108] As described in Fig. 8, the solid lipid particles comprised an outer layer of amphiphilic stabilizer that provides stability in gastric and storage environments, and the encapsulated functional compounds were surrounded by the lipid phase. The ratio of liquid-to-solid fat within the lipid core can be varied to enhance lipid encapsulation efficiency and functionality.[65] Solid lipid nano/microparticles provide a low-cost, solvent-free delivery system for functional lipids with increased stability and scalability.[110]

4. Impact of encapsulation techniques on the stability of functional lipids

Over the past few decades, researchers have focused on the commercialization of fortified food products with functional lipids. Increased consumption of functional lipids can be achieved by fortifying them with staple foods such as breads,

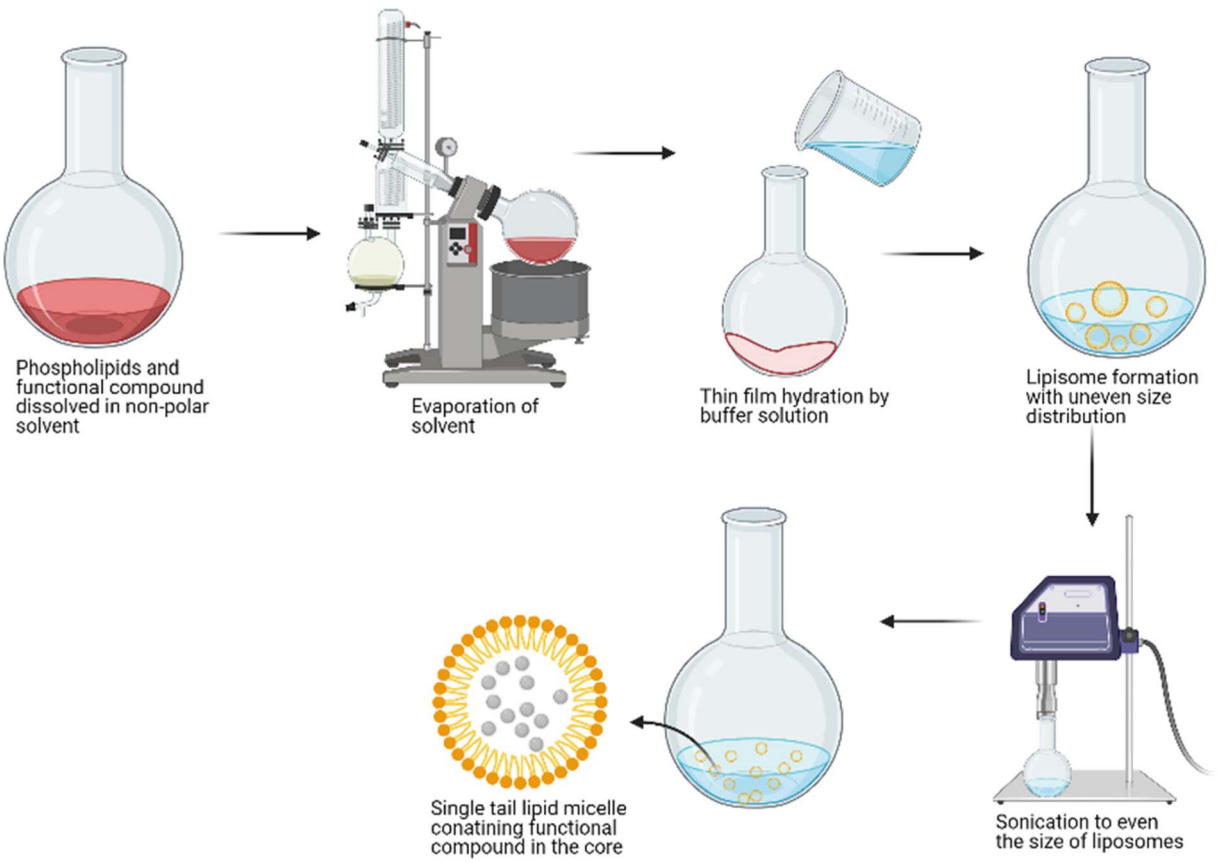

Fig. 7 Liposome production by thin film hydration.

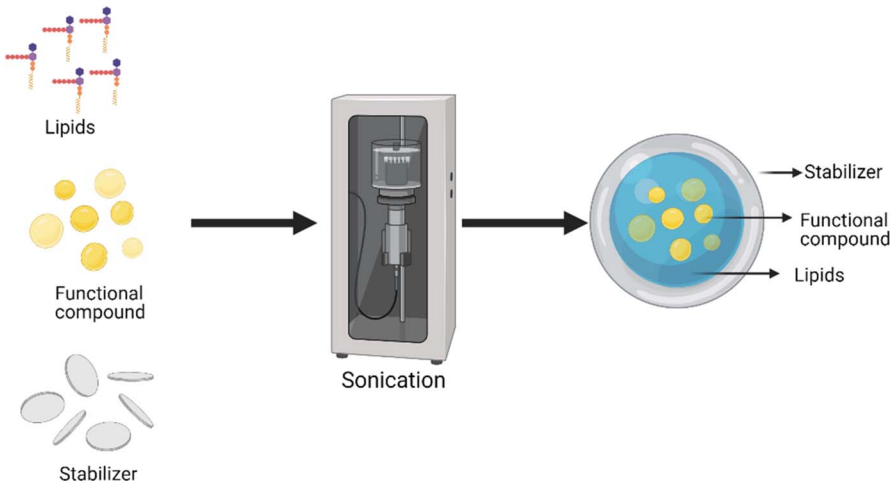

Fig. 8 Solid lipid nanoparticles[82] developed O3FA-rich resveratrol-based solid lipid nanoparticles by hot homogenization at 65 °C for the delivery of ALA (74% EE; 840 nm) and DHA (100% EE; 1000 nm). The encapsulation efficiency and particle size of solid lipid nanoparticles are affected by the chain length of lipid carriers.[83,109] High-pressure homogenization, ultrasonication and supercritical CO_2 are the most efficient methods for preparing solid lipid micro/nanoparticles for omega-3-rich oils with high encapsulation efficiency (95–99%) (Table 2).

milk, fruits, juice, yogurt, cheese, *etc.* However, the major challenge of the fortification of functional lipids is their unstable nature due to their unsaturated structure, which makes them more prone to lipid oxidation by oxygen, heat and light during processing as well as storage.[111] Encapsulation techniques provide oxidative stability by utilizing interfacial technologies to prevent oxygen from contacting functional lipids and incorporating antioxidants and other protective substances, which ultimately increases the bioavailability of functional lipids.[42,96,112,113]

Storage stability and heat stability are proposed considerations for the encapsulation of functional lipids. They are affected by various parameters, including the wall/carrier matrix, emulsifiers, wall matrix properties, glass transition temperature, crystallinity, chemical and physical interaction mechanisms, and processing conditions (temperature, pressure, ratio of wall to core material, particle size and surface area, and oil distribution within the particle).[114] Moreover, the amount of free surface oil on the surface of encapsulated particles is the most critical parameter, while considering the encapsulation strategies for functional lipids, as free surface oil is most prone to environmental stress.[115] Many researchers have successfully entrapped functional lipids with enhanced storage and heat stability, as shown in Table 2.

Li *et al.*[86] reported 100% stability of fucoxanthin nanoparticles entrapped by a zein–casein wall matrix after heating at 75 °C. Static quenching, corresponding to the formation of complexes between fucoxanthin and casein–zein, also provided an oil retention of up to 72% after 16 days of storage at ambient temperature. Similarly, the zein–lutein complex formed by non-covalent bonding retained approximately 96% of the oil in egg yolk nanoparticles after storage at 25 °C for 15 days[59]. Sathasivam *et al.*[63] reported that freeze-drying diminished the migration of red palm oil to the surface of microbeads as the freezing temperature solidified the oil in the core of the carboxymethyl cellulose, which resulted in the lowest peroxide values (25 meq. of O_2 per kg of oil) after 6 days of storage at room temperature. In contrast, Anwar *et al.*[94] reported that freeze drying produced a porous powder of encapsulates, which allowed more oxygen to interact and generate higher peroxide concentrations.

Gelatin- and gum arabic-based coacervation entraps echium oil with greater storage stability and less oxidative degradation, which retains approximately 96% of the oil after 30 days of storage at 37 °C[64]. Rios-Mera *et al.*[66] developed a stable emulsion of cod liver oil by complex coacervation of inulin and soy protein, where approximately 72% oil retention was obtained after the emulsion was heated at 90 °C for 30 min. Hexanal is considered an end product of lipid oxidation, which impairs the sensorial attributes of fortified products. Yuan *et al.*[67] reported that hexanal production is reduced when algal oil is encapsulated in the complex coacervation of soy protein and chitosan. Researchers have also reported a decrease in peroxide concentrations during the storage of various encapsulated functional lipids *via* the use of electrostatic encapsulation techniques.[72,75,76] Certain antioxidants and biopolymers provide additional benefits in terms of enhancing the stability of functional lipids when combined with different encapsulation techniques. Liposomal nanoparticles of astaxanthin coated with lactoferrin enhance oxidative stability because of the antioxidant effect of lactoferrin[80]. Zamani-Ghaleshahi *et al.*[81] reported that perilla oil liposomes crosslinked with biopolymers have greater physical stability. Table 2 summarizes the effects of various encapsulation techniques and wall matrices on the storage and heat stability of encapsulated functional lipids.

5. Influence of encapsulation techniques on the gastrointestinal stability and bioavailability of functional lipids

The bioavailability and bioaccessibility of functional lipids are the only concerns when they are encapsulated in any colloidal

system for oral delivery. The ultimate goal of the encapsulation technique is to absorb functional compounds in accessible forms at specific delivery sites, *i.e.*, the aqueous intestinal lumen and intestinal cells. The bioavailability of encapsulated functional compounds is dependent on various factors, such as the solubility of colloidal carriers in aqueous gastrointestinal solution, the physical and biochemical stability of the wall matrix in the gastric environment, and the release efficacy of the core compound in the intestinal environment. In addition to the encapsulation efficiency, the particle size and intermolecular interactions of the core and wall materials also affect the bioavailability and efficiency of the delivery system. Many *in vitro* studies in a simulated gastrointestinal environment have proven the efficient delivery of functional lipids at targeted sites in micro- or nanoencapsulated forms, and the results are summarized in Table 2.

The wakame algae oil entrapped in the zein–casein complex showed approximately 20% oil loss under simulated gastric conditions after 6 h, which might be due to strong static quenching between the zein–casein complex and the core compound.[86] Similarly, Li *et al.*[59] reported that the zein–lutein complex provided gastrointestinal stability to lutein nanoparticles through only 33% oil loss in gastric fluid after 6 h, which might be the result of strong noncovalent interactions between the wall and core material. Surfactants used in colloidal delivery systems, such as Tween 80, have also been shown to enhance the GI stability of DHA in fish oil-encapsulated nanoparticles.[62] The freeze-dried red palm oil-loaded microbeads retained approximately 90% of the oil in the simulated gastric environment due to the presence of less free surface oil, as discussed earlier.[63] The coacervation complex and ionic gelation technique also provided GI stability for various functional lipids by retaining up to 80% of the oil under simulated gastric conditions.[65,66] Tirado *et al.*[73] noted that the encapsulated structure of shrimp oil is easily ionized in simulated intestinal fluid, which increases the solubility of astaxanthin in the intestinal environment. Table 2 summarizes the effects of various encapsulation techniques and wall matrices on the gastrointestinal stability of encapsulated functional lipids.

The studies presented in Table 2 offer valuable insights into encapsulation techniques and the release behavior of functional lipids in simulated gastrointestinal environments. However, understanding bioavailability requires more comprehensive investigations, including studies that go beyond *in vitro* digestion and evaluate the actual absorption and efficacy of these encapsulated compounds in living systems. Several research groups have investigated the bioavailability of encapsulated lipids through cell culture and animal studies. For example, Serini *et al.*[82] investigated the antitumor efficacy of solid lipid nanoparticles (SLNs) encapsulating resveratrol and omega-3 fatty acids (ALA and DHA) in a colon cancer model. These findings demonstrated that these SLNs could reduce cell proliferation and exhibit antitumor activity, suggesting improved bioavailability and therapeutic potential *in vivo*. Similarly, Barbosa *et al.*[116] studied the stability and bioactivity of encapsulated echium oil in various lipid carriers *via* animal models. Research has shown that the chain length of lipid carriers affects the physicochemical properties and stability of the encapsulated oil, which in turn influences its bioavailability when it is administered to animals. In another study, Xie *et al.*[117] used supercritical carbon dioxide to encapsulate fish oil in fully hydrogenated soybean oil and evaluated its bioavailability in an animal model. This study revealed that the initial loading concentration of fish oil was directly proportional to its thermal and storage stability, which impacted its absorption and bioavailability in the tested animals.

These studies illustrate that while *in vitro* digestion studies provide preliminary insights, cell culture and animal studies are crucial for comprehensively evaluating the bioavailability of encapsulated functional lipids. These examples underscore the importance of moving beyond *in vitro* experiments to assess the true bioavailability and efficacy of encapsulated compounds in living systems.

6. Effect of encapsulation techniques on the fortification of functional lipids

The growing market share of food products with healthier nutrient profiles has attracted the interest of many researchers seeking to fortify staple foods with functional lipids, especially O3FA-rich functional foods. Colloidal systems are interesting platforms for enriching functional lipids in staple foods with increased bioavailability. The motive for selecting staple foods for fortification is to increase the regular dietary intake of such functional lipids, which improves human health and markedly reduces metabolic, cardiovascular and metal disorders. The interaction of the food matrix and encapsulates determines the bioavailability of functional lipids in the food system. Moreover, the encapsulated functional lipids affect the physicochemical, structural and sensorial attributes of fortified food products, which are desirable for increasing the commercial importance of such fortified products. Table 3 summarizes the effects of the fortification of encapsulated functional lipids on the physicochemical and functional properties of selected staple foods.

Over the past few decades, there has been a remarkable interest in fortifying milk and dairy products with functional lipids with the aim of increasing the fatty acid profile of such products. Yogurt, cheese and ice creams are the most popular dairy products, and various attempts have been made to fortify such products with various encapsulated functional lipids. The fortification of yogurt with fish oil powder increased its acidity, lowered its pH and increased its water holding capacity, which ultimately increased its shelf-life.[119,120] Moreover, yogurt tends to release whey during storage, which is called syneresis. The addition of fish oil powder can control whey separation due to the ability of the wall material to hold water and increase the stability of yogurt during storage[118,120]. Bermúdez-Aguirre *et al.*[121] reported a similar reduction in whey separation in fish oil microcapsule-fortified cheddar cheese. Moreover, the addition of functional lipids to cheese also increases its textural properties, increasing its shelf stability.[121,122] In addition to enhancing the physiochemical properties of emulsified

Table 3 Fortification of selected staple foods by encapsulated functional lipids

Fortified food products	Encapsulated functional lipids	Encapsulation technique used	Physicochemical properties of fortified products	Rheological properties of fortified products	Sensorial attributes of fortified products	References
Yogurt	Fish oil powder	Complex coacervate of gelatin/gum acacia	Acidity, and water holding capacity were increased; whey separation was decreased	Gel strength decreased and apparent viscosity increased	Fortified yogurt samples were more yellowish compared to control	118
	Fish oil microcapsules	Complex coacervate of gelatin/gum acacia	Fortified yogurt had higher apparent viscosity	Consistency coefficients of the enriched yogurt was 24.42–28.82 Pa s^n	—	119
	Fish oil nanoliposomes	Liposomes by egg yolk lecithin and fish oil	Whey separation was deceased	—	Fish odor was eliminated	120
Cheese	Fish oil powder	Microencapsulation by freeze drying	Whey separation was deceased	Hardness, chewiness and gumminess was increased	—	121
	Fish oil powder	Microencapsulation by spray drying	Milk solid not fat was increased; pH level is maintained up to 30 days of storage	Hardness of enriched cheese is increased after 30 days of storage	Cheese color was changed to yellow after 60 days of storage	122
Bread	Fish oil nanoliposomes	Liposomes by sunflower oil and lecithin	Loaf volume was increased, improved crumb characteristics	Harness was reduced, decrease the level of chewiness and gumminess	Light browning in the crumb color	123
Ice cream	Fish oil powder	Microencapsulation by freeze drying	Saturated fatty acids decreased, PUFA increased	—	—	124
	Flaxseed oil microcapsules	Microencapsulation by freeze drying	Free fatty acid content was increased, melt down rate was decreased	—	Off flavor was masked up to 30 days of storage	125
Frankfurter sausages	Fish oil microcapsules	Monolayer microencapsulation by spray drying	Lower down the pH values, MUFA and PUFA increased	—	—	126
Chicken sausages	Fish oil powder	Microencapsulation by inclusion complex with gelatin wall material	pH was maintained up to 21 days of storage, water binding ability was increased	The sausages with microencapsulated oil showed better ability to accumulate elastic energy (G'); Hardness of sausage was increased	Fortified sausages were rated highest for their consistency (the thickest), especially when they were heated	127

dairy products, the fortification of functional lipids enhances their fatty acid profile by reducing the saturated fatty acids and increasing the PUFAs and MUFAs. The fatty acid profile of ice cream fortified with fish oil powder was greater than that of the control samples.[124] Furthermore, Gowda *et al.*[125] reported a lower melt-down rate in ice cream fortified with flaxseed oil microcapsules, which could be attributed to the encapsulated form of the fortified flaxseed oil, which might have increased flocculation and hence improved the structure of the ice cream.

Bread is another staple diet after milk and dairy products and has been popular among scientific communities for fortification with functional bioactive compounds. In addition to enhancing the fatty acid profile of breads, the encapsulated structure of functional lipids also improved the textural and sensorial attributes. Ojagh *et al.*[123] reported that the loaf volume in bread containing fish oil nanoliposomes increased, possibly due to the surface–active properties of lecithin, an emulsifier, and other ingredients within the liposomal system, which improved gas retention, bread volume, and dough stability. Additionally, lecithin reacts with linear amylose and external amylopectin branches and forms a complex that prevents hardening of the bread's crumb. In addition, some ready-to-eat meat products, such as frankfurt and sausages, have recently been fortified with fish oil encapsulates to enhance their fatty acid profile.[126,127]

7. Factors affecting the industrialization and commercialization of encapsulated functional lipids

The industrialization and commercialization of encapsulated functional lipids are influenced by several factors, each playing a crucial role in determining the success of these products on the market. These factors include the scalability of the encapsulation process, the stability and shelf life of the encapsulated products, regulatory compliance, cost-effectiveness, and consumer acceptance. Below is an exploration of these factors with reference to relevant studies.

7.1. Scalability of the encapsulation process

One of the primary challenges in the industrialization of encapsulated functional lipids is the scalability of the encapsulation process. Techniques that work well in the laboratory setting may not always be feasible on an industrial scale owing to complexities in maintaining consistency, controlling process parameters, and ensuring cost efficiency. For example, a study by Xue *et al.*[128] demonstrated that a synthetic surfactant-free technique for encapsulating curcumin into solid lipid nanoparticles (SLNs) could be promising for food-grade applications. However, scaling this technique to an industrial level requires careful consideration of equipment design, process control, and energy consumption to ensure consistent product quality.

7.2. Stability and shelf life

The stability and shelf-life of encapsulated functional lipids are critical for their commercialization. Encapsulated lipids must maintain their functional properties over time and under various storage conditions. The stability of these products can be influenced by factors such as the choice of encapsulation material, particle size, and physical and chemical environment. Sun *et al.*[129] highlighted that the use of solid lipid nanoparticles (SLNs) can significantly increase the stability of encapsulated curcumin, leading to improved shelf-life and sustained release, which are vital for commercial products.

7.3. Regulatory compliance

For encapsulated functional lipids to be commercialized, they must meet regulatory standards set by health and safety authorities. These regulations can vary by region and include guidelines on the use of encapsulation materials, labeling, and health claims. The study by Shishir *et al.*[130] emphasized the importance of using food-grade materials and processes that comply with regulatory requirements to ensure that the final product is safe for consumption and can be legally marketed in different regions.

7.4. Cost-effectiveness

The cost of production is a significant factor that affects the industrialization and commercialization of encapsulated functional lipids. The choice of encapsulation technique, materials, and processing conditions can impact the overall cost of production. Processes that are energy intensive or require expensive materials may not be viable on a large scale. Ezhilarasi *et al.*[131] discussed the economic considerations of using solid lipid nanoparticles (SLNs) for the encapsulation of hydroxycitric acid (HCA), noting that while SLNs offer superior bioavailability, the cost of production must be balanced to ensure commercial viability.

7.5. Consumer acceptance

Consumer acceptance is another critical factor that influences the success of encapsulated functional lipids on the market. Although consumers are increasingly seeking functional foods with health benefits, they are also concerned about the safety, naturalness, and sustainability of the ingredients and processes used. A study by Guri *et al.*[132] highlighted the importance of consumer-friendly ingredients and processes in the development of encapsulated functional lipids, suggesting that transparent labeling and education about the benefits of these products can increase consumer acceptance.

8. Conclusion and future prospects

Functional lipids such as omega 3 fatty acids, omega 6 fatty acids, linoleic acid, conjugated linoleic acid, carotenoids, and other bioactive lipid compounds have many beneficial effects on human health, such as cardiovascular diseases, mental disorders, and metabolic disorders; hence, they are recommended by medical experts. These compounds are available in a wide range

of natural sources, such as vegetables, seeds, meat, fish, algae and microbes, and have tended to constitute integral parts of the human diet for many years. Owing to improper dietary patterns, the geographical distribution of sources, and the short availability of sources, the direct consumption of such functional lipids still does not satisfy the minimum dietary intake. Several commercial concentrated products rich in these functional lipids are also available on the market, but safety and GI stability are the major concerns of these types of products. Moreover, functional lipids are unsaturated and hydrophobic in nature, so bioavailability and bioaccessibility can be major obstacles for oral delivery or food fortification.

In recent decades, researchers have developed certain encapsulation techniques involving the selection of suitable wall materials for functional lipids to increase bioavailability during oral delivery as well as the enrichment of food products. The mechanism of encapsulation of functional lipids within the wall/carrier matrix by various physical and chemical interactions affects the heat stability, storage stability and GI stability of encapsulates. Furthermore, encapsulated functional lipids tend to be more bioavailable within food systems and enhance the physicochemical and functional properties of food. Further studies are needed to address food safety concerns regarding fortified foods with encapsulated functional lipids, and a clear research gap was found in the utilization of novel sources of functional lipids such as algae, bacteria and fungi for the fortification of common staple foods by means of encapsulation techniques.

The successful industrialization and commercialization of encapsulated functional lipids depend on careful consideration of factors such as scalability, stability, regulatory compliance, cost-effectiveness, and consumer acceptance. Addressing these factors through research and innovation is essential for bringing effective and commercially viable functional lipid products to the market.

Data availability

No primary research results, software or code have been included and no new data were generated or analyzed as part of this review.

Conflicts of interest

There are no conflicts to declare.

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