LIPID-BASED NANOCARRIERS FOR EFFICIENT DELIVERY OF LIPOPHILIC NUTRACEUTICALS

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Abstract

Nutraceuticals have received a lot of attention from consumers due to their numerous health benefits and high safety profiles. Demand for efficient delivery of such substances is also due to increased interest in naturally derived products and a healthy lifestyle. In addition to their nutritional values, these substances have anti-inflammatory, antioxidant, and antimicrobial effects, among others, and can prevent and/or treat chronic diseases. Despite various health benefits that nutraceuticals provide, their use in food preparations is commonly limited due to their high sensitivity to external factors, unpleasant odour or taste, low stability, and susceptibility to degradation during in vivo digestion. In addition, many nutraceuticals, including flavonoids, vitamins, fatty acids, curcuminoids, and essential oils have low water solubility, resulting in low bioavailability implying limited health effects. These problems can be solved by encapsulating nutraceuticals in nanocarriers. In particular, lipid-based carriers, including liposomes, nanoemulsions, nanostructured lipid carriers, niosomes, solid lipid nanoparticles, and self-emulsifying drug delivery systems are suitable for incorporating such compounds in the food industry due to their high biocompatibility. In addition, they can increase the bioavailability and stability of encapsulated substances and deliver the substance to a specific place in the body. This review covers characterization of various lipid-based nanocarriers and provides examples of these types of carriers developed in recent years for nutraceutical delivery, along with the benefits they provide.

Keywords: *lipid-based nanocarriers, nutraceuticals, bioavailability, encapsulation, lipophilic bioactives*

Introduction

In recent years, interest in nutraceuticals has increased significantly, reflecting a broader trend toward integrating nutrition and therapeutic health strategies [1]. Such substances include carotenoids, vitamins, flavonoids, polyphenols, fatty acids, herbs, etc. Their high safety profile and health effects, including reducing the risk of diabetes, hypertension, cardiovascular disease, slowing aging, and improving cognitive function make them an important element in healthcare [2-4]. In addition, the synergistic effect that can be obtained by co-delivering two or more nutraceuticals simultaneously can enhance their effects, including anti-inflammatory, antioxidant, antimicrobial, antiviral, cardioprotective, or anti-obesity-enhancing effects [5]. These substances also play an important role in anticancer therapy, as they can sensitize cancer cells to anticancer drugs, reducing their toxicity and the occurrence of side effects, and can combat resistance to the drugs used [6]. The use of some nutraceuticals is limited, as many have poor water solubility resulting in low bioavailability [7]. These substances are often sensitive to environmental factors such as oxygen, elevated temperature, or light. They may be susceptible to degradation during processing or storage and some may have an unpleasant odour or taste [8-10].

Encapsulation in a variety of nanocarriers can address these problems, since, in addition to increasing bioavailability, it can provide protection of encapsulated substances from degradation or interaction with other ingredients and improve the stability of encapsulated substances [11-12]. Encapsulation also offers advantages such as prevention of ingredient deterioration, thus increased storage stability and shelf life, taste and odour masking, increased food safety, and the possibility of large-scale applications [13]. In particular, employing lipid-based carriers is a promising strategy to solve the problem of low bioavailability of lipophilic nutraceuticals. Lipid-based carriers in addition to improving bioavailability have low toxicity and can be produced on an industrial scale [14].

This paper reviews various lipid-based carriers for the delivery of nutraceuticals showing also some recent examples of their applications. The main focus is on liposomes, nanoemulsions, nanostructured lipid carriers (NLCs), niosomes, solid lipid nanoparticles (SLNs), and self-emulsifying drug delivery systems (SEDDS) (Figure 1 and Table 1). Methods of obtaining them and the types of encapsulated lipophilic nutraceuticals are presented.

Lipid-based nanocarriers

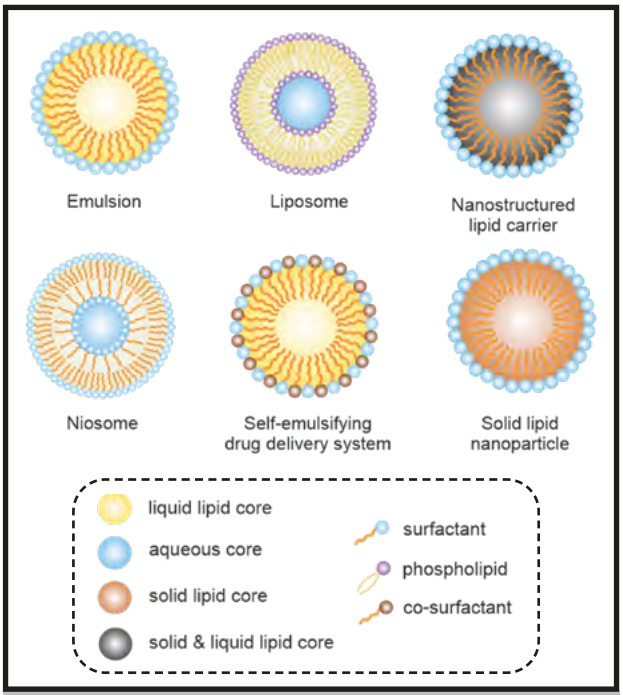

FIG. 1. Schematic illustration of lipid-based nanocarriers.

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TABLE 1. Overview of lipid-based nanocarriers.

Lipid nanocarrier	Size (nm)	Definition and properties	Methods of preparation
Liposomes [15-17]	SUVs 30–100 LUVs >100 GUVs >1000	Self-organized spherical phospholipid vesicles consist of an aqueous core and one or more phospholipid bilayers (lamellae). Hydrophilic compounds are encapsulated in the aqueous core, hydrophobic compounds in the lipid bilayer, and amphiphilic compounds may be present at the water/lipid bilayer interface.	– Thin film hydration (TFH), – Ethanol injection, – Microfluidics, – Extrusion, – Reverse phase evaporation, – Detergent depletion, – Super critical fluid technology, – Dual Asymmetric Centrifugation, – High sheer homogenization, – Lyophilization Monophase Solution, – Sonication
Emulsions [18-21]	NEs 10-100 MEs 100-1000 Macroemulsion 500-100000	Colloidal systems composed of two immiscible liquids, such as an oil phase dispersed in an aqueous phase (O/W), an aqueous phase dispersed in an oil phase (W/O) or double emulsions (W/O/W or O/W/O). Emulsifiers that reduce surface tension (lipids, surfactants, proteins, amphiphilic polymers) are used to stabilize emulsions.	– High-pressure homogenization (HPH), – Microfluidization, – Ultrasonic homogenization, – Rotor-stator homogenization, – Phase inversion, – Solvent displacement, – Spontaneous emulsification, – Membrane emulsification method
Nanostructured lipid carriers (NLCs) [22-24]	10-1000	Developed due to the limitations of the SLNs core crystallinity. Unlike SLNs, the matrix of NLCs consists of a mixture of solid and liquid lipids, which provides larger empty spaces, creating a non-ideal crystalline structure that affects higher encapsulation efficiency and prevents leakage of the encapsulated substance.	– High-pressure homogenization, – Microemulsion, – Phase inversion, – Emulsification-ultrasonication, – Solvent emulsification-evaporation, – Solvent diffusion, – Solvent injection, – Film-ultrasonication, – Hot melt extrusion, – Supercritical fluid (SCF) technology
Niosomes [25,26]	SUVs 10-100 LUVs 100-3000	Spherical monolayer vesicles (having a single bilayer) or multilayer vesicles (composed of several bilayers) formed from non-ionic surfactants, while they may also contain other compounds such as cholesterol or its derivatives. The amphiphilic structure allows coencapsulation of substances that differ in solubility.	– Bubble method, – Ether injection method, – Hand shaking method, – Heating method, – Microfluidization method, – Multiple membrane extrusion method, – Reverse phase evaporation method, – Sonication method, – Thin film hydration method, – Transmembrane pH gradient, – Supercritical carbon dioxide fluid
Solid lipid nanoparticles (SLNs) [27,28]	50-1000	Developed as a substitute for liposomes to overcome their drawbacks. They are defined as spherical nanoparticles composed of a solid lipid matrix (fatty acids, triglycerides, waxes) dispersed in water or surfactant solutions.	Preparation methods are the same as for NLCs
Self-emulsifying drug delivery systems (SEDDS) [29-31]	SNEDDS <100 SMEDDS 100–250 SEDDS 250–5000	An isotropic mixture of oil, surfactant (solid or liquid), and active substance forming an oil-in-water (O/W) emulsion under the influence of mixing induced by peristaltic motion and dilution in an aqueous environment (gastrointestinal).	Preparation of liquid SEDDS involves mixing oils, surfactants, and co-surfactants, usually using homogenization. Methods of preparation of solid SEDDS: – Hot-melt extrusion, – Spray drying, – Lyophilization, – Three-dimensional printing, – Adsorption onto solid carriers

SUVs – small unilamellar vesicles, LUVs – large unilamellar vesicles, GUVs – giant unilamellar vesicles, NEs – nanoemulsions, MEs – microemulsions, SMEDDS – self-microemulsifying drug delivery systems, SNEDDS – self-nanoemulsifying drug delivery systems

The choice of the appropriate carrier depends on the properties of the encapsulated active substance, as well as the desired functions. For this purpose, it is useful to know the advantages and limitations of carriers, differences between them, and the parameters that affect their properties. The advantages of emulsions, which are systems composed of two immiscible liquids, are their high stability and permeability, ability to increase bioavailability of the carried cargo, and ease of preparation [32]. Physical destabilization can occur as a result of flocculation, Ostwald ripening, phase reversal or coalescence, among others [33]. In order to obtain emulsions with specific droplet sizes and encapsulation efficiencies, the concentration of the lipid and aqueous phase, the type and amount of surfactant, as well as the preparation method must be tailored accordingly. The droplet size is very important because it affects other physicochemical or structural properties including bioavailability [34]. In addition to traditional O/W or W/O emulsions, there are double emulsions, which allow simultaneous encapsulation of a hydrophilic and hydrophobic compound. However, they are often unstable, which can lead to low encapsulation efficiency, so salt addition or increased viscosity can be used to improve their stability [35]. The success of liposomes is mainly due to the use of phospholipids, which give this carrier biocompatibility with the cell membrane. They can encapsulate substances of different polarity, because the aqueous core allows for the encapsulation of hydrophilic substances, while hydrophobic substances can be located in the hydrophobic region. Niosomes were created in response to the limitations of liposomes related to the availability of phospholipids, stability and high production costs. Unlike liposomes, they are composed of non-ionic surfactants, that are commonly more stable and their production costs are lower [36]. To overcome the limitations of emulsions related to faster release of active ingredients and reduced oxidative stability, SLNs have been developed using solid lipids [37]. While their advantages include high stability, biocompatibility, prolonged release, or ease of scale-up, they also have disadvantages, which include low loading capacity and drug excretion due to polymorphic transitions. For this reason, NLCs were introduced, in which solid lipids were replaced by a mixture of solid and liquid lipids. This allows for reduced excretion of active ingredients due to the larger space between fatty acid chains. The advantages of NLCs over SLNs include greater stability and bioavailability of encapsulated substances, greater encapsulation efficiency and loading capacity, and greater control over release [38]. For SLNs and NLCs, it is very important to choose the right lipid matrix, as it affects the stability of encapsulated substances, encapsulation efficiency and loading capacity. When choosing a lipid matrix, the solubility of the substance and possible interactions between the compound and the lipid should be taken into account [39]. SEDDS, on the other hand, are systems that are easily scalable, their preparation is an easy and economical process compared to other carriers, as it only involves dissolving the active substance in oil and mixing it with surfactants and co-surfactants [40]. It is worth bearing in mind that the process of self-emulsification depends on pH, temperature, as well as the chosen surfactants and their concentration, the oil and the ratio of oil to surfactant. These systems guarantee dose uniformity, are stable and resistant to small temperature changes. SEDDS formulation requires a large amount of surfactant, and therefore, in addition to the ability to self-emulsify, attention must be paid to its toxicity. Interestingly, the potential of these systems has greatly increased following the discovery of solid SEDDS, which provide precise dosing, longer gastric residence time, high stability and regulated drug release. However, research is needed on the features that affect drug absorption in vivo [41].

Lipophilic nutraceuticals

Nutraceuticals that are insoluble in water include phenolic compounds, fat-soluble vitamins, unsaturated fatty acids, and essential oils. A large group of compounds are polyphenols, which are divided into flavonoids (anthocyanins, flavones, flavanones, flavanols, flavonols, isoflavonoids, etc.) and non-flavonoids (stilbenes, lignans, coumarins, curcuminoids, tannins, phenolic acids, etc.) [42]. They have antioxidant, anti-inflammatory, anticancer, antimicrobial, anti-anxiety, and other therapeutically relevant properties. These compounds can be extracted from various plants, vegetables, fruits, including coffee and tea [43]. In addition to their low solubility, their use is limited due to the bitter taste of some of them and sensitivity to increased temperature or light [10].

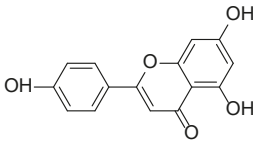
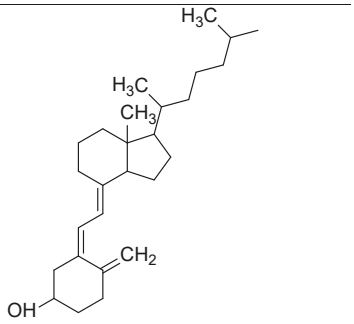
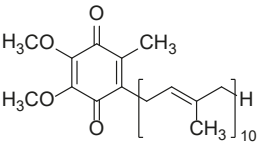
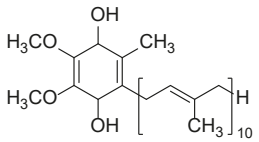
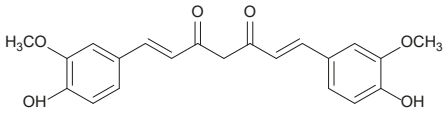
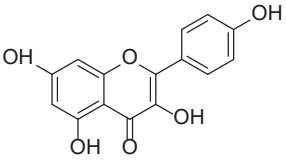
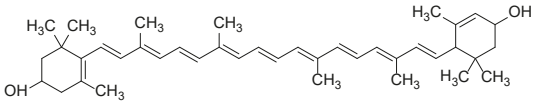
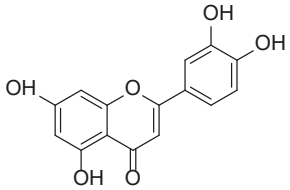
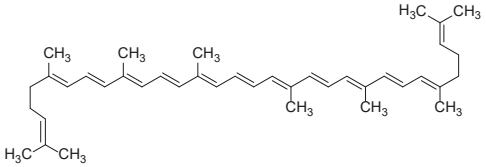
Fat-soluble vitamins (A, D, E, K) are essential for the proper functioning of the body and show therapeutic potential against many chronic diseases. Their deficiency can lead to many diseases, for example, night blindness, xerophthalmia, hyperkeratosis (vitamin A deficiency) [34], fractures and loss of bone mass (vitamin D group deficiency) [45], spinocerebellar ataxia, anemia, cervical dystonia, macular degeneration or retinitis pigmentosa (vitamin E deficiency) [46], osteoporosis, vascular calcification, and deterioration of endothelial function (vitamin K deficiency) [47,48].

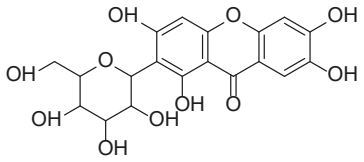
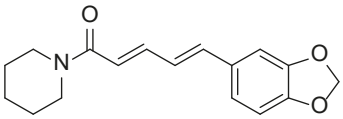
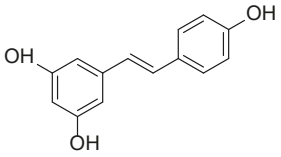
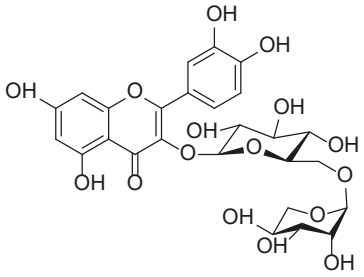
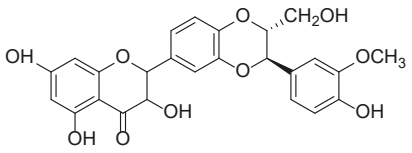
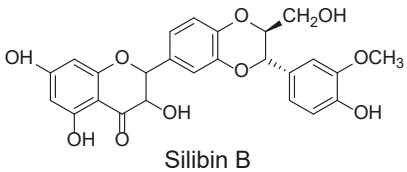
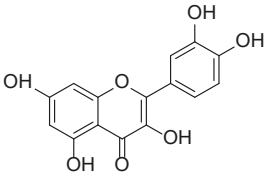
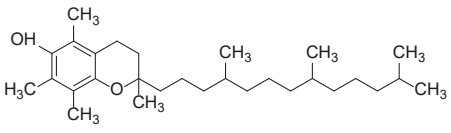
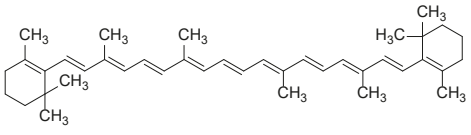
Carotenoids are precursors of vitamin A and are an important source of antioxidants. They are synthesized by fungi, plants, algae, and bacteria, but are not produced by humans. Their consumption has many health benefits, including boosting the immune system, cognitive function, reducing the incidence of chronic diseases, and anti-adiposity action [49].

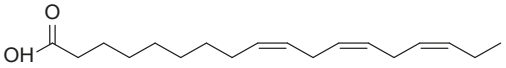
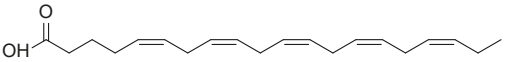
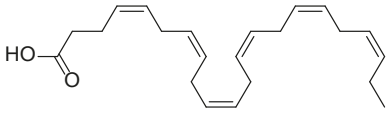
Polyunsaturated fatty acids (PUFA), particularly ω-3 and ω-6 fatty acids, are also an important group of compounds. They take part in cell signaling, regulation of glucose levels and blood pressure, as well as blood clotting. These compounds are not produced by the body that is why it is so important to supply them. ω-3 fatty acids, which include eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA), α-linolenic acid (ALA) are found in plant seeds (flax, chia), fish oils or grain products. The ω-6 acids include for example linoleic acid (LA) and arachidonic acid (ARA), and their sources are vegetable oils. These compounds have anti-inflammatory effects, and they can also protect against cancer, osteoarthritis, and autoimmune disorders [50].

Essential oils are extracted from plant materials and are valued for their antimicrobial, antioxidant, anti-inflammatory, anti-anxiety, and wound-healing properties. However, they are characterized by high lipophilicity and volatility, as well as low stability, which limits their use [51]. Examples of specific lipophilic nutraceuticals, along with their structure and the benefits they provide are shown in Table 2.

TABLE 2. Overview of lipophilic nutraceuticals and their beneficial effects.

Nutraceutical/ reference	Class of compounds	Structure	Beneficial effects
Apigenin [52]	Flavonoids (flavones)		Antioxidant, anti-inflammatory, neuroprotective properties
Cholecalciferol (vitamin D3) [53]	Vitamins		Immunomodulatory
Coenzyme Q10 [54,55]	-	 Ubiquinone (oxidized form of coenzyme Q10)  Ubiquinol (reduced form of coenzyme Q10)	Antioxidant, anti-inflammatory
Curcumin [56]	Polyphenols (curcuminoids)		Antioxidant, anti-inflammatory, anticancer
Kaempferol [57]	Flavonoids (flavonols)		Antiinflammatory
Lutein [58]	Carotenoids		Antioxidant, anti-inflammatory, antimicrobial, antiosteoporosis, neuroprotective, ophthalmological
Luteolin [59]	Flavonoids (flavones)		Antiinflammatory, anticardiovascular, anticancer, anti-neurodegenerative properties
Lycopene [60]	Carotenoids		Antioxidant

Nutraceutical/ reference	Class of compounds	Structure	Beneficial effects
Mangiferin [61]	Xanthones		Antioxidant, antiapoptotic, neuroprotective
Piperine [62,63]	Alkaloids		Antiinflammatory, anticancer, insecticidal, antiviral, antiallergic activity, bioavailability enhancer
Resveratrol [64]	Stilbenes		Antioxidant, anti-inflammatory, anti-cancer activity
Rutin [65,66]	Flavonoids (flavones)		Antioxidant, anti-inflammatory, antiangiogenic, anticancer, antidiabetic, antimicrobial properties
Silibinin [67]	Polyphenols (flavonolignans)	 Silibin A  Silibin B	Antioxidant, anti-inflammatory
Quercetin [68]	Flavonoids (flavonols)		Antioxidant and anti-inflammatory
α-tocopherol (vitamin E) [69]	Vitamins		Antioxidant, neuroprotective
β- Carotene [70]	Carotenoids		Antioxidant, anti-inflammatory, anti-angiogenesis, anticancer

Nutraceutical/ reference	Class of compounds	Structure	Beneficial effects
ω-3 fatty acids [71]	Polyunsaturated fatty acids	 α- linolenic acid (ALA)  eicosapentaenoic acid (EPA)  docosahexaenoic acid (DHA)	Antiinflammatory, antiaggregatory

Encapsulation of nutraceuticals

One of the most commonly encapsulated nutraceuticals is curcumin, which belongs to the curcuminoids. Bender et al. prepared liposomes with curcumin using three different methods: thin-film hydration method (TFH), lipid film method (LF-DC), and powder method (P-DC). The preparation method used affected the lamellarity of the obtained structures. The use of the TFH method resulted in single-cell liposomes with double lipid layers, the P-DC method contributed to the formation of additional lamellar structures and multilayered vesicles, and the LF-DC method produced less uniformly sized round vesicles. Internalization of curcumin and phototoxic effects of liposomes against lung adenocarcinoma cells (A549) were confirmed. Liposomes prepared by TFH and LF-DC method proved more effective than free curcumin and liposomes prepared by P-DC method. After nebulization, curcumin-loaded liposomes completely eliminated xenografted cancer cells in the 3D model [72]. Effective delivery of curcumin in a dispersion of capsules consisting of a modified hyaluronate-based shell and liquid oil core was demonstrated by Czyzynska et al. After administration of a low dose of curcumin encapsulated in a dispersion of capsules, hypotensive effects were observed in rats, and delivery of the formulation to blood vessel walls was confirmed [73]. Abasi et al. developed curcumin-loaded niosomes with a sustained release profile and encapsulation efficiency reaching 97.96%. The authors evaluated their anticancer activity and apoptotic effect against a subtype of triple-negative breast cancer using the MDA-MB-231 cell line. The obtained IC50 value of curcumin-loaded niosomes was twice lower than that of free curcumin. Compared with free curcumin and empty niosomes, curcumin-loaded niosomes significantly inhibited cell viability and induced the expression of essential apoptotic genes. After administration of curcumin-loaded niosomes, inhibition of cell migration, invasion, and mammosphere formation was also observed [74].

Wan B et al. developed quercetin-loaded liposomes that were coated with whey protein isolate (WPI) using two methods: coating and inserting. Compared to physical mixing, liposomes inserted with WPI and coated with WPI effectively masked the bitter taste of quercetin and improved the thermal stability of the liposomes [75]. De Barros et al. developed NLCs based on natural oils (sunflower, olive, corn, coconut, and castor oil) loaded with quercetin for the topical treatment of bacterial skin infections. The study showed an increase in the antimicrobial activity of NLCs with quercetin against Staphylococcus aureus, an increase in antioxidant activity, and a decrease in cytotoxicity against HaCaT cells compared to NLCs without quercetin [76]. Talarico et al. encapsulated quercetin in SLNs that were obtained by coacervation. They showed that quercetin could be homogeneously distributed throughout the nanoparticle structure, and the antioxidant activity of quercetin loaded in SLNs was preserved [77]. Lin et al. developed SEDDS with quercetin, which showed higher antimicrobial activity against Escherichia coli, Staphylococcus aureus, and Salmonella compared to free quercetin. In addition, compared to free quercetin, the developed system showed improved antioxidant activity of quercetin in vitro and in vivo [78].

Research conducted by Valia et al. on pea protein-stabilized nanoemulsions for vitamin D3 delivery showed that cellular uptake of nanoemulsions with smaller sizes occurs more efficiently (~2.5 times) than nanoemulsions with larger sizes. In addition, the efficiency of vitamin D3 delivery to Caco-2 cells using nanoemulsions with smaller sizes equal to 233 nm was ~5.3 times higher compared to free vitamin D3 suspension. A high encapsulation efficiency of 94-96% was also achieved [79]. Zou et al. developed an emulsion with loaded vitamin A acetate, and the resulting microparticles improved their thermal stability, storage stability, and protection from UV light [80]. Vitamin D3 was also encapsulated in NLCs by Barri et al. A high EE value of 96.14% was obtained. The in vitro cytotoxic effect against colon cancer cells (HT29) was investigated, and the results indicate that the NLCs with vitamin D3 prevent cancer cell proliferation to a greater extent than free vitamin D3 [81].

Wang et al. developed iRGD peptide-modified liposomes with curcumin and piperine. In vitro cytotoxicity studies have shown that liposomes with a combination of curcumin and piperine have a more cytotoxic effect on A549 cells than liposomes with curcumin alone, indicating a synergistic effect of these nutraceuticals. Moreover, an inhibition of cancer cell proliferation and invasion has been observed. In vivo results showed that the treatment using liposomes with curcumin and piperine inhibited tumor volume growth, and the attached iRGD peptide supported active targeting to the tumor site [82]. He et al. investigated a microemulsion for co-delivery of curcumin and DHA in mild non-alcoholic fatty liver disease (NAFLD). Synergistic effect of the nutraceutical combination on liver protection was observed. In mice with NAFLD, disease amelioration, lower serum triacylglycerols, and low-density lipoprotein cholesterol levels were observed [83]. A microemulsion for co-delivery of vitamin A (retinol) and vitamin E (α-tocopherol) was developed by Praça et al.

The vitamins combination showed additive effects against acute skin inflammation, as tested against TPA-induced skin inflammation in mice [84].

Regardless of the type of lipid-based carrier, nutraceuticals can be encapsulated successfully, as indicated by the high encapsulation efficiencies obtained. The most commonly encapsulated lipophilic nutraceuticals are vitamins, curcumin or quercetin, among others. As the literature review shows, a specific nutraceutical can be effectively encapsulated in different types of systems, and the choice of a particular carrier often depends on the purpose of the therapy. It is worth noting the great potential of encapsulating several nutraceuticals in one nanocarrier, as the synergistic effect that can be obtained increases the therapeutic efficacy. The examples described also indicate the wide applications of lipid-based carriers with nutraceuticals, including for the treatment of metabolic diseases, cardiovascular diseases, inflammation or in anticancer therapy. Table 3 shows recent work on the encapsulation of nutraceuticals in lipid-based carriers.

TABLE 3. Recent research (between 2020-2025) on lipid-based carriers for nutraceutical delivery.

Nanocarrier/ nutraceutical/ reference	Size (nm)*	ZP (mV)	EE (%)	Components of the carrier	Method of preparation	Comments
Liposomes/ resveratrol [85]	80.33 ± 0.62 (without resveratrol) 155.0 ± 1.62 (with resveratrol)	− 0.49 ± 0.012 (without resveratrol) − 2.59 ± 0.020 (with resveratrol)	76.62 ± 3.43	Phospholipon 90G, cholesterol, DSPE-mPEG$_{2000}$	Single-emulsion solvent evaporation	-
Liposomes/rutin [86]	99.78 ± 3.68	1.16 ± 0.21	88.1 ± 2.1	DMPC	pH-driven method	-
Liposomes/ curcumin [76]	154.3 ± 35.2 (TFH) 323.8 ± 39.0 (LF-DC) 185.4 ± 4.2 (P-DC)	− 4.9 ± 2.2 (TFH) − 7.0 ± 1.9 (LF-DC) − 2.6 ± 0.9 (P-DC)	29.86 ± 2.85 (TFH) 29.28 ± 5.22 (LF-DC) 69.26 ± 5.76 (P-DC)	DPPC, cholesterol, HEPES buffer	TFH, LF-DC, P-DC	Chloroform and methanol were used during the preparation of the liposomes, which were later evaporated.
Liposome/ quercetin [75]	Without WPI: ~40 – 180 Coated with WPI: ~ 65 – 135 Inserted with WPI: ~ 65 – 160	Without WPI: −13.40 ± 0.98 Coated with WPI: −2.5 – 10 Inserted with WPI: ~ −17.5 – −13	Without WPI: ~50 – 75 Coated with WPI: ~65% Inserted with WPI: ~65 – 75%	Egg yolk lecithin, Tween 80,	Thin-film method assisted with ultrasonication	During the preparation, ethanol was used, which was then evaporated. The values of size, ZP, and EE depending on loading concentration.
Liposome/ luteolin [87]	104.10 ± 1.74 – 109.60 ± 1.77 (luteolin liposomes) 105.50 ± 6.71 – 139.80 ± 14.21 (SOP-decorated luteolin liposomes)	−20.6 ±1.6 – −11.6 ± 3.6 (SOP-decorated luteolin liposomes)	~30 – 48 (luteolin liposomes) ~40-52 (SOP-decorated luteolin liposomes)	Lecithin from soybean (SOP), cholesterol, Tween-80, PBS	Thin-film dispersion method	The range of sizes, ZP, EE depending on NaCl concentration. During the preparation, ethanol was used, which was then evaporated.
Liposome/ lycopene [88]	250.2 ± 15.26	−6.43 ± 1.27	85.13 ± 3.78	Phospholipon 90 G, cholesterol, sucrose	Ether injection approach	During the preparation, diethyl ether was used, which was then removed.
Emulsion/ curcumin [89]	681.03 ± 18.58	29.73 ± 1.53	90.15 ± 0.67	MCT, gum arabic, soybean whey protein	Homogenization through a high-pressure homogenizer	The values of sizes, ZP, and EE at pH 6.0.
Emulsion/ curcumin [73]	389 ± 5 (without curcumin) 403 ± 20 (with curcumin)	−29.1 ± 0.3 (without curcumin) −17 ± 1 (with curcumin)	-	Hydrophobically modified hyaluronate, corn oil	Emulsification process (mechanical shaking and sonication)	-
Emulsion/ β-carotene [90]	239.60 ± 5.21 – 303.63 ± 10.46	−47.97 ± 0.45 – −35.33 ± 0.76	-	WPI-GA (whey protein isolate-gum Acacia), corn oil	Homogenization with a high-pressure microfluidizer	-
Emulsion/ vitamin D3 [79]	170-350	−25	94 – 96	Canola oil, pea protein in phosphate buffer	Homogenization with high speed mixer and high pressure homogenizer	-

Nanocarrier/ nutraceutical/ reference	Size (nm)*	ZP (mV)	EE (%)	Components of the carrier	Method of preparation	Comments
Emulsion/ vitamin A acetate [80]	571.2 – 2700	43.5 – 52.1	76.4	Sodium caseinate, sodium alginate, soybean oil	Homogenization with a high-speed homogenizer and a high-pressure microjet nano-homogenizer	Values of size depending on sodium alginate concentration.
Emulsion/ garlic oil compounds [91]	480 – 560	−19 – −16	-	Hydrophobically modified hyaluronate, corn oil	Emulsification process (mechanical shaking and sonication)	-
NLCs/ curcumin [92]	210 – 260	−27 – −22	>90	GTS, MCT, OVA-HA conjugates	Hot homogenization and ultrasonication method	-
NLCs/ pterostilbene [93]	88.38 ± 0.23 (without pterostilbene) 95.06 ± 4.2 (with pterostilbene)	−7.67 ± 0.92 (without pterostilbene) −8.42 ± 0.56 (with pterostilbene)	98.02± 0.43	Kolliphor® HS, isopropyl myristate, Epikuron 200	Phase inversion	-
NLCs/ Vitamin D3 [81]	120.67 ± 5.47	−31.4	96.33 ± 2.29	Anhydrous milk fat, vitamin E acetate, polyglycerol ester, hydrated sodium caseinate	Hot homogenization-sonication technique	-
NLCs/ quercetin [72]	160.5 ± 5.9 (without quercetin) 505.9 ± 31.8 (with quercetin)	~ −50 (without quercetin) −51.9 ± 4.7 – −33.7 ± 1.2 (with quercetin)	>99	Sunflower/ olive/ corn/castor/coconut oil, Span 80, myristic acid	Mini-emulsion methodology using an ultrasonication step	Size and ZP values refer to NLCs with sunflower oil.
Niosomes/ curcumin [74]	251 ± 7.14	−35.3 ± 0.68	97.96 ± 0.55	Tween 80, sorbitan monostearate, cholesterol, hyaluronan	TFH	-
Niosomes/ curcumin [94]	277.4 ± 6.2 (without curcumin) 564.2 ± 28.1 (with curcumin)	−28.3 ± 1.28 (without curcumin) −29.2 ± 1.21 (with curcumin)	64.1 ± 10.6	N, N diphthalimide decane, cholesterol	Thin layer hydration	During the preparation process dichloromethane and methanol were used, which were then evaporated.
Niosomes/ Vitamin D3 [95]	76 (without vitamin D3) 74 – 197 (with vitamin D3)	~ +20 (without vitamin D3) −15 – +29 (with vitamin D3)	75.3 – 94.3	Span 60, tween 80, vitamin E− acetate, cholesterol, Polyethylene Glycol 400	Thin layer hydration-sonication	Sizes, ZP, and EE values of niosomes with vitamin D3 depending on the composition of the niosomes. During the preparation process isopropyl alcohol was used, which was then evaporated.
Niosomes/ quercetin [96]	86.16 ± 0.70 – 149.57 ± 1.01	−28.58 ± 0.99 – −8.59 ± 1.39	61.49 – 95.68	Span 60, tween 80, phytosterol, PEG400	Thin layer hydration	Chloroform and ethanol were used during the preparation process, which were then evaporated.
Niosomes/ Lippia citriodora essential oil (LCEO) [97]	57.6 – 594.4	−3 – −21.9	31.29 – 91.20	Span 60, Tween 60 cholesterol, vitamin D3, PBS	TFH	Ethanol was used during the preparation process, which was then evaporated.
SLNs/ kaempferol [98]	451.2	−15.0	84.92	Stearic acid, polysorbate 80	Ultrasonication method	-
SLNs/quercetin [77]	480.1 ± 112.0	−27.4 ± 0.6	80.4 ± 0.26	Sodium stearate, arabic gum, citric acid,	Coacervation method	-
SLNs/ linolenic Acid [99]	258.9 ± 8.3 – 395 ± 39.5 (without linolenic acid) 271.8 ± 4.0 – 493.6 ± 183.90 (with linolenic acid)	-	62 – 99	Curcumin monooleate/capsaicin oleate/ resveratrol monooleate, Tween 20, sodium taurocholate, butanol,	Microemulsion technique	-

Nanocarrier/ nutraceutical/ reference	Size (nm)*	ZP (mV)	EE (%)	Components of the carrier	Method of preparation	Comments
SLNs, NLCs/ zeaxanthin [100]	77.49 ± 1.70 – 179.16 ± 0.94 (SLNs) 71.13 ± 0.88 – 130.16 ± 1.58 (NLCs)	−20.03 ± 0.48 – −12.11 ± 0.80 (SLNs) −22.23 ± 0.41 – 16.88 ± 0.61 (NLCs)	81.14 –85.38 (SLNs) 88.10 ± 2.19 – 90.43 ± 2.85 (NLCs)	GMS, soy lecithin, Tween 80, GDS, MCT	High shear homogenization and ultrasonic methods	-
SEDDS/ quercetin [78]	50.53 ± 0,087 (without quercetin) 41.60 ± 0,051– 46.15 ± 0.206 (with quercetin)	−4.513 ± 0.564 (without quercetin) −7.513 ± 0.170 – −6.127 ± 0.538 (with quercetin)	-	Ethyl oleate, RH40, TPGS, QS, isopropanol	-	Values of size depending of quercetin concentration.
SEDDS/ black seed oil [101]	183	−40.6	-	Kolliphor® P188, polyethylene glycol (PEG) 600	Mixing and heating	-
SNEDDS/ sesamin [102]	66.4 ± 31.4	-	-	GT, MCT, labrasol, Tween 20, Transcutol HP/ Cremophor EL	-	-
SNEDDS/ apigenin [103]	10.46 ± 0.08 – 17.08 ± 0.09 (without apigenin) 10.59 ± 0.08 – 58.61 ± 1.56 (with apigenin)	−5.51 ± 2.50 – 0.61 ± 1.54 (without apigenin) −13.67 ± 0.32 – −0.89 ± 1.08 (with apigenin)	84.20 ± 0.03	Gelucire 44/14, Tween 80, PEG 400	-	-
SEDDS/ ginger extract [104]	242 (with glycerin), 276 (with PEG)	-	-	Glycerin/PEG, krill oil	-	-
Co-delivery						
Liposome/ curcumin + piperine [82]	93.9 ± 0.9	0.3 ± 0.1	95.23% ± 1.08 (curcumin) 97.04% ± 1.16 (piperine)	Lecithin, cholesterol, DSPE-PEG2000-Irgd, DSPE-PEG2000, PBS	TFH	Chloroform was used during the preparation of the niosomes, which was later evaporated.
Emulsion/ curcumin + DHA-rich algal oil [83]	179.37 ± 2.90	−35.28 ± 3.23	99.53 ± 0.20	MCT, lecithin, Tween 80	Ultrasonic emulsification	-
Emulsion/ vitamin E + vitamin A [84]	129.1 ± 2.61 (without nutraceuticals) 135.9 ± 17.90 (with nutraceuticals)	−10.04 ± 0.5 (without nutraceuticals) −9.63 ± 0.39 (with nutraceuticals)	90%	Isopropyl myristate, Tween 80, propylene glycol	Emulsification	-
Liposomes/ vitamin E + β-carotene [105]	100 – 200	-	92.49 ± 0.76 (β-carotene), 86.16 ± 0.58 (vitamin E)	Soybean phospholipid, hydro-genated soybean phospholipid, choles-terol	TFH	Mixture of chloroform and ethanol was used during the preparation process, which was then evaporated.
SLNs/Omega-3 fatty acids (DHA) + vitamin D3 [106]	63.5	−32	92.30 ± 1.20 (vitamin D3) 86.30 ± 1.40 (omega-3 fatty acids)	Beeswax, lecithin, Tween 80	Nanoemulsion method	-

* Unless otherwise stated, the data refers to the size of the carrier with nutraceutical/s.

DMPC – 1,2-Dimyristoyl-sn-glycero-3-phosphocholine, DC – Dual centrifugation, LF-DC – Lipid film method DC, P-DC – Powder method DC, DPPC – 1,2-dipalmitoyl-sn-glycero-3-phosphocholine, HEPES – 4-(2- hydroxyethyl)-1-piperazineethanesulfonic acid, SOP – Soybean oleosome-associated protein, DPPH – 2,2-diphenyl-1-picrylhydrazyl, GTS – glyceryl tristearate, MCT – medium-chain triglycerides, OVA – ovalbumin , HA – hyaluronic acid, ICG – indocyanine green , PEG 400 – polyethylene glycol 400, GS – glyceryl stearate , HPO – hydrogenated palm oil, GMS – glycerol monostearate , GDS – glycerol distearate, GT – glyceryl trioctanoate, TPGS – D-a-Tocopheryl Polyethylene Glycol Succinate, QS – Quillaja Saponin.

Future Perspectives

The rapid development of nanotechnology has resulted in ever-improving carriers for nutraceutical delivery, and new technologies are setting the stage for further research. A promising strategy includes fabrication of responsive carriers. This technology was introduced to deliver the active ingredient to a specific location at a specific time, increasing uptake and avoiding impact on healthy tissues and cells. Carriers that respond to exogenous stimuli (light, ultrasound, magnetic field) or endogenous stimuli (redox, pH, ROS (reactive oxygen species)) are being successfully developed [107]. The use of nutraceutical carriers for personalized nutrition is another interesting research direction. Customization of the carrier to individual patients is particularly attractive in terms of metabolic diseases or treatment of nutritional deficiencies. A variety of biomimetic strategies that, in terms of nutraceutical delivery, may involve the use of carriers that mimic various biological functions of cellular systems, such as the structure of cell membranes, may significantly enhance treatment efficacy. Moreover, combining such strategies with devices that enable real-time health monitoring takes into account changes in a given patient's needs and can allow nutraceuticals to be released at the right time, such as at a certain glucose level [108]. Recently, attention is also being paid to the use of naturally occurring ingredients in the production of carriers so as to obtain systems that are biocompatible, biodegradable and safe for use. Also of great potential are hybrid carriers combining lipids with other materials (proteins, polysaccharides), which offer possibilities for better biodistribution, increased permeability, stability and controlled release, among others [109]. For example, a nanoemulsion that replaces a low molecular weight surfactant with an amphiphilic modified polysaccharide reduces surfactant toxicity and significantly increases the stability of the system. Appropriate selection of the shell also makes it possible to increase the efficiency of cellular uptake of such carriers [12]. A limitation associated with bringing new carrier technologies to market is the lack of clear regulation of nanocarriers for nutraceutical delivery. Another problem is the cost of new technologies, in view of which efforts should be made to make these systems cost-effective and achievable. In addition, promising carriers should be thoroughly investigated for efficacy and safety in human use, as most data currently comes from in vitro studies.

Summary

With the ever-increasing health awareness, interest in a variety of nutraceuticals continues to grow. They have a high safety profile and provide nutritional value, in addition to a variety of activities, such as anti-inflammatory, antimicrobial, antioxidant, cardioprotective, anti-obesity treating and/or preventing and curing diseases, improving cognitive function, slowing aging, reducing side effects of chemotherapy. At the same time, many of them have low water solubility, their oral absorption, bioavailability, and permeability is poor, and many are susceptible to various external factors such as light, oxygen, pH. In addition, they can have a variable molecular weight and an unpleasant taste or odor. All these factors make their use in the food and pharmaceutical industries limited, and the development of new formulations difficult.

Lipid-based carriers represent a promising strategy for their encapsulation. As shown in specific examples, they can, among other things, enhance efficient delivery of nutraceuticals, provide a protective function against external factors, improve stability during storage, mask unpleasant taste, and provide prolonged release. They enable high encapsulation efficiencies and can be easily functionalized for targeted delivery. In addition, the use of these types of carriers can not only preserve but also enhance the effects of nutraceuticals, consequently demonstrating better performance than a free nutraceutical, such as enhancing antimicrobial, antioxidant, or anticancer activity. More than one substance can also be encapsulated in these carriers - this approach creates opportunities to study different combinations of nutraceuticals for synergistic effects. As reported, some combinations of nutraceuticals show better effects than each of them given individually, which can lead to lower doses used in future therapies.

All these advantages of nanocarriers can improve treatment and reduce side effects. At the same time, when developing a new nanoformulation for nutraceutical delivery, it is important to keep in mind the appropriate choice of carrier type, preparation method or selection of appropriate excipients. Importantly, the nanocarriers under development are costly, and efforts should be made to make them cost-effective. Despite great advances in this field, further research is needed to investigate possible interactions of nutraceuticals with drugs to prevent possible side effects. Further research is also needed on the targeted and controlled release of such substances from nanocarriers.

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References

[1] DeFelice S. L.: The Nutraceutical Revolution: Its Impact on Food Industry R&D. Trends in Food Science & Technology 6 (1995) 59–61.
[2] Puri V., Nagpal M., Singh I., Singh M., Dhingra GA., Huanbutta K., Dheer D., Sharma A., Sangnim T.: A Comprehensive Review on Nutraceuticals: Therapy Support and Formulation Challenges. Nutrients 14 (2022) 4637.
[3] Guarnieri L., Bosco F., Leo A., Citraro R., Palma E., De Sarro G., Mollace V.: Impact of Micronutrients and Nutraceuticals on Cognitive Function and Performance in Alzheimer's Disease. Ageing Research Reviews 95 (2024) 102210.
[4] Singh P., Sivanandam TM., Konar A., Thakur MK.: Role of Nutraceuticals in Cognition During Aging and Related Disorders. Neurochemistry International 143 (2021) 104928.
[5] Leena M. M., Silvia G., Kannadasan V., Jeyan M., Anandharamakrishnan, C.: Synergistic Potential of Nutraceuticals: Mechanisms and Prospects for Futuristic Medicine. Food Function 11 (2020) 9317-9337.
[6] Gao Q., Feng J., Liu W., Wen C., Wu Y., Liao Q., Zou L., Sui X., Xie T., Zhang J., Hu Y.: Opportunities and Challenges for Co-delivery Nanomedicines Based on Combination of Phytochemicals with Chemotherapeutic Drugs in Cancer Treatment. Advanced Drug Delivery Reviews 188 (2022) 114445.
[7] Abuhassira-Cohen Y., Livney Y. D.: Enhancing the Bioavailability of Encapsulated Hydrophobic Nutraceuticals: Insights from In Vitro, In Vivo, and Clinical Studies. Current Opinion in Food Science 45 (2022) 100832.
[8] Xiao S., Ahn D. U.: Co-encapsulation of Fish Oil with Essential Oils and Lutein/Curcumin to Increase the Oxidative Stability of Fish Oil Powder. Food Chemistry 410 (2023) 135465.

[9] Ma C., Xie Y., Huang X., Zhang L., McClements D. J., Zou L., Liu W.: Encapsulation of (-)-Epigallocatechin Gallate (EGCG) within Phospholipid-based Nanovesicles Using W/O Emulsion-Transfer Methods: Masking Bitterness and Delaying Release of EGCG. Food Chemistry 437 (2024) 137913.
[10] Rezaei A., Fathi M., Jafari S. M.: Nanoencapsulation of Hydrophobic and Low-soluble Food Bioactive Compounds within Different Nanocarriers. Food Hydrocolloids 88 (2019) 146-162.
[11] Szafraniec-Szczęsny J., Janik-Hazuka M., Odrobińska J., Zapotoczny S.: Polymer Capsules with Hydrophobic Liquid Cores as Functional Nanocarriers. Polymers 12(9) (2020) 1999.
[12] Janik-Hazuka M., Szafraniec-Szczęsny J., Kamiński K., Odrobińska J., Zapotoczny S.: Uptake and In Vitro Anticancer Activity of Oleic Acid Delivered in Nanocapsules Stabilized by Amphiphilic Derivatives of Hyaluronic Acid and Chitosan. International Journal of Biological Macromolecules 164 (2020) 2000-2009.
[13] Barroso L., Viegas C., Vieira J., Ferreira-Pêgo C., Costa J., Fonte P.: Lipid-Based Carriers for Food Ingredients Delivery. Journal of Food Engineering 295 (2021) 110451.
[14] Molaveisi M., Zhao Y., Shi Q., Fang Z.: Function of Vitamin D3-loaded Lipid-based Nanocarriers in Food Industry: Principles, Applications, and Challenges. Trends in Food Science & Technology 155 (2025) 104798.
[15] Liu P., Chen G., Zhang J.: A Review of Liposomes as a Drug Delivery System: Current Status of Approved Products, Regulatory Environments, and Future Perspectives. Molecules 27 (2022), 1372.
[16] Guimarães D., Cavaco-Paulo A., Nogueira E.: Design of Liposomes as Drug Delivery System for Therapeutic Applications. International Journal of Pharmaceutics 601 (2021) 120571.
[17] Eugster R., Luciani P.: Liposomes: Bridging the Gap from Lab to Pharmaceuticals. Current Opinion in Colloid & Interface Science 75 (2025) 101875.
[18] Mushtaq A., Mohd Wani S., Malik A. R., Gull A., Ramniwas S., Ahmad Nayik G., Ercisli S., Alina Marc R., Ullah R., Bari A.: Recent Insights into Nanoemulsions: Their Preparation, Properties and Applications. Food Chemistry: X 18 (2023) 100684.
[19] Manzoor M., Sharma P., Murtaza M., Jaiswal A. K., Jaglan S.: Fabrication, Characterization, and Interventions of Protein, Polysaccharide and Lipid-Based Nanoemulsions in Food and Nutraceutical Delivery Applications: A Review. International Journal of Biological Macromolecules 241 (2023) 124485.
[20] Singh I. R., Pulikkal A. K.: Preparation, Stability and Biological Activity of Essential Oil-based Nano Emulsions: A Comprehensive Review. OpenNano 8 (2022) 100066.
[21] Bednorz J., Smela K., Zapotoczny S.: Tailoring Properties of Hyaluronate-Based Core–Shell Nanocapsules with Encapsulation of Mixtures of Edible Oils. International Journal of Molecular Sciences 24(19) 14995.
[22] Varela-Fernández R., García-Otero X., Díaz-Tomé V., Regueiro U., López-López M., González-Barcia M., Isabel Lema M., Javier Otero-Espinar F.: Lactoferrin-loaded Nanostructured Lipid Carriers (NLCs) as a New Formulation for Optimized Ocular Drug Delivery. European Journal of Pharmaceutics and Biopharmaceutics 172 (2022) 144-156.
[23] Salvi V.R., Pawar P. Nanostructured Lipid Carriers (NLC) System: A Novel Drug Targeting Carrier. Journal of Drug Delivery Science and Technology 51 (2019) 255-267.
[24] Nobari Azar F. A., Pezeshki A., Ghanbarzadeh B., Hamishehkar H., Mohammadi M.: Nanostructured Lipid Carriers: Promising Delivery Systems for Encapsulation of Food Ingredients. Journal of Agriculture and Food Research 2 (2020) 100084.
[25] Moammeri A., Chegeni M.M., Sahrayi H., Ghafelehbashi R., Memarzadeh F., Mansouri A., Akbarzadeh I., Maryam Sadat Abtahi, Hejabi F., Ren Q.: Current Advances in Niosomes Applications for Drug Delivery and Cancer Treatment. Materials Today Bio 23 (2023) 100837.
[26] Bhardwaj P., Tripathi P., Gupta R., Pandey S.: Niosomes: A Review on Niosomal Research in the Last Decade. Journal of Drug Delivery Science and Technology 56 Part A (2020) 101581.
[27] Gunawan M., Boonkanokwong V.: Current Applications of Solid Lipid Nanoparticles and Nanostructured Lipid Carriers as Vehicles in Oral Delivery Systems for Antioxidant Nutraceuticals: A Review. Colloids and Surfaces B: Biointerfaces 233 (2024) 113608.
[28] Katopodi A., Detsi A.: Solid Lipid Nanoparticles and Nanostructured Lipid Carriers of Natural Products as Promising Systems for Their Bioactivity Enhancement: The Case of Essential Oils and Flavonoids. Colloids and Surfaces A: Physicochemical and Engineering Aspects 630 (2021) 127529.
[29] Uttreja P., Karnik I., Adel Ali Youssef A., Narala N., Elkanayati RM., Baisa S., Alshammari ND., Banda S., Vemula SK., Repka MA.: Self-Emulsifying Drug Delivery Systems (SEDDS): Transition from Liquid to Solid—A Comprehensive Review of Formulation, Characterization, Applications, and Future Trends. Pharmaceutics 17(1) (2025) 63.
[30] Maji I., Mahajan S., Sriram A., Medtiya P., Vasave R., Khatri DK., Kumar R., Singh SB., Madan J., Singh PK.: Solid Self Emulsifying Drug Delivery System: Superior Mode for Oral Delivery of Hydrophobic Cargos. Journal of Controlled Release 337 (2021) 646-660.
[31] Arshad A., Arshad S., Alamgeer, Mahmood A., Hussain Asim M., Ijaz M., Muhammad Irfan H., Rubab M., Ali S., Raza Hashmi A.: Zeta Potential Changing Self-nanoemulsifying Drug Delivery Systems: A Newfangled Approach for Enhancing Oral Bioavailability of Poorly Soluble Drugs. International Journal of Pharmaceutics 655 (2024) 123998.
[32] Ali A., Mekhloufi G., Huang N., Agnely F.: β-lactoglobulin Stabilized Nanemulsions-Formulation and Process Factors Affecting Droplet Size and Nanoemulsion Stability. International Journal of Pharmaceutics 500(1-2) (2016) 291-304.
[33] Simonazzi A., Cid A. G., Villegas M., Romero A. I., Palma S. D., Bermúdez J. M.: Chapter 3 - Nanotechnology Applications in Drug Controlled Release. Drug Targeting and Stimuli Sensitive Drug Delivery Systems, William Andrew Publishing (2018) 81-116.
[34] Salvia-Trujillo L., Soliva-Fortuny R., Rojas-Graü M.A., McClements D.J., Martín-Belloso O. Edible Nanoemulsions as Carriers of Active Ingredients: A Review. Annual Review of Food Science and Technology 8 (2017) 439-466.
[35] Eisinaite V., Duque Estrada P., Schroën K., Berton-Carabin C., Leskauskaite D.: Tayloring W/O/W Emulsion Composition for Effective Encapsulation: The Role of PGPR in Water Transfer-Induced Swelling. Food Research International 106 (2018) 722–728.
[36] Kodel H.A.C., Alizadeh P., Ebrahimi S.N., Machado T.O.X., Oliveira M.B.P.P., Fathi F., Souto E.B.: Liposomes and Niosomes: New Trends and Applications in the Delivery of Bioactive Agents for Cancer Therapy. International Journal of Pharmaceutics 668 (2025) 124994.
[37] Müller R.H., Radtk M., Wissing S.A.: Solid Lipid Nanoparticles (SLN) and Nanostructured Lipid Carriers (NLC) in Cosmetic and Dermatological Preparations. Advanced Drug Delivery Reviews 54 Suppl. 1 (2002) S131-S155.
[38] Da Silva Santos V., Ribeiro A.P.B., Santana M.H.A.: Solid Lipid Nanoparticles as Carriers for Lipophilic Compounds for Applications in Foods. Food Research International 122 (2019) 610-626.
[39] Tang C.-H., Chen H.-L., Dong J.-R.: Solid Lipid Nanoparticles (SLNs) and Nanostructured Lipid Carriers (NLCs) as Food-Grade Nanovehicles for Hydrophobic Nutraceuticals or Bioactives. Applied Sciences 13 (2023) 1726.
[40] Yan S., Cheng Y., Li L., Zhong C., Chen C., Gao X.: Lipid-Based Formulations: A Promising Approach for Poorly Soluble Drug Delivery via the Intestinal Lymphatic System. Journal of Drug Delivery Science and Technology 87 (2023) 104770.
[41] Salawi A.: Self-emulsifying Drug Delivery Systems: a Novel Approach to Deliver Drugs. Drug Delivery 29 (2022) 1811-1823.
[42] Gasmi A., Mujawdiya P.K., Noor S., Lysiuk R., Darmohray R., Piscopo S., Lenchyk L., Antonyak H., Dehtiarova K., Shanaida M., Peana M., Bjørklund G.: Polyphenols in Metabolic Diseases. Molecules 27(19) (2022) 6280.
[43] Yuan D., Guo Y., Pu F., Yang C., Xiao X., Du H., He J., Lu S.: Opportunities and Challenges in Enhancing the Bioavailability and Bioactivity of Dietary Flavonoids: A Novel Delivery System Perspective. Food Chemistry 430 (2024) 137115.
[44] Tan Y., McClements D.J.: Improving the Bioavailability of Oil-soluble Vitamins by Optimizing Food Matrix Effects: A Review. Food Chemistry 348 (2021) 129148.
[45] Amrein K., Scherkl M., Hoffmann M., Neuwersch-Sommeregger S., Köstenberger M., Tmava Berisha A., Martucci G., Pilz S., Malle O.: Vitamin D Deficiency 2.0: an Update on the Current Status Worldwide. European Journal of Clinical Nutrition 74 (2020) 1498-1513.

[46] Traber M.G.: Human Vitamin E Deficiency, and What Is and Is Not Vitamin E? Free Radical Biology and Medicine 213 (2024) 285-292.
[47] Fusaro M., Cianciolo G., Brandi M.L., Ferrari S., Nickolas T.L., Tripepi G., Plebani M., Zaninotto M., Iervasi G., La Manna G., Gallieni M., Vettor R., Aghi A., Gasperoni L., Giannini S., Sella S., M Cheung A.: Vitamin K and Osteoporosis. Nutrients 12(12) (2020) 3625.
[48] Kij A., Kieronska-Rudek A., Bar A., Czyzynska-Cichon I., Strus M., Kozien L., Wiecek G., Zeber-Lubecka N., Kulecka M., Kwiatkowski G., Przyborowski K., Mohaissen T., Sternak M., Buczek E., Zakrzewska A., Proniewski B., Kus K., Franczyk-Zarow M., Kostogrys R.B., Pieterman E.J., Princen H.M.G., Chlopicki S.: Low Phylloquinone Intake Deteriorates Endothelial Function in Normolipidemic and Dyslipidaemic Mice. The Journal of Nutritional Biochemistry 140 (2025) 109867.
[49] Rodriguez-Concepcion M., Avalos J., Bonet M.L., Boronat A., Gomez-Gomez L., Hornero-Mendez D., Limon M.C., Meléndez-Martínez A.J., Olmedilla-Alonso B., Palou A., Ribot J., Rodrigo M.J., Zacarias L., Zhu C.: A Global Perspective on Carotenoids: Metabolism, Biotechnology, and Benefits for Nutrition and Health. Progress in Lipid Research 70 (2018) 62-93.
[50] Kapoor B., Kapoor D., Gautam S., Singh R., Bhardwaj S.: Dietary Polyunsaturated Fatty Acids (PUFAs): Uses and Potential Health Benefits. Current Nutrition Reports 10(3) (2021) 232-242.
[51] Cimino C., Maurel O. M., Musumeci T., Bonaccorso A., Drago F., Souto E. M. B., Pignatello R., Carbone, C.: Essential Oils: Pharmaceutical Applications and Encapsulation Strategies into Lipid-Based Delivery Systems. Pharmaceutics 13(3) (2021) 327.
[52] Mohammadkhanizadeh A., Sheibani M., Taherkhani S., Nourabadi D., Mohamadi-Zarch S.M., Nikbakht F., Azizi Y.: Protective Effects of Apigenin in Neurodegeneration: An Update on the Potential Mechanisms. Brain Disorders 17 (2025) 100189.
[53] Argano C., Mirarchi L., Amodeo S., Orlando V., Torres A., Corrao S.: The Role of Vitamin D and Its Molecular Bases in Insulin Resistance, Diabetes, Metabolic Syndrome, and Cardiovascular Disease: State of the Art. International Journal of Molecular Sciences 24(20) (2023) 15485.
[54] Freire de Carvalho J., Skare T.: Coenzyme Q10 Supplementation in Rheumatic Diseases: A Systematic Review. Clinical Nutrition ESPEN 59 (2024) 63-69.
[55] Ghasempour Dabaghi G., Rabiee Rad M., Mohammad-Zamani M., Karimi Shervedani A., Bahrami-Samani F., Heshmat-Ghahdarijani K.: The Role of Coenzyme Q10 as a Preventive and Therapeutic Agent for the Treatment of Cancers. Current Problems in Cancer 48 (2024) 101063.
[56] Jabczyk M., Nowak J., Hudzik B., Zubelewicz-Szkodzińska B.: Curcumin in Metabolic Health and Disease. Nutrients 13(12) (2021) 4440.
[57] Alam W., Khan H., Shah M.A., Cauli O., Saso L.: Kaempferol as a Dietary Anti-Inflammatory Agent: Current Therapeutic Standing. Molecules. 25(18) (2020) 4073.
[58] Mitra S., Rauf A., Tareq A.M., Jahan S., Emran T.B., Shahriar T.G., Dhama K., Alhumaydhi F.A., Aljohani A.S.M., Rebezov M., Uddin M.S., Jeandet P., Shah Z.A., Shariati M.A., Rengasamy K.R.: Potential Health Benefits of Carotenoid Lutein: An Updated Review. Food and Chemical Toxicology 154 (2021) 112328.
[59] Huang L., Kim M-Y., Cho J.Y.: Immunopharmacological Activities of Luteolin in Chronic Diseases. International Journal of Molecular Sciences 24(3) (2023) 2136.
[60] Pan X., Zhu R., Pei J., Zhang L.: Lycopene: A Potent Antioxidant to Alleviate Kidney Disease. International Immunopharmacology 151 (2025) 114363.
[61] Walia V., Chaudhary S.K., Kumar Sethiya N.: Therapeutic Potential of Mangiferin in the Treatment of Various Neuropsychiatric and Neurodegenerative Disorders. Neurochemistry International 143 (2021) 104939.
[62] Tiwari A., Mahadik K.R., Gabhe S.Y.: Piperine: A Comprehensive Review of Methods of Isolation, Purification, and Biological Properties. Medicine in Drug Discovery 7 (2020) 100027.
[63] Han J., Zhang S., He J., Li T.: Piperine: Chemistry and Biology. Toxins 15(12) (2023) 696.
[64] Khattar S., Khan S.A., Zaidi S.A.A., Darvishikolour M., Farooq U., Naseef P.P., Kurunian M.S., Khan M.Z., Shamim A., Khan M.M.U., Iqbal Z., Mirza M. A.: Resveratrol from Dietary Supplement to a Drug Candidate: An Assessment of Potential. Pharmaceuticals 15(8) (2022) 957.
[65] Muvhulawa N., Dludla P.V., Ziqubu K., Mthembu S..X.H., Mthiyane F., Nkambule B.B., Mazibuko-Mbeje S.E.: Rutin Ameliorates Inflammation and Improves Metabolic Function: A Comprehensive Analysis of Scientific Literature. Pharmacological Research 178 (2022) 106163.
[66] Pandey P., Khan F., Qari H.A., Oves M.: Rutin (Bioflavonoid) as Cell Signaling Pathway Modulator: Prospects in Treatment and Chemoprevention. Pharmaceuticals 14(11) (2021) 1069.
[67] Mashhadi Akbar Boojar M., Mashhadi Akbar Boojar M., Golmohammad S.: Overview of Silibinin Anti-Tumor Effects. Journal of Herbal Medicine 23 (2020) 100375.
[68] Xu D., Hu M.J., Wang Y.Q., Cui .YL.: Antioxidant Activities of Quercetin and Its Complexes for Medicinal Application. Molecules 24(6) (2019) 1123.
[69] Chen M., Ghelfi M., Poon J., Jeon N., Boccalon N., Rubsamen M., Valentino S., Mehta V., Stamper M., Tariq H., Zunica E., Ulatowski L., Chung S., Fritz C., Cameron M., Cameron C., Pratt D.A., Atkinson J., Finno C.J., Manor D.: Antioxidant-Independent Activities of Alpha-Tocopherol. Journal of Biological Chemistry 301(4) (2025) 108327.
[70] Wang J., Hu X., Chen J., Wang T., Huang X., Chen G. The Extraction of β-Carotene from Microalgae for Testing Their Health Benefits. Foods 11(4) (2022) 502.
[71] Golanski J., Szymanska P., Rozalski M.: Effects of Omega-3 Polyunsaturated Fatty Acids and Their Metabolites on Haemostasis-Current Perspectives in Cardiovascular Disease. International Journal of Molecular Sciences 22(5) (2021) 2394.
[72] Bender L., Abdallah M. Ayoub, Schulze J., Amin M.U., Librizzi D., Engelhardt K.H., Roschenko V., Yousefi B.H., Schäfer J., Preis E., Bakowsky U.: Evaluating the Photodynamic Efficacy of Nebulized Curcumin-Loaded Liposomes Prepared by Thin-Film Hydration and Dual Centrifugation: In Vitro and In Ovo Studies. Biomaterials Advances 159 (2024) 213823.
[73] Czyzynska-Cichon I., Janik-Hazuka M., Szafraniec-Szczęsny J., Jasinski K., Węglarz W.P., Zapotoczny S., Chlopicki S.: Low Dose Curcumin Administered in Hyaluronic Acid-Based Nanocapsules Induces Hypotensive Effect in Hypertensive Rats. International Journal of Nanomedicine 16 (2021) 1377-1390.
[74] Abasi M., Ghadi Z.S., Pilehvar Y., Ebrahimnejad P.: Curcumin Loaded Hyaluronan Modified Niosomes: Preparation, Characterization and Anti-Cancer Activity on Triple-Negative Breast Cancer Cells. Journal of Drug Delivery Science and Technology 108 (2025) 106869.
[75] Wan B., Xiao Q., Huang M., Ying R.: Masking the Bitter Taste of Quercetin by Liposomes Modified with Whey Protein Isolate: Better to Be Coated or Inserted? Food Hydrocolloids 149 (2024) 109540.
[76] de Barros D.P.C., Santos R., Reed P., Fonseca L.P., Oliva A.: Design of Quercetin-Loaded Natural Oil-Based Nanostructured Lipid Carriers for the Treatment of Bacterial Skin Infections. Molecules 27(24) (2022) 8818.
[77] Talarico L., Consumi M., Leone G., Tamasi G., Magnani A.: Solid Lipid Nanoparticles Produced via a Coacervation Method as Promising Carriers for Controlled Release of Quercetin. Molecules 26 (2021) 2694.
[78] Lin S.Y., Chen T.T., Farag M.A., Teng H., Cao H.: A Modified Self-Micro Emulsifying Liposome for Bioavailability Enhancement of Quercetin and Its Biological Effects. Food Bioscience 62 (2024) 105352.
[79] Walia N., Chen L.: Pea Protein Based Vitamin D Nanoemulsions: Fabrication, Stability and In Vitro Study Using Caco-2 Cells. Food Chemistry 305 (2020) 125475.
[80] Zou K., Zhang F., Lv W., Chen W., He J., Alouk I, Hou Z., Ren S., Gong G., Wang Y., Xu D.: Fabrication of Emulsion Microparticles to Improve the Physicochemical Stability of Vitamin A Acetate. Food Chemistry 469 (2025) 142620.
[81] Barri A., Ghanbarzadeh B., Mohammadi M., Pezeshki A.: Application of Sodium Caseinate as Protein Based Coating/Stabilizing Agent in Development and Optimization of Vitamin D3-Loaded

Nanostructured Lipid Carriers (NLCs). Food Hydrocolloids 144 (2023) 108747.
[82] Wang Y., Huang X., Chen H., Wu Q., Zhao Q., Fu D., Liu Q., Wang Y. The Antitumour Activity of a Curcumin and Piperine Loaded iRGD-Modified Liposome: In Vitro and In Vivo Evaluation. Molecules 28 (2023) 6532.
[83] He J., Chen W., Chen S., Shi M., Lin L., Zhang Y., Hong B.: Microemulsion Co-Delivering Curcumin and DHA-Rich Algal Oil Alleviates Nonalcoholic Fatty Liver Disease. Journal of Functional Foods 112 (2024) 105998.
[84] Praça F. G., Viegas J. S. R., Peh H. Y., Garbin T. N., Medina W. S. G., Bentley M. V. L. B.: Microemulsion Co-Delivering Vitamin A and Vitamin E as a New Platform for Topical Treatment of Acute Skin Inflammation. Materials Science and Engineering: C 110 (2020) 110639.
[85] Paranthaman S., Uthaiah C.A., Hani U.: Comprehensive Evaluation of EGFR and AKT Targeting Efficacy of Resveratrol Loaded PEGylated Liposomes for the Glioblastoma Management: In silico, in vitro BBB Permeation Studies. Bioorganic Chemistry 154 (2025) 108077.
[86] Sengupta P., Das D., Bhattacharya S., Sur R., Bose A., Sen K.: A pH-Driven Method for Liposomal Encapsulation of Dietary Flavonoid Rutin: Sustained Release and Enhanced Bioefficacy. Food Bioscience 52 (2023) 102392.
[87] Li R., Pu C., Sun Y., Sun Q., Tang W.: Interaction Between Soybean Oleosome-Associated Proteins and Phospholipid Bilayer and Its Influence on Environmental Stability of Luteolin-Loaded Liposomes. Food Hydrocolloids 130 (2022) 107721.
[88] Salem G.A., Mohamed A.A., Khater S.I., Noreldin A.E., Alosaimi M., Alansari W.S., Shamlan G., Eskandrani A.A., Awad M.M., El-Shaer R.A.A., Nassan M.A., Mostafa M., Khamis T.: Enhancement of Biochemical and Genomic Pathways Through Lycopene-Loaded Nano-Liposomes: Alleviating Insulin Resistance, Hepatic Steatosis, and Autophagy in Obese Rats with Non-Alcoholic Fatty Liver Disease: Involvement of SMO, GLI-1, and PTCH-1 Genes. Gene 883 (2023) 147670.
[89] Cao J., Tong X., Cao X., Peng Z., Zheng L., Dai J., Zhang X., Cheng J., Wang H., Jiang L.: Effect of pH on the Soybean Whey Protein-Gum Arabic Emulsion Delivery Systems for Curcumin: Emulsifying, Stability, and Digestive Properties. Food Chemistry 456 (2024) 139938.
[90] Chen W., Wang W., Guo M., Li Y., Meng F., Liu D.: Whey Protein Isolate-Gum Acacia Maillard Conjugates as Emulsifiers for Nutraceutical Emulsions: Impact of Glycation Methods on Physicochemical Stability and In Vitro Bioaccessibility of β-carotene Emulsions. Food Chemistry 375 (2022) 131706.
[91] Janik-Hazuka M., Kamiński K., Kaczor-Kamińska M., Szafraniec-Szczęsny J., Kmak A., Kassassir H., Watała C., Wróbel M., Zapotoczny S.: Hyaluronic Acid-Based Nanocapsules as Efficient Delivery Systems of Garlic Oil Active Components with Anticancer Activity. Nanomaterials 11(5) (2021) 1354.
[92] Feng J., Wang Z., Song H., Huang W., Xu L., Teng C., Li Y.: Boosting Curcumin's Chemical Stability and Intestinal Absorption via Nanostructured Lipid Carriers: The Impact of Lipid Composition. Food Chemistry 479 (2025) 143785.
[93] Abdel Gaber S.A., Nasr M., Hamzawy M.A.: Pterostilbene Lipid Nanocapsules as a Promising System for Treatment of Hepatocellular Carcinoma: Formulation, Characterization, and Cellular/In Vivo Appraisal. Journal of Drug Delivery Science and Technology 92 (2024) 105310.
[94] Habib S.M., Imran M., Kawish M., Mansoor F., Maharjan R., Balouch A.A., Jabeen A., Simjee S.U., Shah M.R.: Synthesis and Characterization of Phthalimide-Based Niosomes and Its Investigation as a Nano-Drug Delivery Carrier to Enhance the Therapeutic Efficacy of Curcumin. Journal of Molecular Liquids 410 (2024) 125516.
[95] Talebi V., Ghanbarzadeh B., Hamishehkar H., Pezeshki A., Ostadrahimi A.: Effects of Different Stabilizers on Colloidal Properties and Encapsulation Efficiency of Vitamin D3 Loaded Nano-Niosomes. Journal of Drug Delivery Science and Technology 61 (2021) 101284.
[96] Elmi N., Ghanbarzadeh B., Ayaseh A., Sahraee S., Khakbaz Heshmati M., Hoseini M., Pezeshki A.: Physical Properties and Stability of Quercetin Loaded Niosomes: Stabilizing Effects of Phytosterol and Polyethylene Glycol in Orange Juice Model. Journal of Food Engineering 296 (2021) 110463.
[97] Saleh A., Pirouzifard M., Alizadeh M., Almasi H.: Optimization and Characterization of Lippia citriodora Essential Oil Loaded Niosomes: A Novel Plant-based Food Nano Preservative. Colloids and Surfaces A: Physicochemical and Engineering Aspects 650 (2022) 129480.
[98] Ghosh A., Khanam N., Nath D.: Solid Lipid Nanoparticle: A Potent Vehicle of the Kaempferol for Brain Delivery Through the Blood-Brain Barrier in the Focal Cerebral Ischemic Rat. Chemico-Biological Interactions 397 (2024) 111084.
[99] Cassano R., Serini S., Curcio F., Trombino S., Calviello G.: Preparation and Study of Solid Lipid Nanoparticles Based on Curcumin, Resveratrol and Capsaicin Containing Linolenic Acid. Pharmaceutics 14(8) (2022) 1593.
[100] Osanlou R., Emtyazjoo M., Banaei A., Hesarinejad M.A., Ashrafi F.: Preparation of Solid Lipid Nanoparticles and Nanostructured Lipid Carriers Containing Zeaxanthin and Evaluation of Physicochemical Properties. Colloids and Surfaces A: Physicochemical and Engineering Aspects 641 (2022) 128588.
[101] Halder S., Islam A., Muhit M.A., Shill M.C., Haider S.S.: Self-Emulsifying Drug Delivery System of Black Seed Oil with Improved Hypotriglyceridemic Effect and Enhanced Hepatoprotective Function. Journal of Functional Foods 78 (2021) 104391.
[102] Wang C.Y., Yen C.C., Hsu M.C., Wu Y.T.: Self-Nanoemulsifying Drug Delivery Systems for Enhancing Solubility, Permeability, and Bioavailability of Sesamin. Molecules 25(14) (2020) 3119.
[103] Morakul B., Teeranachaideekul V., Limwikrant W., Junyaprasert V.B.: Dissolution and Antioxidant Potential of Apigenin Self Nanoemulsifying Drug Delivery System (SNEDDS) for Oral Delivery. Scientific Reports 14(1) (2024) 8851.
[104] Ogino M., Nakazawa A., Shiokawa K., Kikuchi H., Sato H., Onoue S.: Krill Oil-Based Self-Emulsifying Drug Delivery System to Improve Oral Absorption and Renoprotective Function of Ginger Extract. PharmaNutrition 19 (2022) 100285.
[105] Xu T., Zhang J., Jin R., Cheng R., Wang X., Yuan C., Gan C.: Physicochemical Properties, Antioxidant Activities and In Vitro Sustained Release Behaviour of Co-Encapsulated Liposomes as Vehicle for Vitamin E and β-Carotene. Journal of the Science of Food and Agriculture 102(13) (2022) 5759-5767.
[106] Shakeri M., Ghobadi R., Sohrabvandi S., Khanniri E., Mollakhalili-Meybodi N.: Co-Encapsulation of Omega-3 and Vitamin D3 in Beeswax Solid Lipid Nanoparticles to Evaluate Physicochemical and In Vitro Release Properties. Frontiers in Nutrition 11 (2024) 1323067.
[107] Bilal M., Qindeel M., Raza A., Mehmood S., Rahdar A.: Stimuli-responsive Nanoliposomes as Prospective Nanocarriers for Targeted Drug Delivery. Journal of Drug Delivery Science and Technology 66 (2021) 102916.
[108] Clemente-Suárez V.J., Bustamante-Sanchez A., Rubio-Zarapuz A., Martín-Rodríguez A., Tornero-Aguilera J.F., Beltrán-Velasco A.I.: Biomimetic Strategies for Nutraceutical Delivery: Advances in Bionanomedicine for Enhanced Nutritional Health. Biomimetics 10 (2025) 426.
[109] Sawant R.B., Nikam S.P., Roy A., Kumar A., Mohammed O.A., Sharma K., Rai A.K., Roy A., Gaur A., Verma R.: Nanocarriers for Nutraceutical Delivery: A Miniaturized Revolution in Health. Nano-Structures & Nano-Objects 39 (2024) 101321.