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REVIEW

Encapsulation of functional ingredients in lipidic nanocarriers and antimicrobial applications: a review

Anuradha Saini[1] · Divyani Panwar[1] · Parmjit Singh Panesar[1] · Manab Bandhu Bera[1]

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Abstract

Global food demand and security are attracting stakeholders' attention to food quality and safety. In particular, there is an urgent need for efficient techniques to preserve food for a long time. This can be done by encapsulation in nanocarriers such as nanoemulsions, nanoliposomes and nanolipid carriers. These nanocarriers protect functional ingredients such as polyphenols, vitamins, minerals, flavors and antimicrobial agents. Nanocarriers improve stability, functionality, entrapment efficiency and controlled-release of functional ingredients. Antimicrobial ingredients are among the most promising tools for food preservation. The nanoencapsulated form of antimicrobial agents showed an increase in surface area, passive transport and sustained release, which enhance the antimicrobial efficiency by comparison with the direct application of antimicrobial agents. Here, we review lipid-based nanocarriers, nanoencapsulation of functional ingredients, and food application of lipid-based nanocarriers as antimicrobial agents.

Keywords Encapsulation · Nanoemulsions · Nanoliposomes · Nanolipid carriers · Functional ingredients · Antimicrobial agents

Introduction

The health awareness among consumers has increased the demand for the development of functional or novel food products containing bioactive compounds to impart certain health benefits. However, the utilization of bioactive compounds in food products has certain limitations in terms of decomposition, low stability during food processing conditions, which reduces their bioavailability as well as functional properties (Saini et al. 2019a). Such drawbacks can be overcome by a technique known as encapsulation to encase these compounds in suitable matrices or a combination thereof, which not only enhances their stability but also improves physicochemical properties (Lohith Kumar and Sarkar 2017). This technique has significant applications in the food as well as pharmaceutical industries and aims at preserving the sensitive compounds against undesirable circumstances until the controlled release of functional food ingredients. The most widely used technique is microencapsulation that increases the bioavailability of the components, enables the modification of ingredients' properties, masks the undesirable aroma as well as taste and prevents the interactions with other chemical structures (Barbosa-Cánovas et al. 2005; Ting et al. 2014; Assadpour and Jafari 2018; Jafari 2017).

Microencapsulation is a broad category for the delivery of functional food ingredients and is defined as the technique to entrap the active components/agents such as antioxidant, vitamins, minerals, fatty acids, phytosterols, lycopene and living cells in another substance called wall material (Burey et al. 2008; Champagne and Fustier 2007; McClements et al. 2009a, b). These encapsulating/wall materials are also known as shell, capsules, carrier material, coating, membrane, matrix, or external phase (Wandrey et al. 2009; Fang and Bhandari 2010). Microencapsulation techniques involve the mechanical processes such as spray drying, fluidization bed coating, spray cooling/chilling and extrusion as well as chemical techniques such as molecular inclusion, interfacial polymerization, coacervation and co-crystallization (Gibbs et al. 1999; Zuidam and Shimoni 2009). Among different mechanical processes, approximately 80–90% of encapsulates are generally produced by spray drying (Porzio 2007;

✉ Parmjit Singh Panesar
pspanesarrr@yahoo.com

[1] Department of Food Engineering and Technology, Sant Longowal Institute of Engineering and Technology, Longowal, Punjab 148106, India

Milanovic et al. 2010). Spray cooling and chilling techniques operate at different melting points of lipids to fabricate the lipid-coated active agents, whereas in extrusion methods, the dripping tools such as a syringe, pipette, a vibrating nozzle or atomizing disk are used for releasing droplets of an aqueous solution of polymer into a gelling bath (Gouin 2004; Zuidam and Shimoni 2009; Wandrey et al. 2009). The fluidization bed technique is generally applied on the lightweight particles such as granules or powder particles either in drying or in encapsulation by fluid-bed coating (Dewettinck and Huyghebaert 1999). However, remarkable interest has been developed in nanoscale delivery systems owing to their better functional properties including more encapsulation efficiency, controlled release, improved stability, masking of undesirable flavors and enhanced bioavailability of various functional ingredients by reducing particle size as compared to microencapsulation (Shishir et al. 2018).

With the advancements of nanotechnology in the food sector, various other techniques are being devised to ensure the safe delivery and bioavailability of different functional compounds. At present, the traditional microencapsulation systems are being replaced with nanoencapsulation systems (having a size less than 1000 nm) that enhance bioavailability by increasing the surface-to-volume ratio without affecting the appearance of food products. These nanocarriers have a high possibility of muco-adhesiveness and interaction with metabolic factors and enzymes. Thus, these can easily penetrate into target cells and release their cargos (Jafari and McClements 2017; Katouzian et al. 2017; McClements and Jafari 2017).

Nanocarriers can be classified as lipid-based (nanoemulsions, nanostructured phospholipid carriers, nanolipid carriers), nature-inspired (caseins, cyclodextrins, amylose), special equipment-based (electrospinning, electrospraying, nanospray dryer, micro-/nanofluidics) and biopolymers that include single biopolymer nanoparticles, complex biopolymer nanoparticles, nanogels, nanotubes/nanofibrils (Assadpour and Jafari 2018). This review encompasses the important information regarding lipid-based nanocarriers for the delivery of different functional ingredients and their food application as antimicrobial agents.

Different types of lipid-based nanocarriers

Lipid-based nanocarriers are one of the major classes of nanoencapsulation for the delivery of polyphenols in different food systems. These are divided into three groups, which include nanoemulsions, nanoliposomes (nanostructured phospholipid carriers) and nanolipid carriers (Fig. 1). Lipid-based nanoemulsions are important nanocarriers formulated by the oil, water and emulsifiers or biopolymers. These systems are further divided into different subgroups such as single (oil-in-water (O/W)), water-in-oil (W/O), double (oil-in-water-in-oil (O/W/O)), water-in-oil-in-water (W/O/W), pickering and structural (single interface layer, double interface layer) nanoemulsions (Jafari et al. 2017; Akhavan et al. 2018). Another group of lipid-based nanocarriers involves nanoliposomes (nanostructured phospholipid carriers), which are produced using oils, phospholipids and different solvents. Moreover, this group can be a monolayer, multilayer or in combination with coating as in the case of structured nanoliposomes/phytosomes (Demirci et al. 2017). Finally, the last group in lipid-based nanocarriers is nanolipid carriers, subgrouped into solid lipid nanoparticles, nanostructured lipid carriers and smart lipid nanocarriers that can be formulated by solid lipids or oils and solid lipids (Pyo et al. 2017; Katouzian et al. 2017). The overall classification of lipid-based nanocarriers along with their fabrication methods is shown in Table 1.

Nanoencapsulation of different functional ingredients

Functional ingredients such as antioxidants are the compounds that inhibit the oxidation for the prevention of cellular damage. These are classified as enzymatic and non-enzymatic antioxidants. The enzymatic class of antioxidants generally includes primary (catalase, superoxide dismutase, glutathione peroxidase) and secondary (glutathione reductase, glucose-6-phosphate) antioxidants. Non-enzymatic antioxidants involve vitamins, minerals, carotenoids and plant polyphenols. However, among these, polyphenols are considered as the main subgroup of non-enzymatic antioxidants (Esfanjani and Jafari 2017). These non-enzymatic antioxidants (hydrophobic and hydrophilic) are nanoencapsulated using different approaches to protect them from adverse environmental conditions, to facilitate gastrointestinal absorption and to enhance the bioavailability (Paroha et al. 2020). In the last few years, numerous studies have been reported on nanoencapsulation that observed this technique is very useful in the pharmaceutical, food and nutraceutical sectors where proper protection and controlled release of functional compounds are required (Sarkar et al. 2017). Different lipid-based nanocarriers used for the encapsulation of functional food ingredients have been discussed in subsequent sections.

Nanoemulsions

Nanoemulsions are nanosized emulsions that are produced using high and low energy approaches. Firstly, functional ingredients are dissolved in oil (oil phase), which is generally followed by mixing them with aqueous phase using blenders and/or high-speed homogenizers to obtain the

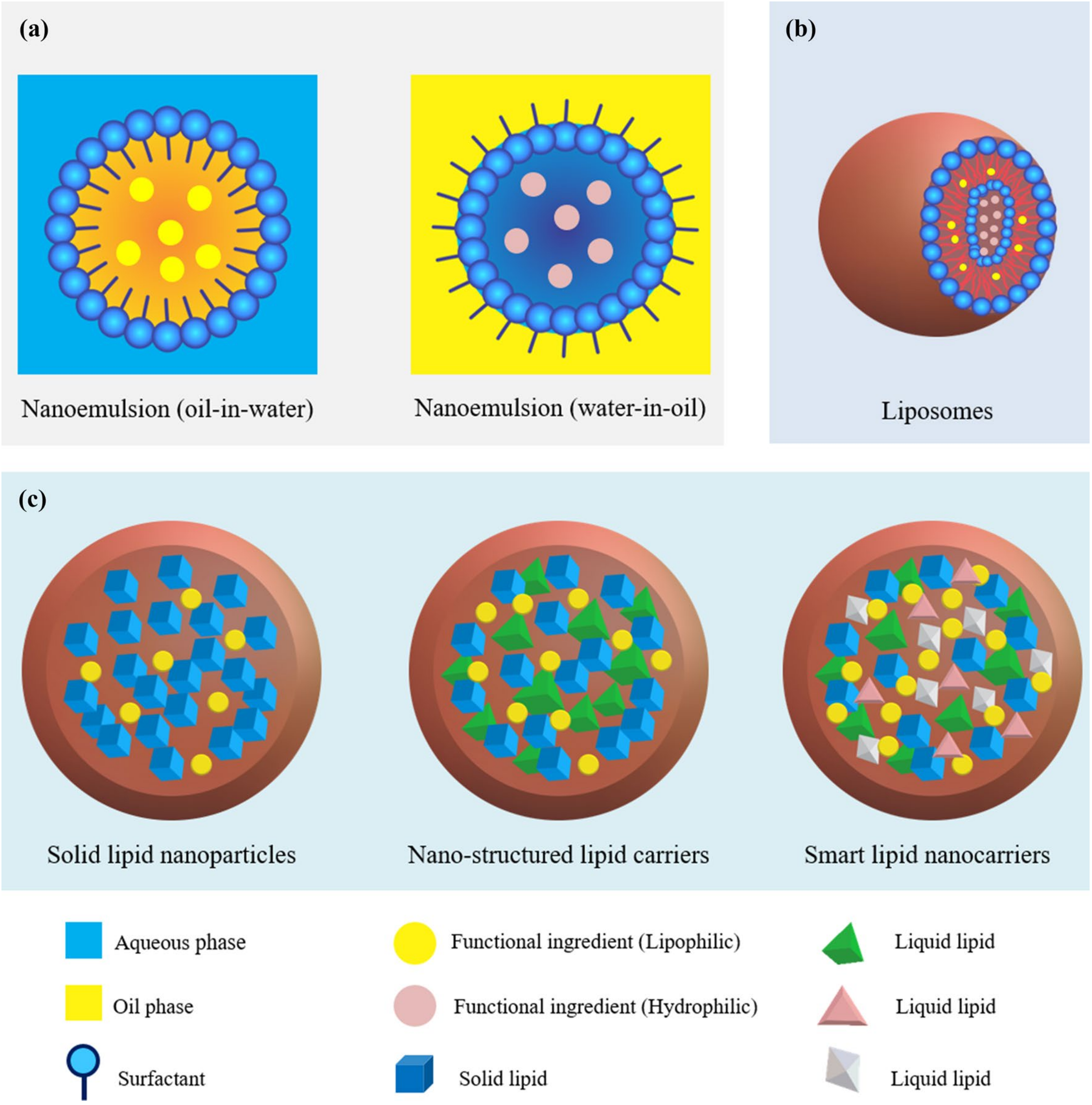

Fig. 1 Lipid-based nanocarriers for the delivery of functional ingredients. **a** Nanoemulsions indicating the formational ingredients such as surfactant, oil and aqueous phase with lipophilic or hydrophilic functional ingredients. **b** Liposomes encapsulating the lipophilic as well as hydrophilic functional ingredients. **c** Various nanolipid carriers consisting of solid lipid, liquid lipid and functional ingredients

coarse emulsions. Finally, the formed coarse emulsions are further treated using high-energy approaches such as ultrasonication, high-pressure homogenization and high-speed homogenization. These nanoemulsions are used to encapsulate different functional compounds such as lutein (Surh et al. 2017), β-carotene (Teixé-Roig et al. 2020), lycopene (Li et al. 2018) and curcumin (Li et al. 2016a) as shown in Table 2. Also, these are used to improve the stability, texture, nutritive and sensorial attributes of different food products (Dasgupta et al. 2019a). Extensive studies have been reported on the O/W nanoemulsions for encapsulating the lipophilic compounds, in contrast to W/O nanoemulsions owing to their significant benefits in various commercial applications. A recent study revealed that the presence of multilayers in nanoemulsions leads to an increase in hydrodynamic diameter along with loading capacity (0.53 ± 0.03%, w/w) and encapsulation efficiency of 99.8 ± 0.8%, when the multilayered nanoemulsions are formed by electrostatic technique (layer-by-layer) to encapsulate the lipophilic compound (e.g., curcumin). Hence, these nanosystems have great potential to protect the functional properties of lipophilic compounds and are used in different applications (Silva et al. 2020). In another study, nanoemulsions loaded with limonene and carvone can be a propitious approach to protect the tissues from cadmium-induced oxidative damage (Shafaei et al. 2020). Some studies focused on the increase

Table 1 Techniques for the preparation of lipid-based nanocarriers for delivery of functional ingredients *Source*: Jafari (2017); Assadpour and Jafari (2018)

Nanoencapsulation systems	Nanocarriers	Examples of nanocarriers	Preparation techniques	Summary
Nanoemulsions	Single nanoemulsions	Water-in-oil, oil-in-water	Hot emulsification, cold emulsification, solvent emulsification-evaporation, high-pressure homogenization, ultrasonication, microemulsion, melting dispersion, solvent injection, solvent emulsification-diffusion, double emulsion technique	Typically, droplet size of dispersed phase is less than 500 nm
	Double nanoemulsions	Water-in-oil-in-water, oil-in-water-in-oil		Kinetically stable and thermodynamically unstable
	Structural nanoemulsions	Single and double interface layer		Milky to optical clear in appearance
	Pickering nanoemulsions	–		
Nanostructured phospholipid carriers	Nanoliposomes	Mono- and multilayer	Thin–film dispersion, ethanol/ether injection, probe/bath ultrasonication, membrane extrusion, freeze-dried rehydration vesicles, reverse-phase evaporation, microfluidic channel, detergent depletion, high-pressure homogenization, supercritical fluid injection & decompression, microfluidization, dense gas, dual asymmetric centrifugation, heating method	Encapsulate both the hydrophilic and lipophilic bioactive compounds
	Nanophytosomes	Mono- and multilayer		Spherical particles containing phospholipids
	Structural nanoliposomes/phytosomes	With coating		
Nanolipid carriers	Solid lipid nanocarriers	–	Hot emulsification, cold emulsification, high-pressure homogenization, microemulsion, solvent emulsification-evaporation, melting dispersion, solvent emulsification-diffusion, ultrasonication, solvent injection, double emulsion technique	Average size is 10–500 nm
	Nanostructured lipid carriers			Formulation includes the binary mixture of solid lipids or solid lipids and liquid lipid which are spatially different
	Smart lipid nanocarriers			

Table 2 Examples of lipid-based nanocarriers loaded with functional ingredients

Food ingredients	Encapsulated materials	References
Nanoemulsions		
Phenolic compounds	β-carotene	Chen et al. (2020a, b)
	Lycopene	Zhao et al. (2020)
	β-carotene	Chen et al. (2020a, b)
	Tocopherol	Feng et al. (2020b)
	Carotenoids (Paprika)	Jimenez-Escobar et al. (2020)
	Capsanthin	Kulkarni et al. (2020)
	Resveratrol	Shehzad et al. (2019)
	Curcumin	Pinheiro et al. (2016)
	Eugenol	Majeed et al. (2016)
	Quercetin	Ni et al. (2017)
	Curcumin	Liu et al. (2020a)
	Rutin and anthocynin	Akhtar (2014)
	Olive leaf extract	Mohammadi et al. (2016)
	Resveratrol	Davidov-Pardo and McClements (2015)
Natural food colorants	Crocin	Mehrnia et al. (2016)
	β-carotene	Barman et al. (2020)
Food flavors	Peppermint	Liang et al. (2012)
	D-limonene	Jafari et al. (2007)
Essential oils	Thyme oil	Wu et al. (2014)
	Eugenol	Ma et al. (2016)
	Krill oil	El-Messery et al. (2020)
	Ricinus communis L. oil	Javanshir et al. (2020)
	Borage seed oil	Rehman et al. (2020)
	D-limonene	Feng et al. (2020a)
	Thyme oil	Guo et al. (2020)
	Bunium persicum Boiss & Zataria *Multiflora Boiss* oil	Keykhosravy et al. (2020)
	Araucaria heterophylla resin oil	
		Elshamy et al. (2020)
Vitamins	D_3	Schoener et al. (2019)
	E	Dasgupta et al. (2016)
	D	Guttoff et al. (2015)
	D_3	Ozturk et al. (2015)
	B_9	Assadpour et al. (2017)
	B_2	Bou et al. (2014)
Nanostructured phospholipid carriers		
Phenolic compounds	Curcumin	Mourtas et al. (2014)
	Luteolin	Wu et al. (2018)
	Quercetin & resveratrol	Cadena et al. (2013)
	Epigallocatechin gallate	Zou et al. (2014b)
	Rutin	Babazadeh et al. (2017)
	Quercetin	Frenzel et al. (2015)
	Phenolic compounds of tea	Zou et al. (2014a)
	Catechin & epigallocatechin gallate	Rashidinejad et al. (2016)
	Hesperetin	Mukherjee et al. (2008)
Mineral ions/salts	$FeSO_4.7H_2O$	Kosaraju et al. (2005)
Essential oils	*Anethum graveolens* essential oil	Ortan et al. (2009)
	Rose essential oil	Wen et al. (2011)
	Cinnamon essential oil	Wu et al. (2015)
	Perilla oil	Zamani-Ghaleshahi et al. (2020)

Table 2 (continued)

Food ingredients	Encapsulated materials	References
Antimicrobial agents	Nisin	Taylor et al. (2008)
	Daptomycin	Li et al. (2013)
Vitamins	β-carotene	Tan et al. (2016)
	B_1	Fathima et al. (2016)
	A palmitate	Pezeshky et al. (2016)
	E & C	Marsanasco et al. (2011)
	A	Pezeshky et al. (2016)
	E, B_{12}, D_2	Bochicchio et al. (2016)
	C	Liu et al. (2017)
	C	Hamadou et al. (2020b)
Nanolipid carriers		
Phenolic compounds	Curcumin	Mulik et al. (2010)
	Resveratrol	Pandita et al. (2014)
	Quercetin	Liu et al. (2014)
	Myricetin	Gaber et al. (2017)
	Ferulic acid	Hassanzadeh et al. (2018)
	Epigallocatechin gallate	Radhakrishnan et al. (2016)
	Hesperetin	Fathi and Varshosaz (2013)
	Curcumin	Righeschi et al. (2016)
	Quercetin	Huang et al. (2017)
	β-carotene	Oliveira et al. (2016)
	Rutin	Babazadeh et al. (2016)
	Curcumin & genistein	Aditya et al. (2013)
Natural food colorants	α-tocopherol	de Carvalho et al. (2013)
	Lutein	Lacatusu et al. (2013)
	β-carotene	Zhang et al. (2013)
	Astaxanthin	Li et al. (2016b)
Essential oils	Cardamom essential oil	Nahr et al. (2018)
	Pomegranate seed oil	Soleimanian et al. (2018)
Vitamins	B_2	Couto et al. (2016)
	E	Uraiwan and Satirapipathkul (2016)
	D_3	Mohammadi et al. (2017)

in shelf life of perishable products such as strawberry, meat and fish sausages through nanoemulsion-based films and coatings (Xiong et al. 2020; Chu et al. 2020; Feng et al. 2020b) as shown in Table 3. Chu et al. (2020) revealed that the pullulan–cinnamon essential oil nanoemulsions coating enhanced the shelf life of strawberry at room storage. Moreover, the better preservation (i.e., maintaining tenderness, minimizing the color and pH change, inhibiting the microbial growth and retarding the protein and lipid oxidation) of fresh pork loin under high oxygen-modified atmosphere packaging was reported using nanoemulsions of oregano essential oil and resveratrol loaded pectin edible coating (Xiong et al. 2020). The tocopherol-loaded nanoemulsions were formulated and added in fish sausages. The results indicated better fish sausage quality was obtained when nanoemulsions were incorporated at the concentration of 250 mg/kg (Feng et al. 2020b). In a study, Huang et al. (2020) enhanced the shelf life of carbonado chicken (ready-to-eat) with nanoemulsion-based edible coating loaded with ε-poly-l-lysine and rosemary extract. Also, an improvement was observed in the shelf life of Yao meat products (ready-to-eat) through nanoemulsions-based coating containing the mixture of nisin, star anise essential oil and polylysine (Liu et al. 2020b). In addition, the nanoemulsions coating formed with *Zataria multiflora* Boiss essential oil and alginate (coating material) was used to increase the shelf life of fish fillets and inhibit the microbial flora than coarse emulsion (Khanzadi et al. 2020). Furthermore, the shelf life of edible oils could be enhanced by biopolymer nanoemulsions of *Orchis mascula* and *Lepidium perfoliatum* loaded with *Hyssopus officinalis* L. plant extract (Savadkouhi et al. 2020). However, in one study the authors reported that active films loaded with pickering emulsion of *Marjoram* essential oil showed strong antimicrobial and antioxidant activity

Table 3 Applications of nanocarriers as coating material for enhancing the functional properties of food products. The following abbreviations denote: solid lipid nanoparticles (SLN) and nanostructured lipid carriers (NLC)

Functional food ingredients	Preparation techniques	Emulsifiers	Remarks	Target food products	References
Nanoemulsions					
Lemongrass	High-pressure homogenization	Tween-80	Improved texture and antimicrobial properties	Grape berry	Oh et al. (2017)
Carvacrol	High-pressure homogenization	Tween-20	Enhanced antioxidant & antimicrobial properties	Cucumber slices	Taştan et al. (2017)
Carvacrol	High-pressure homogenization	Tween-80	Enhanced antioxidant & antimicrobial properties	Shredded cabbages	Sow et al. (2017)
Oregano essential oil	Combination of high shear homogenization and microfluidization	Tween-80	Extend the shelf-life	Low-fat-cut cheese	Artiga-Artigas et al. (2017)
Trans-cinnamic acid	Low-energy method (mixing)	Tween-80	Improved antimicrobial properties	Fresh-cut lettuce	Letsididi et al. (2018)
Orange peel essential oil & pectin	Combination of ultrasonication & stirring	Tween-80	Improved texture and antimicrobial properties	Orange slices	Radi et al. (2018)
Zingiber officinale essential oil	Ultrasonication	Tween-80	Increased antimicrobial activity	Chicken breast fillets	Noori et al. (2018)
Citral	Ultrasonication	Tween-80	Reduction in respiration rate and microbial growth, long-lasting color retention	Fresh-cut pineapples	Prakash et al. (2019)
Zataria multiflora Boiss essential oil	Ultrasonication	Tween-80	Inhibit the microbial growth and increase in shelf life	Fish fillets	Khanzadi et al. (2020)
Ferulago angulata essential oil	Ultrasonication	Tween-80	Reduced the increase in lipid oxidation & total volatile basic nitrogen	Rainbow trout fillets	Shokri et al. (2020)
Polyphenols (gallic acid, curcumin and quercetin)	Combination of high-speed & high-pressure homogenizer	Hi-Cap 100	Increase in shelf life	Fresh broiler meat	Khan et al. (2020)
Cumin seed essential oil	Ultrasonication	Tween-80	Enhanced the shelf life	Beef Hamburger	Hemmatkhah et al. (2020)
Nanostructured phospholipid carriers					
Artemisia annua oil	Thin-film hydration	Soy lecithin and cholesterol	Antibacterial activity against *E. coli* O157:H7	Cherry tomatoes	Cui et al. (2017)
Satureja plant essential oil	Combination of thin-film hydration and sonication method	Lecithin and cholesterol	Inhibit the microbial and chemical spoilage	Lamb meat	Pabast et al. (2018)
Nettle (*Urtica dioica* L.) extract	Combination of thin-film hydration and sonication method	Soy lecithin	Decrease in antimicrobial activity, owing to the encapsulation that restricts the release of nettle extract from the matrix	–	Haghju et al. (2016)

Table 3 (continued)

Functional food ingredients	Preparation techniques	Emulsifiers	Remarks	Target food products	References
Garlic essential oil	Combination of thin-film hydration and sonication method	Cholesterol & soybean phosphatidylcholine	Retarded microbial growth and lipid oxidation	Vacuum-packed sausages	Esmaeili et al. (2020)
Nanolipid carriers					
-	Hot high-shear stirring method	Poloxamer 407	Lower the respiration rate and reduced the weight loss when fruit coated with 65 g/L of SLN	Guava (*Psidium guajava* L.)	García-Betanzos et al. (2017)
Pomegranate seed oil	Combination of melt-emulsification and ultrasonication	Tween-80 & lecithin	Excellent physical stability with particle range of NLC (71 to 366 nm)	–	Soleimanian et al. (2018)
Cardamom essential oil	Low-energy nanoemulsification	Tween-80	Protect the antimicrobial activity and provide good chemical & physical stability by NLC	–	Nahr et al. (2018)
Betasitosterol	Hot melt homogenization	Poloxame® 407 & poly ethylene glycol	Betasitosterol-loaded NLC incorporated in butter showed good stability during storage (3 months)	Butter	Bagherpouret al. (2017)
	Hot high-stirring method	Polyvinyl alcohol (Mowiol® 4–88, Mw ≈ 31,000)	The best results were obtained by 10 g/L of beeswax-SLN with lowest weight loss (6.1%), loss of firmness (34%) and decay index (31%) during storage	Strawberry	Zambrano-Zaragoza et al. (2020)

than loaded nanoemulsion-based films (Almasi et al. 2020). Moreover, functional food ingredients like omega-3 fatty acids are very susceptible to oxidation and have poor water solubility, although physical stability was maintained at 4 ℃ storage temperature through nanoemulsions formulated using lactoferrin concentrations higher than 2% (Nunes et al. 2020). Besides that, multiple nanoemulsions (e.g., W/O/W) that encapsulate both hydrophilic (caffeic acid) and hydrophobic (tocotrienols) bioactive ingredients were formulated using the microfluidizer and ultrasound technique. The results revealed that the ultrasound technique used lesser energy (~ 12 times) than the microfluidizer to produce the droplet size of ~ 235 nm (Raviadaran et al. 2020).

Valorization of various food industry wastes was done for the extraction of bioactive compounds (Saini et al. 2019b; Saini and Panesar 2020; Panwar et al. 2019) such as lutein (Saini et al. 2020) and β-carotene (Barman et al. 2020) and their use in the formation of nanoemulsions, which have better functional properties in food systems (Dasgupta et al. 2019b). The phenolic extracts of grape and apple pomace used for the formation of nanocapsules can be used as edible materials with improved antioxidant properties (Ahmed et al. 2020). In another research, β-carotene was extracted from orange (*Citrus reticulata*) peel waste and encapsulated in nanoemulsion-based delivery system. It was also reported that β-carotene-loaded nanoemulsion improved the color and enhanced the bioaccessibility of β-carotene when it was added in fruit juice (Barman et al. 2020).

Vitamins are lipophilic (vitamins A, E, K and D) and hydrophilic (vitamins C and B vitamins) in nature, and different nanocarriers are used for their improved delivery. These include nanoemulsions (Vit-D), nanodouble emulsion (folic acid), nanoliposomes (Vit-B_{12}), biopolymer nanoparticles (D_3), solid lipid nanoparticles (Vit-D_2), nanohydrogels (Vit-B_6) and nano-organogels (Vit-C) (Almajwal et al. 2016; Assadpour et al. 2017; Bochicchio et al. 2016; Lee et al. 2016; Patel and San Martin-Gonzalez 2012; Tsuchido et al. 2015; Lo Nostro et al. 2007). Vitamins are susceptible to different conditions such as temperature, oxygen and light and can be oxidized during processing and storage depending upon their types (Katouzian and Jafari 2016). Herein, vitamins usage in food supplements indicates shortcomings (e.g., low stability and poor bioavailability) in the gastrointestinal tract situations (Walia et al. 2019). However, these undesirable conditions can be circumvented using different encapsulation techniques, which can be further used in numerous food applications. O/W nanoemulsions of vitamin D_3 were formulated by quillaja saponin as a natural surfactant using different oils such as corn and fish oil, medium-chain triglycerides, orange and mineral oil where the highest bioaccessibility levels for vitamin D_3 were found in nanoemulsions prepared from corn and fish oil as compared to other oil phases (Ozturk et al. 2015). In another study, vitamin D nanoemulsions were successfully prepared and fed to different groups of healthy male albino rats. Noticeable changes were reported in the levels of phosphorus, parathyroid hormone, calcium and alkaline phosphatase (Almajwal et al. 2016). The formation of nanoemulsions loaded with vitamin D_3 and calcium citrate revealed that the presence of vitamin D_3 affects the size of oil core (dispersed oil phase), whereas the calcium ions showed the impact on the stability of nanoemulsions loaded with both oil- and water-soluble micronutrients in the aqueous phase (Demisli et al. 2020). Moreover, pea protein-stabilized nanoemulsions loaded with vitamin D were formulated and reported that transport efficiency of nanoencapsulated vitamin D across Caco-2 cells was ~ 5.3 times greater than the free form of vitamin D suspension (Walia and Chen 2020). These loaded nanoemulsions can be used for vitamin D fortifications in nondairy foods. In another study, the formation of vitamin D-encapsulated nanoemulsions by soya lecithin and Tween 80 reported that the mixed-surfactant-based nanoemulsions of vitamin D can be used in the food and beverage industry to overcome the deficiency of vitamin D (Mehmood and Ahmed 2020).

Various studies have been conducted on the fabrication of nanoemulsions for food colorants such as β-carotene (Qian et al. 2012) and lycopene (Li et al. 2018). Generally, most of the food colorants, which include flavonoids, carotenoids, betalains and chlorophylls, are unstable, hydrophobic and susceptible to degradation in nature (Akhavan and Jafari 2017) making their encapsulation desirable using suitable delivery systems such as nanoemulsions.

Food flavors such as allypyrazine, methoxypyrazines, 2-isobutyl-3-methoxypyrazine, acetyl-L-pyrazine, aldehydes, phenolics and terpenoids are important food ingredients, which improve the organoleptic properties of food to attract consumers (Asghari et al. 2017). Many of food flavor structures show instability due to different processing and environmental conditions. Therefore, it is a logical means that these compounds are encapsulated by nanoemulsions to preserve the functional and structural properties. Several studies have been reported for the formation of nanoemulsions containing food flavors such as peppermint, citral, β-carotene and D-limonene using different wall materials, which include the medium-chain triacylglycerol (MCT)-starch, MCT-buffer solution and maltodextrin (Liang et al. 2012; Zhao et al. 2013; Jafari et al. 2007).

Minerals are valuable food ingredients, which cannot be synthesized by animals. Fruit and vegetables are the main sources of these nutrient ions that play a major role in the proper metabolic and biological activities to perform different functions in the body (Gharibzahedi and Jafari 2017b). These minerals are divided into two classes: macro-minerals (Ca, Mg, Na, K, P, Cl, S) and microminerals (Fe, Mn, Cu, I, Zn, Co, Mo, F, Se, Cr, B). Owing to their lack of solubility, stability and liability to oxidative degradation, it is required to encapsulate these nutrient ions and salts in different nanocarriers and protect them from undesirable reactions with other components, thereby decreasing the sensory score of the food product (Gharibzahedi and Jafari 2017a). Numerous research studies for the nanoencapsulation of mineral ions and salts have been successfully reported. For example, Fe ions and $C_4H_2FeO_4$ were loaded in nanoemulsions using cholesterol, phosphatidylcholine and gelatin as wall materials (Tang and Sivakumar 2013; Naveen and Kanum 2014). Fe-loaded nanoemulsions showed the enhancement in bioavailability under in vivo studies when compared with the direct addition of Fe for milk enrichment (Naveen and Kanum 2014). These different functional ingredient-loaded nanoemulsions are characterized by various techniques such as physical (dynamic light scattering, zeta potential, nuclear magnetic resonance, X-ray diffraction, small-angle X-ray scattering), separation (chromatography, field flow fractionation) and imaging (transmission electron microscopy, scanning electron microscopy, atomic force microscopy) (Silva et al. 2012). Apart from enhancing the antioxidant properties of these functional food ingredients, various studies have also been reported on the nanoencapsulation of antimicrobial agents and essential oils to increase their antimicrobial properties (Ma et al. 2016; Xue et al. 2015). This application of loaded nanoemulsions is most suitable for the food industry. Some of the examples related to antimicrobial agents/essential oils containing nanoemulsions include peppermint oil (Liang et al. 2012), thyme oil (Xue et al. 2015) and sago oil (Moghimi et al. 2016). Moreover, nanoemulsions have a wide scope to modify the texture of food products. For example, a reduction in fat content from 16 to 1% of ice cream has been successfully done by food industries like Unilever through nanoemulsions. The phenomenon of gelation is possible in nanoemulsions at a low concentration of fat when compared with the emulsion. This functional property can be useful in food industries for producing products such as dressings, mayonnaise along with the desired texture and flavor. Numerous patents have been developed on the use of nanoemulsions for different applications such as the manufacturing of clear beverages (US20150030748, WO2011119228) and improved delivery of active ingredients (US20170246303) (Schultz and Monnier 2013; Bromley 2011; Wooster et al. 2017).

Nanostructured phospholipid carriers

At the nanoscale, nanoliposomes are colloidal structures, which are formed by the right combinations of phospholipids, oil and various solvents along with efficient energy input. These nanolipid vesicles are being used in numerous industries such as food, pharmaceutical and cosmetics (Mozafari et al. 2008). Various research studies have been conducted on nanoliposomes for encapsulation of functional ingredients such as antioxidants, phenolic compounds, antimicrobial agents, food colorants, essential oils, mineral ions and salts. The synthesis of nanoliposomes loaded with β-carotene was done using egg and marine phospholipids as compositional ingredients. It was reported that marine phospholipids exhibit lower polydispersity index and mean size, inhibit lipid peroxidation, higher encapsulation efficiency and better stability at 4 ℃ for 70 days than egg phospholipids (Hamadou et al. 2020a). Different techniques have been used for the preparation of liposomes such as thin-film hydration, sonication and homogenization. Moreover, these techniques also have been used in combinations such as thin-film hydration & sonication for the fabrication of nanoliposomes containing epigallocatechin-3-gallate (de Pace et al. 2013). In addition, the combination of sonication and homogenization has been successfully used for the preparation of nanoliposomes containing curcumin (Hasan et al. 2014). In a recent study, the nanoliposomes loaded with oleic palm oil were formed using different homogenization techniques like ultrasonication, microfluidization and high shear homogenization (rotor–stator); the results showed that microfluidization provided better physical stability in terms of minimum polydispersity index and particle size (Beltrán et al. 2020). However, in another study, the nanoliposomes containing shrimp oil were synthesized by ultrasonication and microfluidization techniques. It revealed that ultrasonication technique showed better results regarding nanoencapsulation efficiency (93.64%), better retention (e.g., docosahexaenoic acid & eicosapentaenoic acid) and prevention from oxidation during storage (Gulzar and Benjakul 2020).

These nanoliposomes when loaded with antioxidants and phenolic compounds are improved the functional properties such as antioxidant capabilities and solubility. For instance, nanoliposomes loaded with quercetin and resveratrol (flavonoids) showed an increment in their antioxidant capabilities (Cadena et al. 2013). In one study, fish oil was encapsulated in nanoliposome, which was further incorporated in yogurt. That indicated a higher content of eicosapentaenoic acid and docosahexaenoic acid present in fortified yogurt. Also, fortified yogurt showed closer results in terms of sensory evaluation as compared to the control sample (Ghorbanzade et al. 2017). In a similar study, the olive leaf extract was loaded in nanoliposomes and added in yogurt. The results observed the enhanced antioxidant properties and no significant changes in sensory characteristics and minimized the syneresis rate in fortified yogurt. Therefore, these loaded nanoliposomes can be used in different food systems to increase their nutritive value and shelf life (Tavakoli et al. 2018).

Several studies also focused on the coating/films based on the nanoliposomes and used in various food applications. In a recent study, nanoliposomes doped with flaxseed–peptide fractions were formed and coated with chitosan (0.4%) and showed an increase in encapsulation efficiency, antioxidant activity and physical stability after the reconstitution process of powder (Sarabandi and Jafari 2020).

Different coloring compounds such as β-carotene and astaxanthin loaded in nanoliposomes showed high solubility, high retention (> 90%) of encased β-carotene and high resistance against the thermal processing and UV rays (Moraes et al. 2013; Yoo et al. 2010). Furthermore, the incorporation of different carotenoids (e.g., lutein, β-carotene, lycopene, canthaxanthin) through nanoliposomes also improved their bioaccessibility (Tan et al. 2014).

Mineral ions/salts that include $FeSO_4$ and ferrous glycinate were encapsulated using different wall materials such as chitosan, soybean phosphatidylcholine, cholesterol, hydrogenated phosphatidylcholine, cationic phospholipids and egg-phosphatidylcholine (Ding et al. 2011a; Hermida et al. 2011). These nanoliposomes exhibited high barrier properties against the oxidative reactions, high stability, acceptable encapsulation efficiency (69.6–76.2%) and decreased deficiency of iron in rats more significantly than two free forms of iron (Ding et al. 2011a, 2011b; Hermida et al. 2011).

Nanoliposomes have a high potential for nanoencapsulation of essential oils and antimicrobial agents due to their high loading capacity, high penetration ability into cells and decreased potential toxicity of antimicrobial agents (Thamphiwatana et al. 2013; Halwani et al. 2008; Mugabe et al. 2006). Several studies have been done on nanoliposomes loaded with nisin (Taylor et al. 2008), daptomycin (Li et al. 2013), *Anethum graveolens* essential oil (Ortan et al. 2009), and it was revealed that these nanocarriers successfully improved the functional properties of antimicrobial agents and essential oils. Another study conducted on the encapsulation of rose essential oil in nanoliposomes reported the entrapment efficiency of 89.46% along with an average size of 94 nm (Wen et al. 2011).

Nanolipid carriers

The last group of lipid-based nanocarriers is nanolipid carriers. It is claimed that nanolipid carriers perform various functions more efficiently than classical nanoemulsions, for example, better control on release process, particle size and less leakage of encased functional compounds (Pyo et al. 2017; Katouzian et al. 2017). Various studies have been done on both subgroups of nanolipid carriers, which include solid lipid nanoparticles and nanostructured lipid carriers. These are formulated using different techniques such as hot homogenization, ultrasonication, emulsification-evaporation and cold homogenization or the combinations thereof. Solid lipid nanoparticles loaded with different phenolic compounds such as curcumin (Wang et al. 2015), resveratrol (Jose et al. 2014) and nanostructured lipid carriers loaded with quercetin (Sun et al. 2014), curcumin (Aditya et al. 2014) and silymarin (Shangguan et al. 2014) have also been studied. It has been reported that solid lipid nanoparticles loaded with resveratrol formulated using Tween 80 or a combination of polyvinyl alcohol and Tween 80 sustainably release the compound and were found effective in the treatment of neoplastic diseases (Jose et al. 2014). As compared to solid lipid nanoparticles, nanostructured lipid carriers formed a combination of oil and fat having an 18% higher loading capacity for dermal applications (Gokce et al. 2012).

Recent studies related to nanolipid carriers were conducted to enhance various properties for extended shelf life of food products. For example, lipid carriers loaded with cinnamon essential oil and coated by chitosan showed stability against oxidation, when these nanocarriers were added into the milk (Bashiri et al. 2020). Besides, the nanostructured lipid carriers and solid lipid nanoparticles loaded with lycopene were formed using high shear homogenization and ultrasonication technique to incorporate in orange juice. It was reported that these nanocarriers can be used in liquid food samples after improving their solubility and homogeneity (Zardini et al. 2017). Therefore, these nanocarrier systems can be used in different food products like yogurt, fruit juices, etc., to extend their shelf life due to retardation in oxidation. In a recent study, a snack bar was formulated with sesame paste, date syrup and thymol-loaded nanostructured lipid carriers. It revealed that the addition of 100 ppm of thymol-loaded nanostructured lipid carriers showed better results in terms of oxidation stability of sesame paste/date syrup mixture as compared to butylated hydroxytoluene (Baqeri et al. 2020). Furthermore, the effects of different emulsifiers and pH conditions on the stability of nanostructured lipid carriers containing wheat germ oil were also studied. It was observed that poloxamer (nonionic surfactant) showed high oxidative stability at high pH, whereas sodium dodecyl sulfate (ionic surfactant) indicated at low pH (Mirtalebi et al. 2020).

Various food colorants like α-tocopherol (de Carvalho et al. 2013), astaxanthin (Li et al. 2016b) and anthocyanins (Ravanfar et al. 2016) have been successfully entrapped in solid lipid nanoparticles and nanostructured lipid carriers. Solid lipid nanoparticles containing anthocyanins have shown the 89.2% encapsulation efficiency, and the average size of the particle was 455 nm (Ravanfar et al. 2016). Also, nanostructured lipid carriers loaded with lutein was reported 89% entrapment efficiency along with a particle size of 200 nm (Lacatusu et al. 2013). Therefore, these loaded colorants in nanocarriers show better functional and structural properties as compared to their free form.

The study on the fabrication of solid lipid nanoparticles containing $FeSO_4$ was conducted using encapsulating material such as Compritol 888 ATO and lecithin, reported the encapsulation efficiency of 92.3% (Hosny et al. 2015). In another study, $FeSO_4$-loaded solid lipid nanoparticles were formulated using chitosan-HCL, stearic acid and polyvinyl alcohol as compositional ingredients (Zariwala et al. 2013). These nanocarriers have also been used for the entrapment of nisin in solid lipid nanoparticles and inhibit the growth of *Lactobacillus plantarum* and *Listeria monocytogenes* over at least 15–20 days (Prombutara et al. 2012). Figure 2 shows the outcomes of these nanoencapsulated functional food ingredients in different lipid-based nanocarriers as shown in Fig. 1.

Application of lipid-based nanocarriers as antimicrobial agents

Nanoencapsulation of different functional ingredients is one of the most effective approaches used to enhance their functional properties such as antioxidant activity, thermal and storage stability, bioaccessibility, antimicrobial effect, anticarcinogenic activity and to improve the intestinal absorption. Lipid-based nanocarriers are currently used for a wide range of applications as shown in Fig. 2. However, much focus is being recently given on the antimicrobial studies using different antimicrobial agents, which is used directly into the food systems required to ensure food safety. However, the direct use of antimicrobial agents in food systems has some disadvantages owing to the low solubility, low chemical stability and negative impact on the organoleptic properties of food. Therefore, the utilization of lipid-based nanocarriers as the delivery systems for the encapsulation of different antimicrobial ingredients is considered a promising tool for their improved properties in the food sector (Fig. 3). Various studies have been conducted on the antibacterial effect of functional food ingredients in their pure as well as encapsulated forms (nanocarriers) that were compared and analyzed based on three criteria such as minimum bacterial concentration, minimum inhibition concentration and inhibition zone as shown in Table 4. The majority of studies showed that values of minimum bacterial concentration and minimum inhibition concentration were lower in the case of encapsulated compounds as compared to their pure form. For example, *Allium sativum* essential oil encapsulated

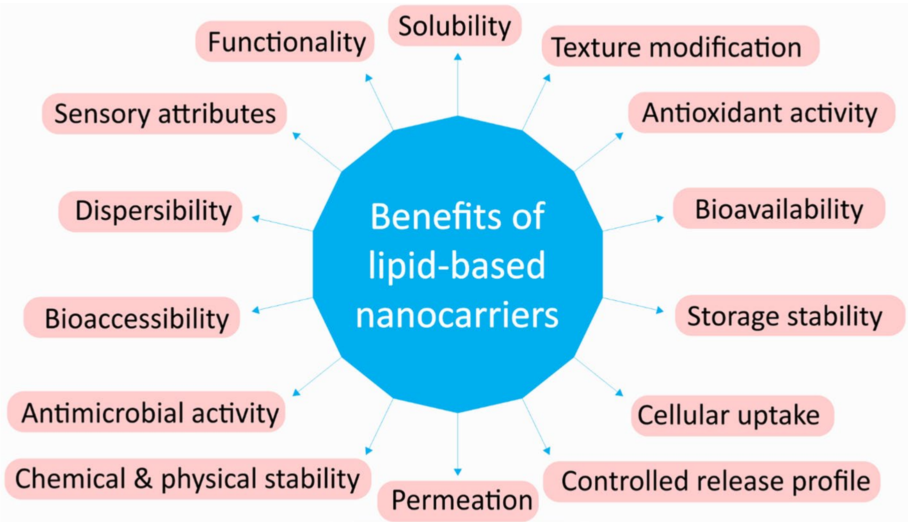

Fig. 2 Benefits of nanoencapsulation of functional ingredients through lipid-based nanocarriers which are used in food and pharmaceutical industries

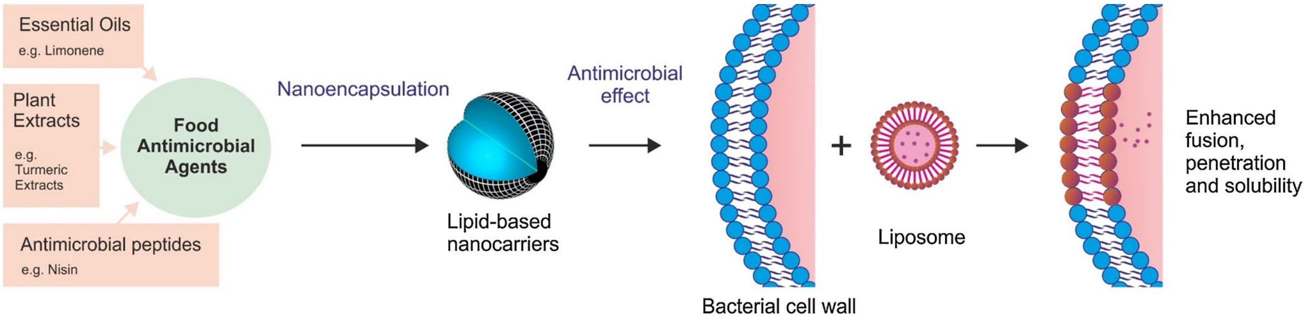

Fig. 3 Delivery of food antimicrobial agents through lipid-based nanocarriers (e.g., liposome) for improved antimicrobial effect on bacterial cell via better fusion, penetration and solubility

Table 4 Lipid-based nanocarriers as antimicrobial agents for food applications. The following abbreviations denote: minimum bacterial concentration (MBC); minimum inhibition concentration (MIC); inhibition zone (IZ); nanostructured lipid carriers (NLC); virgin coconut oil (VCO); and propylene glycol (PG)

Antimicrobial agents	Preparation techniques	Target microorganisms	Antimicrobial effects		Remarks	References
			Pure	Encapsulated		
Nanoemulsions						
Thyme oil	Self-emulsification	*Escherichia coli* O157:H7	MIC: 0.4 g/L	MIC: 0.2 g/L	Encapsulated thyme oil was more active than free thyme oil against target microorganisms when tested in tryptic soy broth & milk	Zhang et al. (2020)
			MBC: 0.6 g/L	MBC: 0.2 g/L	Encapsulation efficiency: > 90%	
		Staphylococcus aureus	MIC: 0.6 g/L	MIC: 0.4 g/L		
			MBC: 0.6 g/L	MBC: 0.4 g/L		
Thyme oil		*Escherichia coli* O157:H7	MIC: 4.0 g/L	MIC: 3.5 g/L		
			MBC: 4.0 g/L	MBC: 3.5 g/L		
		Staphylococcus aureus	MIC: 8.0 g/L	MIC: 4.0 g/L		
			MBC: 8.0 g/L	MBC: 5.0 g/L		
Cinnamon essential oil	Ultrasonication	*Aspergillus niger*	IZ: 12.29 mm	IZ: 23.74 mm	Cinnamon essential oil containing nanoemulsions has higher antifungal activity than coarse emulsion	Pongsumpun et al. (2020)
		Rhizopus arrhizus	IZ: 10.43 mm	IZ: 22.12 mm		
		Penicillium sp.	IZ: 9.31 mm	IZ: 19.27 mm		
		Colletotrichum gloeosporioides	IZ: 7.62 mm	IZ: 16.34 mm		
Lavandula x intermedia essential oil	Solvent displacement	*Escherichia coli*	MIC: 1.87 (v/v%)	MIC: 0.37 (v/v%)	Nanoemulsions of *Lavandula x intermedia* essential oil showed higher antibacterial activity than crude form	Garzoli et al. (2020)
			MBC: 1.87 (v/v%)	MBC: 0.37 (v/v%)		
		Bacillus cereus	MIC: 0.94 (v/v%)	MIC: 0.01 (v/v%)		
				MBC: 0.02 (v/v%)		
Mangostin extract (VCO)	Combination of homogenization and ultrasonication	*Escherichia coli*	MIC: 3.13 mg/mL	MIC: 1.56 mg/mL	Nanoemulsions containing mangostin exhibited the high antioxidant and antimicrobial activities as compared to extract	Sungpud et al. (2020)

Table 4 (continued)

Antimicrobial agents	Preparation techniques	Target microorganisms	Antimicrobial effects		Remarks	References
			Pure	Encapsulated		
Mangostin extract (Mixed VCO-PG)		*Staphylococcus aureus*	MIC: 1.56 mg/mL	MIC: 0.79 mg/mL		
		Escherichia coli	MIC: 1.56 mg/mL	MIC: 0.79 mg/mL		
Mangostin extract (PG)		*Staphylococcus aureus*	MIC: 1.56 mg/mL	MIC: 0.79 mg/mL		
		Escherichia coli	MIC: 1.56 mg/mL	MIC: 0.79 mg/mL		
		Staphylococcus aureus	MIC: 3.13 mg/mL	MIC: 1.56 mg/mL		
Lemon essential oil	Ultrasonication	*Staphylococcus aureus*	MIC: 12.50 mg/mL	MIC: 3.125 mg/mL	Nanoemulsions containing lemon essential oil was more effective for food pathogens (except *K. pneumoniae*) than pure form of lemon essential oil (100%)	Yazgan et al. (2019)
			MBC: > 25 mg/mL	MBC: > 25 mg/mL	MIC values indicated that nanoemulsions and 100% essential oil are more effective for bacterial pathogens as compared to fish spoilage bacteria	
		Klebsiella pneumonia	MIC: 12.50 mg/mL	MIC: 6.25 mg/mL	MBC values of nanoemulsions and 100% essential oil showed a noticeable bacterial activity against *S. paratyphi*	
			MBC: > 25 mg/mL	MBC: > 25 mg/mL		
		Salmonella Paratyphi A	MIC:1.56 mg/mL	MIC: 12.50 mg/mL		
			MBC: 3.125 mg/mL	MBC: 12.50 mg/mL		
		Enterococcus faecalis	MIC: 12.50 mg/mL	MIC: 12.50 mg/mL		
			MBC: > 25 mg/mL	MBC: > 25 mg/mL		
		Photobacterim damselae	MIC: ≥ 25 mg/mL	MIC: > 25 mg/mL		
			MBC: > 25 mg/mL	MBC: > 25 mg/mL		
		Enterococcus faecalis	MIC: ≥ 25 mg/mL	MIC: > 25 mg/mL		
			MBC: > 25 mg/mL	MBC: > 25 mg/mL		
		Vibrio vulnificus	MIC: > 25 mg/mL	MIC: 25 mg/mL		
			MBC: > 25 mg/mL	MBC: > 25 mg/mL		
		Proteus mirabilis	MIC: > 25 mg/mL	MIC: > 25 mg/mL		
			MBC: > 25 mg/mL	MBC: > 25 mg/mL		

Table 4 (continued)

Antimicrobial agents	Preparation techniques	Target microorganisms	Antimicrobial effects		Remarks	References
			Pure	Encapsulated		
		Serratia liquefaciens	MIC: 6.25 mg/mL	MIC: 6.25 mg/mL		
			MBC: 25 mg/mL	MBC: 25 mg/mL		
		Pseudomonas luteola	MIC: 3.125 mg/mL	MIC: 6.25 mg/mL		
			MBC: 1.56 mg/mL	MBC: 25 mg/mL		
Cinnamon oil	Ultrasonication	Different *Salmonella* strains	–	MIC: 0.039 v/v	0.5% nanoemulsions showed up to 7.7 & 5.5 log reductions in *Listeria monocytogenes* and *Salmonella* spp.	Paudel et al. (2019)
				MBC: 0.78%	Nanoemulsions can be used as natural antimicrobial agent for melons	
		Different *Listeria* strains	–	MIC: 0.78 v/v		
				MBC: 0.78%		
Clove oil	Ultrasonic emulsification	*Staphylococcus aureus*	MIC: 1908 µg/mL	MIC: 856 µg/mL	Nanoemulsions loaded with 7 mg/mL of clove oil showed the lowest MIC values as compared to free clove oil	Meneses et al. (2019)
		Staphylococcus epidermidis	–	MIC: 856 µg/mL	Microbial inhibition kinetics indicates the fast action of nanoemulsions with clove oil against the target microorganisms	
		Streptococcus mutans	–	MIC: 856 µg/mL		
		Escherichia coli	MIC: 2650 µg/mL	MIC: 999 µg/mL		
		Salmonella choleraesuis	MIC: 2650 µg/mL	MIC: 999 µg/mL		
		Klebsiella pneumonia	MIC: 1908 µg/mL	MIC: 999 µg/mL		
Linalool	Ultrasonic homogenization	*Salmonella* Typhimurium	MIC: 1.25 v/v, %	MIC: 0.625 v/v, %	Linalool nanoemulsions showed the twofold higher antibacterial activity	Prakash et al. (2019)
			MBC: 1.25 v/v, %	MBC: 0.625 v/v, %		
Thymus capitatus essential oil	High-pressure homogenization	*Bacillus subtilis*	MIC: 1.5 mg/mL	MIC: 0.0 mg/mL	Encapsulated essential oil exhibited the higher antibacterial activity than bulk one	Benjemaa et al. (2018)
			MBC: > 3 mg/mL	MBC: 0.1 mg/mL		

Table 4 (continued)

Antimicrobial agents	Preparation techniques	Target microorganisms	Antimicrobial effects		Remarks	References
			Pure	Encapsulated		
Nanostructured phospholipid carriers						
Turmeric extract	Combination of thin-layer hydration, homogenization and sonication	*Staphylococcus aureus*	MIC: 20 mg/mL	MIC: 10 mg/mL	Turmeric extract nanoliposomes showed higher antibacterial as well as antioxidant activity as compared to free turmeric extract	Karimi et al. (2019)
		Escherichia coli	MIC: 5 mg/mL	MIC: 1.25 mg/mL	Encapsulation efficiency: 95%	
		Bacillus cereus	MIC: 20 mg/mL	MIC: 10 mg/mL		
		Streptococcus mutans	MIC: 20 mg/mL	MIC: 10 mg/mL		
		Acinetobacter junii	MIC: 20 mg/mL	MIC: 10 mg/mL		
		Pseudomonas aeruginosa	MIC: 40 mg/mL	MIC: 10 mg/mL		
		Candida albicans	MIC: 20 mg/mL	MIC: 10 mg/mL		
Garlic (*Allium sativum* L.) essential oil	Ethanol injection	*Escherichia coli* O157:H7	MIC: 0.03%	MIC: 0.02%	Nanoliposomal garlic essential oil showed higher antimicrobial activity than free form of essential oil	Zabihi et al. (2017)
			MBC: 0.04%	MBC: 0.03%	Encapsulation efficiency: 64.27%	
Zataria multiflora Boiss. essential oil	Thin film hydration	*Escherichia coli* O157:H7	MIC: 0.03% (v/v)	MIC: 0.015% (v/v)	Liposomal essential oil showed higher inhibitory effect on toxin titer than free oil	Khatibi et al. (2018)
Nisin and garlic extract	Thin-film hydration	Some G- & G+ Bacteria (*Listeria monocytogenes, Salmonella* Enteritidis, *Escherichia coli, Staphylococcus aureus*)	Viable count:	Viable count:	Nisin-garlic extract nanoliposome has potential for use as an antimicrobial agent	Pinilla and Brandelli (2016)
			4–5 log CFU/mL lower than control	4–5 log CFU/mL lower than control	Encapsulation efficiency: Nisin (82%) & garlic extract (90%)	
Carvacrol	Lipid film hydration	*Staphylococcus aureus*	MBC: 1.33 mg/mL	MBC: 5.30 mg/mL	Free carvacrol (control) showed better results than encapsulated for inactivation of given microorganisms	Cacciatore et al. (2020)

Table 4 (continued)

Antimicrobial agents	Preparation techniques	Target microorganisms	Antimicrobial effects		Remarks	References
			Pure	Encapsulated		
		Listeria monocytogenes	MBC: 1.77 mg/mL	MBC: 5.30 mg/mL	Encapsulation efficiency: 98%	
		Escherichia coli	MBC: 1.33 mg/mL	MBC: 5.30 mg/mL		
		Salmonella spp.	MBC: 1.77 mg/mL	MBC: 3.53 mg/mL		
Cardamom essential oil	Combination of thin-layer hydration, homogenization and sonication	*Staphylococcus aureus*	MIC: 4400 µg/mL (Emulsion)	MIC: 3000 µg/mL	Nanoliposome system showed the ability to protect the functional properties of cardamom essential oil	Nahr et al. (2019)
					Better antimicrobial properties at nanoscale	
		Escherichia coli	MIC: 2200 µg/mL (Emulsion)	MIC: 1500 µg/mL	Encapsulation efficiency: > 60	
Lupulon & xanthohumol	Ultrasonication	*Clostridium perfringens*	MIC: 64 mg/L	MIC: 32 mg/L	Nanoliposomal system has the potential to replace the synthetic additives in real food systems	Khatib et al. (2019)
			MBC: 128 mg/L	MBC: 64 mg/L	Encapsulation efficiency: Lupulon (71.12%) & xanthohumol (67.81%)	
Nanolipid carriers						
Cardamom essential oil	Combination of low-energy nanoemulsification, high shear homogenization and sonication	*Escherichia coli*	MIC: 2200 µg/mL (Emulsion)	MIC: 1100 µg/mL	High encapsulation efficiency: > 90%	Nahr et al. (2018)
					Loading capacity: > 25%	
		Staphylococcus aureus	MIC: 4400 µg/mL (Emulsion)	MIC: 1100 µg/mL	NLC delivery system shows good chemical and physical stability to cardamom essential oil	
Menthol	Hot-melt homogenization	*Staphylococcus aureus*	MIC: 1000 µg/mL	MIC: 125 µg/mL	Encapsulation efficiency: 98.73%	Piran et al. (2017)
			MBC: 4000 µg/mL (Emulsion)	MBC: 500 µg/mL	Loading capacity: 9.8%	
					Menthol containing NLC indicated better effect on fungi as compared to bacteria	

Table 4 (continued)

Antimicrobial agents	Preparation techniques	Target microorganisms	Antimicrobial effects		Remarks	References
			Pure	Encapsulated		
		Bacillus cereus	MIC: 2000 µg/mL	MIC: 250 µg/mL	In bacteria, G+ bacteria had higher antibacterial efficiency than G- bacteria	
			MBC: 4000 µg/mL (Emulsion)	MBC: 1000 µg/mL		
		Escherichia coli	MIC: 2000 µg/mL	MIC: 500 µg/mL		
			MBC: > 4000 µg/mL (Emulsion)	MBC: > 4000 µg/mL		
		Candida albicans	MIC: 156 µg/mL	MIC: 78 µg/mL		
			MBC: 468 µg/mL (Emulsion)	MBC: 117 µg/mL		
Citral	Hot-melt homogenization	*Staphylococcus aureus*	MIC: 500 µg/mL	MIC: 125 µg/mL	Encapsulation efficiency: 99.84%	Mokarizadeh et al. (2017)
			MBC: 2000 µg/mL (Emulsion)	MBC: 500 µg/mL	Loading capacity: 12.5%	
					Enhanced antimicrobial properties of citral-loaded NLC than citral emulsion for all micro-organisms	
		Bacillus cereus	MIC: 500 µg/mL	MIC: 31.25 µg/mL		
			MBC: 1000 µg/mL (Emulsion)	MBC:125 µg/mL		
		Escherichia coli	MIC: 1000 µg/mL	MIC: 250 µg/mL		
			MBC: > 2000 µg/mL (Emulsion)	MBC: > 2000 µg/mL		
		Candida albicans	MIC: 125 µg/mL	–		
			MBC: 250 µg/mL (Emulsion)			
Turmeric extract	High shear homogenization	*Staphylococcus aureus*	MIC: 20 mg/mL	MIC: 30 mg/mL	NLC loaded with turmeric extract showed high antibacterial activity for *Escherichia coli*	Karimi et al. (2018)
		Escherichia coli	MIC: 5 mg/mL	MIC: 2.5 mg/mL	Turmeric extract–NLC indicated the characteristics of ideal functional food	
		Bacillus cereus	MIC: 20 mg/mL	MIC: 40 mg/mL		

Table 4 (continued)

Antimicrobial agents	Preparation techniques	Target microorganisms	Antimicrobial effects		Remarks	References
			Pure	Encapsulated		
		Streptococcus mutans	MIC: 5 mg/mL	MIC: 30 mg/mL		
		Acinetobacter juni	MIC: 20 mg/mL	MIC: 7.5 mg/mL		
		Pseudomonas aeruginosa	MIC: 40 mg/mL	MIC: 30 mg/mL		
		Candida albicans	MIC: 20 mg/mL	MIC: 40 mg/mL		

through nanoliposomes exhibited the antibacterial effect against *Escherichia coli* at low concentration, whereas the pure form of essential oils produced an antibacterial effect at higher concentration (Zabihi et al. 2017). A recent study observed that the nanoemulsions containing cumin essential oil show a significant effect on *Staphylococcus aureus*. These nanoemulsions have been explored for their antibacterial and anticancer properties of the cumin seed oil (Nirmala et al. 2020). In another study, nanoemulsions prepared using *Citrofortunella microcarpa* essential oil were most effective against *Staphylococcus aureus* (Inhibition zone: 9.98 mm), *Escherichia coli* (Inhibition zone: 8.34) and *Salmonella* spp. (Inhibition zone: 7.71) as compared to other nanoemulsions formed by lime essential oil from *Citrus aurantifolia* and *Citrus hystrix* (Liew et al. 2020). However, in some studies, the pure form and encapsulated form of bioactive ingredients showed a similar additive effect. For example, the copaíba resin oil and its nanoemulsion along with amphotericin B showed the additive effect with a decrease in the values of minimum inhibition concentration (≈ 50%) against the *Paracoccidioides* genus (Silva et al. 2020). Furthermore, the antibacterial activity was more effective toward the gram-positive than gram-negative strains using the nanoemulsions doped with quercetin (Das et al. 2020).

Several studies were also conducted on the nanoliposomes and their function as antimicrobial agents. A study developed surface-modified nanoliposomes doped with cationic peptides (peptide + 2 & peptide + 5). It revealed that polymer-coated nanoliposomes loaded with peptides, increased the antimicrobial activity approximately 2000-fold against the *Listeria monocytogenes* (Cantor et al. 2019). Furthermore, the solid lipid nanoparticles loaded with *Eugenia caryophyllata* essential oil showed the lower values of minimum bacterial concentration and minimum inhibition concentration as compared to the pure form of oil alone against the *Salmonella typhi*, *Staphylococcus aureus*, *Pseudomonas aeruginosa* and *Candida albicans* (Fazly Bazzaz et al. 2018).

On the other hand, another important group of improved delivery systems is nanolipid carriers, which have some major advantages like high stability, high loading capacity with sustained release of functional ingredients. These functional properties were advantageous to overcome the limitations of nanoliposomes and nanoemulsions. Solid lipid nanoparticles and nanostructured lipid carriers are produced by similar techniques, but nanostructured lipid carriers have better functional properties along with the properties of solid lipid nanoparticles. The nanostructured lipid carriers revealed the lower crystallinity index, slower particle growth and polymorphic transition as compared to solid lipid nanoparticles (Gordillo-Galeano and Mora-Huertas 2018). Therefore, lipid-based nanocarriers improve the bioactivity of the various antibacterial agents like essential oils, natural extracts from plant sources, natural, synthetic antibiotics, etc.

Among all the nanocarriers (nanoliposomes, nanoemulsions and nanolipid carriers), the utilization of nanoemulsions for encapsulation of antibacterial ingredients is maximum, which could be exploited in the food sector. This effect of nanoemulsions as antimicrobial agents have been explored mainly in three aspects, which include the utilization of nanoemulsions: a) in its pure form, i.e., nanoemulsions without incorporation of any functional compound, b) loaded with essential oils, c) loaded with a combination of one or more functional ingredients. For example, encapsulation of *trans*-cinnamic acid along with medium-chain triglycerides, Tween 80 & phosphate-buffered saline acetone as compositional ingredients were used against *Salmonella typhimurium* which reported the lower value of minimum inhibition concentration and minimum bacterial concentration (1.5 & 3.1 mg/mL) as compared to pure antibacterial type (12.5 & 25 mg/mL) (Letsididi et al. 2018). Moreover, nanoemulsions are known for several advantages such as targetability, large-scale production and encapsulation of both hydrophobic and hydrophilic compounds. However, nanoemulsions offer only one major limitation of the rapid release of functional ingredients due to their liquid nature. More studies on the antimicrobial effects of nanoemulsions containing soybean oil, black pepper oil, *Piper betle* L. essential oil have also been investigated against *Bacillus subtilis*, *Pseudomonas aeruginosa*, *Klebsiella pneumonia*, respectively (Benjemaa et al. 2018; Swathy et al. 2018; Roy and Guha 2018).

Conclusion

Among all the lipid-based nanocarriers, extensive research has been done on nanoliposomes due to their ability to carry hydrophilic, lipophilic and amphiphilic functional food ingredients. In contrast to all lipid-based nanoencapsulation techniques, nanolipid carriers (solid lipid nanoparticles, nanostructured lipid carriers and smart lipid nanocarriers) are one of the most predominant techniques in terms of loading capacity, sustained release and high stability (quality of functional compound over time). Further, nanolipid carriers showed the best results for the delivery of functional compounds due to their flexibility for the selection of compositional ingredients (solid lipid or solid lipid and oils) and increasing the capacity for holding functional ingredients. Besides, these are also considered as one of the most promising delivery systems to improve the solubility, physical stability, bioavailability as well as functionality of bioactive compounds along with high loading capacity. These nanocarriers can be used in the food industry for texture modification, improved food product quality, extended shelf life of food products and as coloring and antioxidant agents. Despite this, further research is required on the process optimization and engineering aspects to enhance different properties such as structural, physical and mass transfer to obtain productive results at the commercial level. Moreover, these can be loaded with polyphenolic compounds extracted from different natural sources and due to the increase in surface to volume ratio at nanoscale, these loaded nanocarriers can be used as effective preservatives at low concentrations. More in-depth research is also necessary for the safety concerns of these nanocarriers in the human body. Further, the focus should be given on the cost-effective processing operations for the synthesis of nanocarriers to be used in food industries at large scale.

Compliance with ethical standards

Conflicts of interest The authors have declared no conflict of interest.

References

Aditya N, Macedo AS, Doktorovova S, Souto EB, Kim S, Chang PS, Ko S (2014) Development and evaluation of lipid nanocarriers for quercetin delivery: A comparative study of solid lipid nanoparticles (SLN), nanostructured lipid carriers (NLC), and lipid nanoemulsions (LNE). LWT-Food Sci Technol 59(1):115–121. https://doi.org/10.1016/j.lwt.2014.04.058

Aditya N, Shim M, Lee I, Lee Y, Im MH, Ko S (2013) Curcumin and genistein coloaded nanostructured lipid carriers: *in vitro* digestion and antiprostate cancer activity. J Agric Food Chem 61(8):1878–1883. https://doi.org/10.1021/jf305143k

Ahmed GHG, González AF, García MED (2020) Nano-encapsulation of grape and apple pomace phenolic extract in chitosan and soy protein via nanoemulsification. Food Hydrocoll. https://doi.org/10.1016/j.foodhyd.2020.105806

Akhavan S, Assadpour E, Katouzian I, Jafari SM (2018) Lipid nano scale cargos for the protectionand delivery of food bioactive ingredients and nutraceuticals. Trends Food Sci Technol 74:132–146. https://doi.org/10.1016/j.tifs.2018.02.001

Akhavan S, Jafari SM (2017) Nanoencapsulation of natural food colorants. In: Jafari SM (ed) Nanoencapsulation of food bioactive ingredients. Academic Press, Cambridge, pp 223–260

Akhtar M, Murray BS, Afeisume EI, Khew SH (2014) Encapsulation of flavonoid in multiple emulsion using spinning disc reactor technology. Food Hydrocoll 34:62–67. https://doi.org/10.1016/j.foodhyd.2012.12.025

Almajwal AM, Abulmeaty M, Andrade J (2016) Efficacy of a novel food fortification system to combat vitamin D deficiency in rats. FASEB J 30:lb267–lb267

Almasi H, Azizi S, Amjadi S (2020) Development and characterization of pectin films activated by nanoemulsion and pickering emulsion stabilized marjoram (Origanum majorana L.) essential oil. Food Hydrocoll. https://doi.org/10.1016/j.foodhyd.2019.105338

Artiga-Artigas M, Acevedo-Fani A, Martín-Belloso O (2017) Improving the shelf life of low-fat cut cheese using nanoemulsion-based edible coatings containing oregano essential oil and mandarin fiber. Food Control 76:1–12. https://doi.org/10.1016/j.foodcont.2017.01.001

Asghari Ghajari M, Katouzian I, Ganjeh M, Jafari SM (2017) Nanoencapsulation of flavors. In: Jafari SM (ed) Nanoencapsulation of food bioactive ingredients. Academic Press, Cambridge, pp 261–296

Assadpour E, Jafari SM (2018) A systematic review on nanoencapsulation of food bioactive ingredients and nutraceuticals by various nanocarriers. Crit Rev Food Sci Nutr 59(19):3129–3151. https://doi.org/10.1080/10408398.2018.1484687

Assadpour E, Jafari SM, Maghsoudlou Y (2017) Evaluation of folic acid release from spray dried powder particles of pectin-whey protein nano-capsules. Int J Biol Macromol 95:238–247. https://doi.org/10.1016/j.ijbiomac.2016.11.023

Babazadeh A, Ghanbarzadeh B, Hamishehkar H (2016) Novel nanostructured lipid carriers as a promising food grade delivery system for rutin. J Funct Foods 26:167–175. https://doi.org/10.1016/j.jff.2016.07.017

Babazadeh A, Ghanbarzadeh B, Hamishehkar H (2017) Phosphatidylcholine-rutin complex as a potential nanocarrier for food applications. J Funct Foods 33:134–141. https://doi.org/10.1016/j.jff.2017.03.038

Bagherpour S, Alizadeh A, Ghanbarzadeh S, Mohammadi M, Hamishehkar H (2017) Preparation and characterization of betasitosterol-loaded nanostructured lipid carriers for butter enrichment. Food Biosci 20:51–55. https://doi.org/10.1016/j.fbio.2017.07.010

Baqeri F, Nejatian M, Abbaszadeh S, Taghdir M (2020) The effect of gelatin and thymol-loaded nanostructured lipid carrier on physicochemical, rheological and sensory properties of sesame paste/date syrup blends as a snack bar. J Texture Stud. https://doi.org/10.1111/jtxs.12511

Barbosa-Cánovas GV, Ortega-Rivas E, Juliano P, Yan H (2005) Encapsulation processes. Springer, New York

Barman K, Chowdhury D, Baruah PK (2020) Development of β-carotene loaded nanoemulsion using the industrial waste of orange (*Citrus reticulata*) peel to improve *in vitro* bioaccessibility of carotenoids and use as natural food colorant. J Food Process Preserv. https://doi.org/10.1111/jfpp.14429

Bashiri S, Ghanbarzadeh B, Ayaseh A, Dehghannya J, Ehsani A (2020) Preparation and characterization of chitosan-coated nanostructured lipid carriers (CH-NLC) containing cinnamon essential oil for enriching milk and anti-oxidant activity. LWT-Food Sci Technol. https://doi.org/10.1016/j.lwt.2019.108836

Beltrán JD, Ricaurte L, Estrada KB, Quintanilla-Carvajal MX (2020) Effect of homogenization methods on the physical stability of nutrition grade nanoliposomes used for encapsulating high oleic palm oil. LWT-Food Sci Technol. https://doi.org/10.1016/j.lwt.2019.108801

Benjemaa M, Neves MA, Falleh H, Isoda H, Ksouri R, Nakajima M (2018) Nanoencapsulation of *Thymus capitatus* essential oil: formulation process, physical stability characterization and antibacterial efficiency monitoring. Ind Crops Prod 113:414–421. https://doi.org/10.1016/j.indcrop.2018.01.062

Bochicchio S, Barba AA, Grassi G, Lamberti G (2016) Vitamin delivery: carriers based on nanoliposomes produced via ultrasonic irradiation. LWT-Food Sci Technol 69:9–16. https://doi.org/10.1016/j.lwt.2016.01.025

Bou R, Cofrades S, Jiménez-Colmenero F (2014) Physicochemical properties and riboflavin encapsulation in double emulsions with different lipid sources. LWT-Food Sci Technol 59(2):621–628. https://doi.org/10.1016/j.lwt.2014.06.044

Bromley PJ (2011) Nanoemulsion including sucrose fatty acid ester. Patent Application No. PCT/US2011/000538

Burey P, Bhandari BR, Howes T, Gidley MJ (2008) Hydrocolloid gel particles: formation, characterization, and application. Crit Rev Food Sci Nutr 48(5):361–377. https://doi.org/10.1080/10408390701347801

Cacciatore FA, Dalmás M, Maders C, Isaía HA, Brandelli A, da Silva MP (2020) Carvacrol encapsulation into nanostructures: Characterization and antimicrobial activity against food borne pathogens adhered to stainless steel. Food Res Int. https://doi.org/10.1016/j.foodres.2020.109143

Cadena PG, Pereira MA, Cordeiro RB, Cavalcanti IM, Neto BB, Maria Do Carmo C, Lima Filho JL, Silva VL, Santos-Magalhães NS (2013) Nanoencapsulation of quercetin and resveratrol into elastic liposomes. BBA-Biomembranes 1828:309–316. https://doi.org/10.1016/j.bbamem.2012.10.022

Cantor S, Vargas L, Rojas A, Yarce CJ, Salamanca CH, Oñate-Garzón J (2019) Evaluation of the antimicrobial activity of cationic peptides loaded in surface-modified nanoliposomes against foodborne bacteria. Int J Mol Sci. https://doi.org/10.3390/ijms20030680

Champagne CP, Fustier P (2007) Microencapsulation for the improved delivery of bioactive compounds into foods. Curr Opin Biotech 18(2):184–190. https://doi.org/10.1016/j.copbio.2007.03.001

Chen L, Yokoyama W, Liang R, Zhong F (2020) Enzymatic degradation and bioaccessibility of protein encapsulated β-carotene nano-emulsions during *in vitro* gastro-intestinal digestion. Food Hydrocoll. https://doi.org/10.1016/j.foodhyd.2019.105177

Chen Y, Zhang R, Xie B, Sun Z, McClements DJ (2020) Lotus seedpod proanthocyanidin-whey protein complexes: Impact on physical and chemical stability of β-carotene-nanoemulsions. Food Res Int. https://doi.org/10.1016/j.foodres.2019.108738

Chu Y, Gao C, Liu X, Zhang N, Xu T, Feng X, Yang Y, Shen X, Tang X (2020) Improvement of storage quality of strawberries by pullulan coatings incorporated with cinnamon essential oil nanoemulsion. LWT-Food Sci Technol. https://doi.org/10.1016/j.lwt.2020.109054

Couto R, Alvarez V, Temelli F (2016) Encapsulation of vitamin B2 in solid lipid nanoparticles using supercritical CO_2. J Supercrit Fluids 120:432–442. https://doi.org/10.1016/j.supflu.2016.05.036

Cui H, Yuan L, Li W, Lin L (2017) Edible film incorporated with chitosan and *Artemisia annua* oil nanoliposomes for inactivation of *Escherichia coli* O157: H7 on cherry tomato. Int J Food Sci Tech 52(3):687–698. https://doi.org/10.1111/ijfs.13322

Das SS, Verma PRP, Singh SK (2020) Screening and preparation of quercetin doped nanoemulsion: characterizations, antioxidant and anti-bacterial activities. LWT-Food Sci Technol. https://doi.org/10.1016/j.lwt.2020.109141

Dasgupta N, Ranjan S, Gandhi M (2019a) Nanoemulsions in food: market demand. Environ Chem Lett 17(2):1003–1009. https://doi.org/10.1007/s10311-019-00856-2

Dasgupta N, Ranjan S, Gandhi M (2019b) Nanoemulsion ingredients and components. Environ Chem Lett 17(2):917–928. https://doi.org/10.1007/s10311-018-00849-7

Dasgupta N, Ranjan S, Mundra S, Ramalingam C, Kumar A (2016) Fabrication of food grade vitamin E nanoemulsion by low energy approach, characterization and its application. Int J Food Prop 19:700–708. https://doi.org/10.1080/10942912.2015.1042587

Davidov-Pardo G, McClements DJ (2015) Nutraceutical delivery systems: resveratrol encapsulation in grape seed oil nanoemulsions formed by spontaneous emulsification. Food Chem 167:205–212. https://doi.org/10.1016/j.foodchem.2014.06.082

de Carvalho SM, Noronha CM, Floriani CL, Lino RC, Rocha G, Bellettini IC, Ogliari PJ, Barreto PLM (2013) Optimization of α-tocopherol loaded solid lipid nanoparticles by central composite design. Ind Crops and Prod 49:278–285. https://doi.org/10.1016/j.indcrop.2013.04.054

de Meneses AC, Sayer C, Puton BM, Cansian RL, Araújo PH, de Oliveira D (2019) Production of clove oil nanoemulsion with rapid and enhanced antimicrobial activity against gram-positive and gram-negative bacteria. J Food Process Eng. https://doi.org/10.1111/jfpe.13209 de Pace RCC, Liu X, Sun M, Nie S, Zhang J, Cai Q, Gao W, Pan X, Fan Z, Wang S (2013) Anticancer activities of (−)-epigallocatechin-3-gallate encapsulated nanoliposomes in MCF7 breast cancer cells. J Liposome Res 23(3):187–196. https://doi.org/10.3109/08982104.2013.788023

Demirci M, Caglar MY, Cakir B, Gülseren İ (2017) Encapsulation by nanoliposomes. In: Jafari SM (ed) Nanoencapsulation technologies for the food and nutraceutical industries. Academic Press, Cambridge, pp 74–113

Demisli S, Theochari I, Christodoulou P, Zervou M, Xenakis A, Papadimitriou V (2020) Structure, activity and dynamics of extra virgin olive oil-in-water nanoemulsions loaded with vitamin D_3 and calcium citrate. J Mol Liq. https://doi.org/10.1016/j.molliq.2020.112908

Dewettinck K, Huyghebaert A (1999) Fluidized bed coating in food technology. Trends Food Sci Tech 10(4–5):163–168. https://doi.org/10.1016/S0924-2244(99)00041-2

Ding B, Zhang X, Hayat K, Xia S, Jia C, Xie M, Liu C (2011a) Preparation, characterization and the stability of ferrous glycinate nanoliposomes. J Food Eng 102(2):202–208. https://doi.org/10.1016/j.jfoodeng.2010.08.022

Ding BM, Zhang XM, Xia SQ (2011b) Effectiveness of treatment of iron-deficiency anemia in rats with ferrous glycinate nanoliposomes. J Food Sci Biotechnol 30(1):49–54. https://doi.org/10.1039/C3FO60383K

El-Messery TM, Altuntas U, Altin G, Özçelik B (2020) The effect of spray-drying and freeze-drying on encapsulation efficiency, *in vitro* bioaccessibility and oxidative stability of krill oil nanoemulsion system. Food Hydrocoll. https://doi.org/10.1016/j.foodhyd.2020.105890

Elshamy AI, Ammar NM, Hassan HA, Al-Rowaily SL, Ragab TI, El Gendy AENG, Abd-ElGawad AM (2020) Essential oil and its nanoemulsion of *Araucaria heterophylla* resin: Chemical characterization, anti-inflammatory, and antipyretic activities. Ind Crops Prod. https://doi.org/10.1016/j.indcrop.2020.112272

Esfanjani AF, Jafari SM (2017) Nanoencapsulation of phenolic compounds and antioxidants. In: Jafari SM (ed) Nanoencapsulation technologies for the food and nutraceutical industries. Academic Press, Cambridge, pp 63–101

Esmaeili H, Cheraghi N, Khanjari A, Rezaeigolestani M, Basti AA, Kamkar A, Aghaee EM (2020) Incorporation of nanoencapsulated garlic essential oil into edible films: A novel approach for extending shelf life of vacuum-packed sausages. Meat Sci. https://doi.org/10.1016/j.meatsci.2020.108135

Fang Z, Bhandari B (2010) Encapsulation of polyphenols – a review. Trends Food Sci Tech 21(10):510–523. https://doi.org/10.1016/j.tifs.2010.08.003

Fathi M, Varshosaz J (2013) Novel hesperetin loaded nanocarriers for food fortification: production and characterization. J Funct Foods 5(3):1382–1391. https://doi.org/10.1016/j.jff.2013.05.006

Fathima SJ, Fathima I, Abhishek V, Khanum F (2016) Phosphatidylcholine, an edible carrier for nanoencapsulation of unstable thiamine. Food Chem 197:562–570. https://doi.org/10.1016/j.foodchem.2015.11.005

Fazly Bazzaz BS, Khameneh B, Namazi N, Iranshahi M, Davoodi D, Golmohammadzadeh S (2018) Solid lipid nanoparticles carrying *Eugenia caryophyllata* essential oil: the novel nanoparticulate systems with broad-spectrum antimicrobial activity. Letters Appl Microbiol 66(6):506–513. https://doi.org/10.1111/lam.12886

Feng J, Wang R, Chen Z, Zhang S, Yuan S, Cao H, Jafari SM, Yang W (2020a) Formulation optimization of D-limonene-loaded nanoemulsions as a natural and efficient biopesticide. Colloid Surface. https://doi.org/10.1016/j.colsurfa.2020.124746

Feng X, Tjia JYY, Zhou Y, Liu Q, Fu C, Yang H (2020b) Effects of tocopherol nanoemulsion addition on fish sausage properties and fatty acid oxidation. LWT-Food Sci Technol. https://doi.org/10.1016/j.lwt.2019.108737

Frenzel M, Krolak E, Wagner A, Steffen-Heins A (2015) Physicochemical properties of WPI coated liposomes serving as stable transporters in a real food matrix. LWT-Food Sci Technol 63(1):527–534. https://doi.org/10.1016/j.lwt.2015.03.055

Gaber DM, Nafee N, Abdallah OY (2017) Myricetin solid lipid nanoparticles: stability assurance from system preparation to site of action. Eur J Pharm Sci 109:569–580. https://doi.org/10.1016/j.ejps.2017.08.007

García-Betanzos CI, Hernández-Sánchez H, Bernal-Couoh TF, Quintanar-Guerrero D, de la Luz Z-Z (2017) Physicochemical, total phenols and pectin methylesterase changes on quality maintenance on guava fruit (*Psidium guajava* L.) coated with candeuba wax solid lipid nanoparticles-xanthan gum. Food Res Int 101:218–227. https://doi.org/10.1016/j.foodres.2017.08.065

Garzoli S, Petralito S, Ovidi E, Turchetti G, Masci VL, Tiezzi A, Trilli J, Cesa S, Casadei MA, Giacomello P, Paolicelli P (2020) *Lavandula x intermedia* essential oil and hydrolate: Evaluation of chemical composition and antibacterial activity before and after formulation in nanoemulsion. Ind Crops Prod. https://doi.org/10.1016/j.indcrop.2019.112068

Gharibzahedi SMT, Jafari SM (2017a) Nanoencapsulation of minerals. In: Jafari SM (ed) Nanoencapsulation of food bioactive ingredients. Academic Press, Cambridge, pp 333–400

Gharibzahedi SMT, Jafari SM (2017b) The importance of minerals in human nutrition: Bioavailability, food fortification, processing effects and nanoencapsulation. Trends Food Sci Technol 62:119–132. https://doi.org/10.1016/j.tifs.2017.02.017

Ghorbanzade T, Jafari SM, Akhavan S, Hadavi R (2017) Nanoencapsulation of fish oil in nano-liposomes and its application in fortification of yogurt. Food Chem 216:146–152. https://doi.org/10.1016/j.foodchem.2016.08.022

Gibbs BF, Kermasha S, Alli I, Mulligan CN (1999) Encapsulation in the food industry: a review. Int J Food Sci Nutr 50(3):213–224. https://doi.org/10.1080/096374899101256

Gokce EH, Korkmaz E, Dellera E, Sandri G, Bonferoni MC, Ozer O (2012) Resveratrol-loaded solid lipid nanoparticles versus nanostructured lipid carriers: Evaluation of antioxidant potential for dermal applications. Int J Nanomedicine 7:1841–1850. https://doi.org/10.2147/IJN.S29710

Gordillo-Galeano A, Mora-Huertas CE (2018) Solid lipid nanoparticles and nanostructured lipid carriers: A review emphasizing on particle structure and drug release. Eur J Pharm Biopharm 133:285–308. https://doi.org/10.1016/j.ejpb.2018.10.017

Gouin S (2004) Microencapsulation: industrial appraisal of existing technologies and trends. Trends Food Sci Tech 15:330–347. https://doi.org/10.1016/j.tifs.2003.10.005

Gulzar S, Benjakul S (2020) Characteristics and storage stability of nanoliposomes loaded with shrimp oil as affected by ultrasonication and microfluidization. Food Chem. https://doi.org/10.1016/j.foodchem.2019.125916

Guo M, Zhang L, He Q, Arabi SA, Zhao H, Chen W, Ye X, Liu D (2020) Synergistic antibacterial effects of ultrasound and thyme essential oils nanoemulsion against *Escherichia coli* O157: H7. Ultrason Sonochem. https://doi.org/10.1016/j.ultsonch.2020.104988

Guttoff M, Saberi AH, McClements DJ (2015) Formation of vitamin D nanoemulsion-based delivery systems by spontaneous emulsification: factors affecting particle size and stability. Food Chem 171:117–122. https://doi.org/10.1016/j.foodchem.2014.08.087

Haghju S, Beigzadeh S, Almasi H, Hamishehkar H (2016) Chitosan films incorporated with nettle (Urtica dioica L.) extract-loaded nanoliposomes: I. Physicochemical characterisation and antimicrobial properties. J Microencapsul 33(5):438–448. https://doi.org/10.1080/02652048.2016.1208294

Halwani M, Yebio B, Suntres Z, Alipour M, Azghani A, Omri A (2008) Co-encapsulation of gallium with gentamicin in liposomes enhances antimicrobial activity of gentamicin against *Pseudomonas aeruginosa*. J Antimicrob Chemother 62(6):1291–1297. https://doi.org/10.1093/jac/dkn422

Hamadou AH, Huang WC, Xue C, Mao X (2020a) Comparison of β-carotene loaded marine and egg phospholipids nanoliposomes. J Food Eng. https://doi.org/10.1016/j.jfoodeng.2020.110055

Hamadou AH, Huang WC, Xue C, Mao X (2020b) Formulation of vitamin C encapsulation in marine phospholipids nanoliposomes: characterization and stability evaluation during long term storage. LWT-Food Sci Tech. https://doi.org/10.1016/j.lwt.2020.109439

Hasan M, Belhaj N, Benachour H, Barberi-Heyob M, Kahn C, Jabbari E, Linder M, Arab-Tehrany E (2014) Liposome encapsulation of curcumin: physico-chemical characterizations and effects on MCF7 cancer cell proliferation. Int J Pharm 461(1):519–528. https://doi.org/10.1016/j.ijpharm.2013.12.007

Hassanzadeh P, Arbabi E, Atyabi F, Dinarvand R (2018) Ferulic acid-loaded nanostructured lipid carriers: a promising nanoformulation against the ischemic neural injuries. Life Sci 193:64–76. https://doi.org/10.1016/j.lfs.2017.11.046

Hemmatkhah F, Zeynali F, Almasi H (2020) Encapsulated cumin seed essential oil-loaded active papers: Characterization and evaluation of the effect on quality attributes of beef hamburger. Food Bioprocess Tech 13(3):533–547. https://doi.org/10.1007/s11947-020-02418-9

Hermida LG, Roig A, Bregni C, Sabés-Xamaní M, Barnadas-Rodríguez R (2011) Preparation and characterization of iron-containing liposomes: their effect on soluble iron uptake by Caco-2 cells. J Liposome Res 21:203–212. https://doi.org/10.3109/08982104.2010.517536

Hosny KM, Banjar ZM, Hariri AH, Hassan AH (2015) Solid lipid nanoparticles loaded with iron to overcome barriers for treatment of iron deficiency anemia. Drug Des Devel Ther 9:313–320. https://doi.org/10.2147/DDDT.S77702

Huang J, Wang Q, Li T, Xia N, Xia Q (2017) Nanostructured lipid carrier (NLC) as a strategy for encapsulation of quercetin and linseed oil: Preparation and *in vitro* characterization studies. J Food Eng 215:1–12. https://doi.org/10.1016/j.jfoodeng.2017.07.002

Huang M, Wang H, Xu X, Lu X, Song X, Zhou G (2020) Effects of nanoemulsion-based edible coatings with composite mixture of rosemary extract and ε-poly-l-lysine on the shelf life of ready-to-eat carbonado chicken. Food Hydrocoll. https://doi.org/10.1016/j.foodhyd.2019.105576

Jafari SM (2017) An overview of nanoencapsulation techniques and their classification. In: Jafari SM (ed) Nanoencapsulation technologies for the food and nutraceutical industries. Academic Press, Cambridge, pp 1–34

Jafari SM, He Y, Bhandari B (2007) Encapsulation of nanoparticles of d-limonene by spray drying: role of emulsifiers and emulsifying techniques. Dry Technol 25:1069–1079. https://doi.org/10.1080/07373930701396758

Jafari SM, McClements DJ (2017) Nanotechnology approaches for increasing nutrient bioavailability. In: Toldrá F (ed) Advances in food and nutrition research. Academic Press, Cambridge, pp 1–30

Jafari SM, Paximada P, Mandala I, Assadpour E, Mehrnia MA (2017) Encapsulation by nanoemulsions. In: Jafari SM (ed) Nanoencapsulation technologies for the food and nutraceutical industries. Academic Press, Cambridge, pp 36–73

Javanshir A, Karimi E, Maragheh AD, Tabrizi MH (2020) The antioxidant and anticancer potential of *Ricinus communis* L. essential oil nanoemulsions. J Food Meas Charact 14:1356–1365. https://doi.org/10.1007/s11694-020-00385-5

Jimenez-Escobar MP, Pascual-Mathey LI, Beristain CI, Flores-Andrade E, Jiménez M, Pascual-Pineda LA (2020) *In vitro* and *In vivo* antioxidant properties of paprika carotenoids nanoemulsions. LWT-Food Sci Technol. https://doi.org/10.1016/j.lwt.2019.108694

Jose S, Anju S, Cinu T, Aleykutty N, Thomas S, Souto E (2014) *In vivo* pharmacokinetics and biodistribution of resveratrol-loaded solid lipid nanoparticles for brain delivery. Int J Pharm 474:6–13. https://doi.org/10.1016/j.ijpharm.2014.08.003

Karimi N, Ghanbarzadeh B, Hajibonabi F, Hojabri Z, Ganbarov K, Kafil HS, Hamishehkar H, Yousefi M, Mokarram RR, Kamounah FS, Yousefi B (2019) Turmeric extract loaded nanoliposome as a potential antioxidant and antimicrobial nanocarrier for food applications. Food Biosci 29:110–117. https://doi.org/10.1016/j.fbio.2019.04.006

Karimi N, Ghanbarzadeh B, Hamishehkar H, Mehramuz B, Kafil HS (2018) Antioxidant, antimicrobial and physicochemical properties of turmeric extract-loaded nanostructured lipid carrier (NLC). Colloids Interface Sci Commun 22:18–24. https://doi.org/10.1016/j.colcom.2017.11.006

Katouzian I, FaridiEsfanjani A, Jafari SM, Akhavan S (2017) Formulation and application of a new generation of lipid nano-carriers for the food bioactive ingredients. Trends Food Sci Tech 68(Supplement C):14–25. https://doi.org/10.1016/j.tifs.2017.07.017

Katouzian I, Jafari SM (2016) Nano-encapsulation as a promising approach for targeted delivery and controlled release of vitamins. Trends Food Sci Technol 53:34–48. https://doi.org/10.1016/j.tifs.2016.05.002

Keykhosravy K, Khanzadi S, Hashemi M, Azizzadeh M (2020) Chitosan-loaded nanoemulsion containing *Zataria Multiflora* Boiss and *Bunium persicum* Boiss essential oils as edible coatings: Its impact on microbial quality of turkey meat and fate of inoculated pathogens. Int J Biol Macromol 150:904–913. https://doi.org/10.1016/j.ijbiomac.2020.02.092

Khan MR, Sadiq MB, Mehmood Z (2020) Development of edible gelatin composite films enriched with polyphenol loaded nanoemulsions as chicken meat packaging material. CyTA-J Food 18(1):137–146. https://doi.org/10.1080/19476337.2020.1720826

Khanzadi S, Keykhosravy K, Hashemi M, Azizzadeh M (2020) Alginate coarse/nanoemulsions containing *Zataria multiflora* Boiss essential oil as edible coatings and the impact on microbial quality of trout fillet. Aquac Res. https://doi.org/10.1111/are.14418

Khatib N, Varidi MJ, Mohebbi M, Varidi M, Hosseini SMH (2019) Co-encapsulation of lupulon and xanthohumol in lecithin-based nanoliposomes developed by sonication method. J Food Process Preserv. https://doi.org/10.1111/jfpp.14075

Khatibi SA, Misaghi A, Moosavy MH, Akhondzadeh Basti A, Mohamadian S, Khanjari A (2018) Effect of nanoliposomes containing Zataria multiflora Boiss essential oil on gene expression of Shiga toxin 2 in Escherichia coli O157: H7. J Appl Microbiol 124(2):389–397. https://doi.org/10.1111/jam.13641

Kosaraju SL, Tran C, Lawrence A (2006) Liposomal delivery systems for encapsulation of ferrous sulfate: Preparation and characterization. J Liposome Res 16:347–358. https://doi.org/10.1080/08982100600992351

Kulkarni M, Goge N, Date AA (2020) Development of nanoemulsion preconcentrate of capsanthin with improved chemical stability. ASSAY Drug Dev Techn 18(1):34–44. https://doi.org/10.1089/adt.2019.916

Kumar DL, Sarkar P (2018) Encapsulation of bioactive compounds using nanoemulsions. Environ Chem Lett 16(1):59–70. https://doi.org/10.1007/s10311-017-0663-x

Lacatusu I, Mitrea E, Badea N, Stan R, Oprea O, Meghea A (2013) Lipid nanoparticles based on omega-3 fatty acids as effective carriers for lutein delivery. Preparation and in vitro characterization studies. J Funct Foods 5(3):1260–1269. https://doi.org/10.1016/j.jff.2013.04.010

Lee H, Yildiz G, dos Santos L, Jiang S, Andrade J, Engeseth N, Feng H (2016) Soy protein nano-aggregates with improved functional properties prepared by sequential pH treatment and ultrasonication. Food Hydrocoll 55:200–209. https://doi.org/10.1016/j.foodhyd.2015.11.022

Letsididi KS, Lou Z, Letsididi R, Mohammed K, Maguy BL (2018) Antimicrobial and antibiofilm effects of trans-cinnamic acid nanoemulsion and its potential application on lettuce. LWT-Food Sci Tech 94:25–32. https://doi.org/10.1016/j.lwt.2018.04.018

Li C, Zhang X, Huang X, Wang X, Liao G, Chen Z (2013) Preparation and characterization of flexible nanoliposomes loaded with daptomycin, a novel antibiotic, for topical skin therapy. Int J Nanomedicine 8:1285–1292. https://doi.org/10.2147/IJN.S41695

Li D, Li L, Xiao N, Li M, Xie X (2018) Physical properties of oil-in-water nanoemulsions stabilized by OSA-modified starch for the encapsulation of lycopene. Colloids Surf A Physicochem Eng Asp 552:59–66. https://doi.org/10.1016/j.colsurfa.2018.04.055

Li J, Hwang IC, Chen X, Park HJ (2016a) Effects of chitosan coating on curcumin loaded nanoemulsion: study on stability and *in vitro* digestibility. Food Hydrocoll 60:138–147. https://doi.org/10.1016/j.foodhyd.2016.03.016

Li M, Zahi MR, Yuan Q, Tian F, Liang H (2016b) Preparation and stability of astaxanthin solid lipid nanoparticles based on stearic acid. Eur J Lipid Sci Tech 118(4):592–602. https://doi.org/10.1002/ejlt.201400650

Liang R, Xu S, Shoemaker CF, Li Y, Zhong F, Huang Q (2012) Physical and antimicrobial properties of peppermint oil nanoemulsions. J Agric Food Chem 60(30):7548–7555. https://doi.org/10.1021/jf301129k

Liew SN, Utra U, Alias AK, Tan TB, Tan CP, Yussof NS (2020) Physical, morphological and antibacterial properties of lime essential oil nanoemulsions prepared via spontaneous emulsification method. LWT-Food Sci Technol. https://doi.org/10.1016/j.lwt.2020.109388

Liu C, Wang Z, Jin H, Wang X, Gao Y, Zhao Q, Liu C, Xu J (2020a) Effect of enzymolysis and glycosylation on the curcumin nanoemulsions stabilized by β-conglycinin: Formation, stability and *in vitro* digestion. Int J Biol Macromol 142:658–667. https://doi.org/10.1016/j.ijbiomac.2019.10.007

Liu L, Tang Y, Gao C, Li Y, Chen S, Xiong T, Li J, Du M, Gong Z, Chen H (2014) Characterization and biodistribution *in vivo* of quercetin-loaded cationic nanostructured lipid carriers. Colloids Surf B: Biointerfaces 115:125–131. https://doi.org/10.1016/j.colsurfb.2013.11.029

Liu Q, Zhang M, Bhandari B, Xu J, Yang C (2020b) Effects of nanoemulsion-based active coatings with composite mixture of star anise essential oil, polylysine, and nisin on the quality and shelf life of ready-to-eat Yao meat products. Food Control. https://doi.org/10.1016/j.foodcont.2019.106771

Liu W, Tian M, Kong Y, Lu J, Li N, Han J (2017) Multilayered vitamin C nanoliposomes by self-assembly of alginate and chitosan: Long-term stability and feasibility application in mandarin juice. LWT-Food Sci Technol 75:608–615. https://doi.org/10.1016/j.lwt.2016.10.010

Lo Nostro P, Ramsch R, Fratini E, Lagi M, Ridi F, Carretti E, Ambrosi M, Ninham BW, Baglioni P (2007) Organogels from a vitamin C-based surfactant. J Phys Chem B 111:11714–11721. https://doi.org/10.1021/jp0730085

Ma Q, Davidson PM, Zhong Q (2016) Nanoemulsions of thymol and eugenol co-emulsified by lauric arginate and lecithin. Food Chem 206:167–173. https://doi.org/10.1016/j.foodchem.2016.03.065

Majeed H, Antoniou J, Hategekimana J, Sharif HR, Haider J, Liu F, Ali B, Rong L, Ma J, Zhong F (2016) Influence of carrier oil type, particle size on *in vitro* lipid digestion and eugenol release in emulsion and nanoemulsions. Food Hydrocoll 52:415–422. https://doi.org/10.1016/j.foodhyd.2015.07.009

Marsanasco M, Márquez AL, Wagner JR, Alonso SV, Chiaramoni NS (2011) Liposomes as vehicles for vitamins E and C: An alternative to fortify orange juice and offer vitamin C protection after heat treatment. Food Res Int 44(9):3039–3046. https://doi.org/10.1016/j.foodres.2011.07.025

McClements DJ, Decker EA, Park Y (2009) Controlling lipid bioavailability through physicochemical and structural approaches. Crit Rev Food Sci Nutr 49(1):48–67. https://doi.org/10.1080/10408390701764245

McClements DJ, Decker EA, Park Y, Weiss J (2009) Structural design principles for delivery of bioactive components in nutraceuticals and functional foods. Crit Rev Food Sci Nutr 49(6):577–606. https://doi.org/10.1080/10408390902841529

McClements DJ, Jafari SM (2017) General aspects of nanoemulsions and their formulation. In: Jafari SM, McClements DJ (eds) Nanoemulsions. Academic Press, Cambridge, pp 3–20

Mehmood T, Ahmed A (2020) Tween 80 and soya-lecithin-based food-grade nanoemulsions for the effective delivery of vitamin D. Langmuir 36(11):2886–2892. https://doi.org/10.1021/acs.langmuir.9b03944

Mehrnia MA, Jafari SM, Makhmal-Zadeh BS, Maghsoudlou Y (2016) Crocin loaded nanoemulsions: Factors affecting emulsion properties in spontaneous emulsification. Int J Biol Macromol 84:261–267. https://doi.org/10.1016/j.ijbiomac.2015.12.029

Milanovic J, Manojlovic V, Levic S, Rajic N, Nedovic V, Bugarski B (2010) Microencapsulation of flavors in carnauba wax. Sensors 10(1):901–912. https://doi.org/10.3390/s100100901

Mirtalebi M, Rajaei A, Bahmaei M, Khosroushahi AY (2020) Storage stability of wheat germ oil encapsulated within nanostructured lipid carriers. J Nanostruct 10(2):268–278. https://doi.org/https://doi.org/10.22052/JNS.2020.02.007

Moghimi R, Aliahmadi A, McClements DJ, Rafati H (2016) Investigations of the effectiveness of nanoemulsions from sage oil as antibacterial agents on some food borne pathogens. LWT-Food Sci Technol 71:69–76. https://doi.org/10.1016/j.lwt.2016.03.018

Mohammadi A, Jafari SM, Assadpour E, Esfanjani AF (2016) Nano-encapsulation of olive leaf phenolic compounds through WPC–pectin complexes and evaluating their release rate. Int J Biol Macromol 82:816–822. https://doi.org/10.1016/j.ijbiomac.2015.10.025

Mohammadi M, Pezeshki A, Abbasi MM, Ghanbarzadeh B, Hamishehkar H (2017) Vitamin D_3-loaded nanostructured lipid carriers as a potential approach for fortifying food beverages; *in vitro* and *in vivo* evaluation. Adv Pharm Bull 7(1):61–71. https://doi.org/https://doi.org/10.15171/apb.2017.008

Mokarizadeh M, Kafil HS, Ghanbarzadeh S, Alizadeh A, Hamishehkar H (2017) Improvement of citral antimicrobial activity by incorporation into nanostructured lipid carriers: a potential application in food stuffs as a natural preservative. Res Pharm Sci 12(5):409–415. https://doi.org/10.4103/1735-5362.213986

Moraes M, Carvalho JMP, Silva CR, Cho S, Sola MR, Pinho SC (2013) Liposomes encapsulating beta- carotene produced by the proliposomes method: characterisation and shelf life of powders and phospholipid vesicles. Int J Food Sci Tech 48(2):274–282. https://doi.org/10.1111/j.1365-2621.2012.03184.x

Mourtas S, Lazar AN, Markoutsa E, Duyckaerts C, Antimisiaris SG (2014) Multifunctional nanoliposomes with curcumin–lipid derivative and brain targeting functionality with potential applications for Alzheimer disease. Eur J Med Chem 80:175–183. https://doi.org/10.1016/j.ejmech.2014.04.050

Mozafari MR, Johnson C, Hatziantoniou S, Demetzos C (2008) Nanoliposomes and their applications in food nanotechnology. J Liposome Res 18(4):309–327. https://doi.org/10.1080/08982100802465941

Mugabe C, Halwani M, Azghani AO, Lafrenie RM, Omri A (2006) Mechanism of enhanced activity of liposome-entrapped aminoglycosides against resistant strains of *Pseudomonas aeruginosa*. Antimicrob Agents and Chemother 50(6):2016–2022. https://doi.org/10.1128/AAC.01547-05

Mukherjee K, Maiti K, Venkatesh M, Mukherjee PK (2008) Phytosome of hesperetin, a value added formulation with phytomolecules In: 60th Indian pharmaceutical congress, New Delhi, India, p 287

Mulik RS, Mönkkönen J, Juvonen RO, Mahadik KR, Paradkar AR (2010) Transferrin mediated solid lipid nanoparticles containing curcumin: enhanced *in vitro* anticancer activity by induction of apoptosis. Int J Pharm 398(1–2):190–203. https://doi.org/10.1016/j.ijpharm.2010.07.021

Nahr FK, Ghanbarzadeh B, Hamishehkar H, Kafil HS, Hoseini M, Moghadam BE (2019) Investigation of physicochemical properties of essential oil loaded nanoliposome for enrichment purposes. LWT-Food Sci Technol 105:282–289. https://doi.org/10.1016/j.lwt.2019.02.010

Nahr FK, Ghanbarzadeh B, Hamishehkar H, Kafil HS (2018) Food grade nanostructured lipid carrier for cardamom essential oil: Preparation, characterization and antimicrobial activity. J Funct Foods 40:1–8. https://doi.org/10.1016/j.jff.2017.09.028

Naveen S, Kanum F (2014) Characterization and evaluation of iron nano-emulsion prepared by high speed homogenization. IJBPAS 3:45–55

Ni S, Hu C, Sun R, Zhao G, Xia Q (2017) Nanoemulsions-based delivery systems for encapsulation of quercetin: preparation, characterization, and cytotoxicity studies. J Food Process Eng. https://doi.org/10.1111/jfpe.12374

Nirmala MJ, Durai L, Rao KA, Nagarajan R (2020) Ultrasonic nanoemulsification of cuminum cyminum essential oil and its applications in medicine. Int J Nanomedicine 15:795–807. https://doi.org/10.2147/IJN.S230893

Noori S, Zeynali F, Almasi H (2018) Antimicrobial and antioxidant efficiency of nanoemulsion-based edible coating containing ginger (*Zingiber officinale*) essential oil and its effect on safety and quality attributes of chicken breast fillets. Food Control 84:312–320. https://doi.org/10.1016/j.foodcont.2017.08.015

Nunes R, Pereira BDA, Cerqueira MA, Silva P, Pastrana LM, Vicente AA, Martins JT, Bourbon AI (2020) Lactoferrin-based nanoemulsions to improve the physical and chemical stability of omega-3 fatty acids. Food Funct 11(3):1966–1981. https://doi.org/10.1039/C9FO02307K

Oh YA, Oh YJ, Song AY, Won JS, Song KB, Min SC (2017) Comparison of effectiveness of edible coatings using emulsions containing lemongrass oil of different size droplets on grape berry safety and preservation. LWT-Food Sci Technol 75:742–750. https://doi.org/10.1016/j.lwt.2016.10.033

Oliveira DRB, Michelon M, de Figueiredo FG, Sinigaglia-Coimbra R, Cunha RL (2016) β-Carotene-loaded nanostructured lipid carriers produced by solvent displacement method. Food Res Int 90:139–146. https://doi.org/10.1016/j.foodres.2016.10.038

Ortan A, Câmpeanu G, Dinu-Pirvu C, Popescu L (2009) Studies concerning the entrapment of *Anethum graveolens* essential oil in liposomes. Roum Biotechnol Lett 14:4411–4417

Ozturk B, Argin S, Ozilgen M, McClements DJ (2015) Nanoemulsion delivery systems for oil-soluble vitamins: Influence of carrier oil type on lipid digestion and vitamin D_3 bioaccessibility. Food Chem 187:499–506. https://doi.org/10.1016/j.foodchem.2015.04.065

Pabast M, Shariatifar N, Beikzadeh S, Jahed G (2018) Effects of chitosan coatings incorporating with free or nano-encapsulated *Satureja* plant essential oil on quality characteristics of lamb meat. Food Control 91:185–192. https://doi.org/10.1016/j.foodcont.2018.03.047

Pandita D, Kumar S, Poonia N, Lather V (2014) Solid lipid nanoparticles enhance oral bioavailability of resveratrol, a natural polyphenol. Food Res Int 62:1165–1174. https://doi.org/10.1016/j.foodres.2014.05.059

Panwar D, Panesar PS, Chopra HK (2019) Recent trends on the valorization strategies for the management of citrus by-products. Food Rev Int. https://doi.org/10.1080/87559129.2019.1695834

Paroha S, Dewangan RP, Dubey RD, Sahoo PK (2020) Conventional and nanomaterial-based techniques to increase the bioavailability of therapeutic natural products: A review. Environ Chem Lett. https://doi.org/10.1007/s10311-020-01038-1

Patel MR, San Martin-Gonzalez MF (2012) Characterization of ergocalciferol loaded solid lipid nanoparticles. J Food Sci 77:N8–N13. https://doi.org/10.1111/j.1750-3841.2011.02517.x

Paudel SK, Bhargava K, Kotturi H (2019) Antimicrobial activity of cinnamon oil nanoemulsion against *Listeria monocytogenes* and *Salmonella* spp. on melons. LWT-Food Sci Technol 111:682–687. https://doi.org/10.1016/j.lwt.2019.05.087

Pezeshky A, Ghanbarzadeh B, Hamishehkar H, Moghadam M, Babazadeh A (2016) Vitamin A palmitate-bearing nanoliposomes: Preparation and characterization. Food Biosci 13:49–55. https://dspace.tbzmed.ac.ir:8080/xmlui/handle/123456789/47117

Pinheiro AC, Coimbra MA, Vicente AA (2016) *In vitro* behaviour of curcumin nanoemulsions stabilized by biopolymer emulsifiers–Effect of interfacial composition. Food Hydrocoll 52:460–467. https://doi.org/10.1016/j.foodhyd.2015.07.025

Pinilla CMB, Brandelli A (2016) Antimicrobial activity of nanoliposomes co-encapsulating nisin and garlic extract against Gram-positive and Gram-negative bacteria in milk. Innov Food Sci Emerg Technol 36:287–293. https://doi.org/10.1016/j.ifset.2016.07.017

Piran P, Kafil HS, Ghanbarzadeh S, Safdari R, Hamishehkar H (2017) Formulation of menthol-loaded nanostructured lipid carriers to enhance its antimicrobial activity for food preservation. Adv Pharm Bull 7(2):261–268. https://doi.org/https://doi.org/10.15171/apb.2017.031

Pongsumpun P, Iwamoto S, Siripatrawan U (2020) Response surface methodology for optimization of cinnamon essential oil nanoemulsion with improved stability and antifungal activity. Ultrason Sonochem. https://doi.org/10.1016/j.ultsonch.2019.05.021

Porzio MA (2007) Flavor delivery and product development. Food Technol 61(1):22–29

Prakash A, Vadivel V, Rubini D, Nithyanand P (2019) Antibacterial and antibiofilm activities of linalool nanoemulsions against Salmonella Typhimurium. Food Biosci 28:57–65

Prakash A, Baskaran R, Vadivel V (2020) Citral nanoemulsion incorporated edible coating to extend the shelf life of fresh cut pineapples. LWT-Food Sci Technol. https://doi.org/10.1016/j.lwt.2019.108851

Prombutara P, Kulwatthanasal Y, Supaka N, Sramala I, Chareonpornwattana S (2012) Production of nisin-loaded solid lipid nanoparticles for sustained antimicrobial activity. Food Control 24(1):184–190. https://doi.org/10.1016/j.foodcont.2011.09.025

Pyo SM, Müller RH, Keck CM (2017) Encapsulation by nanostructured lipid carriers. In: Jafari SM (ed) Nanoencapsulation technologies for the food and nutraceutical industries. Academic Press, Cambridge, pp 114–137

Qian C, Decker EA, Xiao H, McClements DJ (2012) Nanoemulsion delivery systems: Influence of carrier oil on β-carotene bioaccessibility. Food Chem 135(3):1440–1447. https://doi.org/10.1016/j.foodchem.2012.06.047

Radhakrishnan R, Kulhari H, Pooja D, Gudem S, Bhargava S, Shukla R, Sistla R (2016) Encapsulation of biophenolic phytochemical EGCG within lipid nanoparticles enhances its stability and cytotoxicity against cancer. Chem Phys Lipids 198:51–60. https://doi.org/10.1016/j.chemphyslip.2016.05.006

Radi M, Akhavan-Darabi S, Akhavan HR, Amiri S (2018) The use of orange peel essential oil microemulsion and nanoemulsion in pectin-based coating to extend the shelf life of fresh-cut orange. J Food Process Preserv. https://doi.org/10.1111/jfpp.13441

Rashidinejad A, Birch EJ, Sun-Waterhouse D, Everett DW (2016) Effect of liposomal encapsulation on the recovery and antioxidant properties of green tea catechins incorporated into a hard low-fat cheese following *in vitro* simulated gastrointestinal digestion. Food Bioprod Process 100:238–245. https://doi.org/10.1016/j.fbp.2016.07.005

Ravanfar R, Tamaddon AM, Niakousari M, Moein MR (2016) Preservation of anthocyanins in solid lipid nanoparticles: Optimization of a microemulsion dilution method using the placket–burman and box–behnken designs. Food Chem 199:573–580. https://doi.org/10.1016/j.foodchem.2015.12.061

Raviadaran R, Ng MH, Manickam S, Chandran D (2020) Ultrasound-assisted production of palm oil-based isotonic W/O/W multiple nanoemulsion encapsulating both hydrophobic tocotrienols and hydrophilic caffeic acid with enhanced stability using oil-based sucragel. Ultrason Sonochem. https://doi.org/10.1016/j.ultsonch.2020.104995

Rehman A, Jafari SM, Tong Q, Karim A, Mahdi AA, Iqbal MW, Aadil RM, Ali A, Manzoor MF (2020) Role of peppermint oil in improving the oxidative stability and antioxidant capacity of borage seed oil-loaded nanoemulsions fabricated by modified starch. Int J Biol Macromol 153:697–707. https://doi.org/10.1016/j.ijbiomac.2020.02.292

Righeschi C, Bergonzi MC, Isacchi B, Bazzicalupi C, Gratteri P, Bilia AR (2016) Enhanced curcumin permeability by SLN formulation: the PAMPA approach. LWT-Food Sci Technol 66:475–483. https://doi.org/10.1016/j.lwt.2015.11.008

Roy A, Guha P (2018) Formulation and characterization of betel leaf (*Piper betle* L.) essential oil based nanoemulsion and its *in vitro* antibacterial efficacy against selected food pathogens. J Food Process Preserv. https://doi.org/https://doi.org/10.1111/jfpp.13617

Saini A, Panesar PS (2020) Beneficiation of food processing by-products through extraction of bioactive compounds using neoteric solvents. LWT 134:110263

Saini A, Panesar PS, Bera MB (2019a) Valorization of fruits and vegetables waste through green extraction of bioactive compounds and their nanoemulsions-based delivery system. Bioresour Bioprocess. https://doi.org/10.1186/s40643-019-0261-9

Saini A, Panesar PS, Bera MB (2019b) Comparative study on the extraction and quantification of polyphenols from citrus peels using maceration and ultrasonic technique. Curr Res Nutr Food Sci 7(3):678–685. http://dx.doi.org/https://doi.org/10.12944/CRNFSJ.7.3.08

Saini A, Panesar PS, Bera MB (2020) Valuation of *Citrus reticulata* (kinnow) peel for the extraction of lutein using ultrasonication technique. Biomass Convers Biorefin. https://doi.org/10.1007/s13399-020-00605-4

Sarabandi K, Jafari SM (2020) Effect of chitosan coating on the properties of nanoliposomes loaded with flaxseed-peptide fractions: Stability during spray-drying. Food Chem. https://doi.org/10.1016/j.foodchem.2019.125951

Sarkar P, Choudhary R, Panigrahi S, Syed I, Sivapratha S, Dhumal CV (2017) Nano-inspired systems in food technology and packaging. Environ Chem Lett 15(4):607–622. https://doi.org/10.1007/s10311-017-0649-8

Savadkouhi NR, Ariaii P, Langerodi MC (2020) The effect of encapsulated plant extract of hyssop (*Hyssopus officinalis* L.) in biopolymer nanoemulsions of *Lepidium perfoliatum* and *Orchis mascula* on controlling oxidative stability of soybean oil. Food Sci Nutr 8(2):1264. https://doi.org/https://doi.org/10.1002/fsn3.1415

Schoener AL, Zhang R, Lv S, Weiss J, McClements DJ (2019) Fabrication of plant-based vitamin D_3-fortified nanoemulsions: influence of carrier oil type on vitamin bioaccessibility. Food Funct 10(4):1826–1835. https://doi.org/10.1039/C9FO00116F

Schultz M, Monnier V (2013) Composition and method for manufacturing clear beverages comprising nanoemulsions with quillaja saponins. US Patent Application No. 14/383,645

Shafaei N, Barkhordar SMA, Rahmani F, Nabi S, Idliki RB, Alimirzaei M, Karimi E, Oskoueian E (2020) Protective effects of *Anethum graveolens* seed's oil nanoemulsion against cadmium-induced oxidative stress in mice. Biol Trace Elem Res. https://doi.org/10.1007/s12011-020-02093-z

Shangguan M, Lu Y, Qi J, Han J, Tian Z, Xie Y, Hu F, Yuan H, Wu W (2014) Binary lipids based nanostructured lipid carriers for improved oral bioavailability of silymarin. J Biomater Appl 28(6):887–896. https://doi.org/10.1177/0885328213485141

Shehzad Q, Rehman A, Ali A, Khan S, Mahdi AA, Karim A, Khan S, Yang F, Xia W (2019) Preparation and characterization of resveratrol loaded nanoemulsions. Int J Agric Innov Res 8(4):300–310

Shishir MRI, Xie L, Sun C, Zheng X, Chen W (2018) Advances in micro and nano-encapsulation of bioactive compounds using biopolymer and lipid-based transporters. Trends Food Sci Technol 78:34–60. https://doi.org/10.1016/j.tifs.2018.05.018

Shokri S, Parastouei K, Taghdir M, Abbaszadeh S (2020) Application an edible active coating based on chitosan-*Ferulago angulata* essential oil nanoemulsion to shelf life extension of rainbow trout fillets stored at 4 °C. Int J Biol Macromol 153:846–854. https://doi.org/10.1016/j.ijbiomac.2020.03.080

Silva HD, Cerqueira MÂ, Donsì F, Pinheiro AC, Ferrari G, Vicente AA (2020) Development and characterization of lipid-based nanosystems: effect of interfacial composition on nanoemulsion behavior. Food Bioprocess Tech 13(1):67–87. https://doi.org/10.1007/s11947-019-02372-1

Silva HD, Cerqueira MÂ, Vicente AA (2012) Nanoemulsions for food applications: development and characterization. Food Bioprocess Tech 5(3):854–867. https://doi.org/10.1007/s11947-011-0683-7

Soleimanian Y, Goli SAH, Varshosaz J, Sahafi SM (2018) Formulation and characterization of novel nanostructured lipid carriers made from beeswax, propolis wax and pomegranate seed oil. Food Chem 244:83–92. https://doi.org/10.1016/j.foodchem.2017.10.010

Sow LC, Tirtawinata F, Yang H, Shao Q, Wang S (2017) Carvacrol nanoemulsion combined with acid electrolysed water to inactivate bacteria, yeast *in vitro* and native microflora on shredded cabbages. Food Control 76:88–95. https://doi.org/10.1016/j.foodcont.2017.01.007

Sun M, Nie S, Pan X, Zhang R, Fan Z, Wang S (2014) Quercetin-nanostructured lipid carriers: characteristics and anti-breast cancer activities *in vitro*. Colloid Surf B Biointerfaces 113:15–24. https://doi.org/10.1016/j.colsurfb.2013.08.032

Sungpud C, Panpipat W, Chaijan M, Sae Yoon A (2020) Techno-biofunctionality of mangostin extract-loaded virgin coconut oil nanoemulsion and nanoemulgel. PLoS ONE. https://doi.org/10.1371/journal.pone.0227979

Surh J, Decker EA, McClements DJ (2017) Utilisation of spontaneous emulsification to fabricate lutein-loaded nanoemulsion-based delivery systems: Factors influencing particle size and colour. Int J Food Sci Tech 52(6):1408–1416. https://doi.org/10.1111/ijfs.13395

Swathy JS, Mishra P, Thomas J, Mukherjee A, Chandrasekaran N (2018) Antimicrobial potency of high-energy emulsified black pepper oil nanoemulsion against aquaculture pathogen. Aquaculture 491:210–220. https://doi.org/10.1016/j.aquaculture.2018.03.045

Tan C, Feng B, Zhang X, Xia W, Xia S (2016) Biopolymer-coated liposomes by electrostatic adsorption of chitosan (chitosomes) as novel delivery systems for carotenoids. Food Hydrocoll 52:774–784. https://doi.org/10.1016/j.foodhyd.2015.08.016

Tan C, Xue J, Abbas S, Feng B, Zhang X, Xia S (2014) Liposome as a delivery system for carotenoids: comparative antioxidant activity of carotenoids as measured by ferric reducing antioxidant power, DPPH assay and lipid peroxidation. J Agric Food Chem 62(28):6726–6735. https://doi.org/10.1021/jf405622f

Tang SY, Sivakumar M (2013) A novel and facile liquid whistle hydrodynamic cavitation reactor to produce submicron multiple emulsions. AIChE J 59:155–167. https://doi.org/10.1002/aic.13800

Taştan Ö, Pataro G, Donsì F, Ferrari G, Baysal T (2017) Decontamination of fresh-cut cucumber slices by a combination of a modified chitosan coating containing carvacrol nanoemulsions and pulsed light. Int J Food Microbiol 260:75–80. https://doi.org/10.1016/j.ijfoodmicro.2017.08.011

Tavakoli H, Hosseini O, Jafari SM, Katouzian I (2018) Evaluation of physicochemical and antioxidant properties of yogurt enriched by olive leaf phenolics within nanoliposomes. J Agric Food Chem 66(35):9231–9240. https://doi.org/10.1021/acs.jafc.8b02759

Taylor T, Bruce BD, Weiss J, Davidson PM (2008) *Listeria Monocytogenes* and *Escherichia coli* O157: H7 inhibition *in vitro* by liposome-encapsulated nisin and ethylene diaminetetraacetic acid. J Food Saf 28(2):183–197. https://doi.org/10.1111/j.1745-4565.2008.00113.x

Teixé-Roig J, Oms-Oliu G, Ballesté-Muñoz S, Odriozola-Serrano I, Martín-Belloso O (2020) Improving the *in vitro* bioaccessibility of β-carotene using pectin added nanoemulsions. Foods. https://doi.org/10.3390/foods9040447

Thamphiwatana S, Fu V, Zhu J, Lu D, Gao W, Zhang L (2013) Nanoparticle-stabilized liposomes for pH-responsive gastric drug delivery. Langmuir 29(39):12228–12233. https://doi.org/10.1021/la402695c

Ting Y, Jiang Y, Ho CT, Huang Q (2014) Common delivery systems for enhancing *in vivo* bioavailability and biological efficacy of nutraceuticals. J Funct Foods 7:112–128. https://doi.org/10.1016/j.jff.2013.12.010

Tsuchido Y, Sasaki Y, Sawada SI, Akiyoshi K (2015) Protein nanogelation using vitamin B_6- bearing pullulan: effect of zinc ions. Polym J 47:201–205. https://doi.org/10.1038/pj.2014.120

Uraiwan K, Satirapipathkul C (2016) The entrapment of vitamin E in nanostructured lipid carriers of rambutan seed fat for cosmeceutical uses. Key Eng Mater 675–676:77–80. https://doi.org/10.4028/www.scientific.net/KEM.675-676.77

Walia N, Chen L (2020) Pea protein based vitamin D nanoemulsions: fabrication, stability and *in vitro* study using Caco-2 cells. Food Chem. https://doi.org/10.1016/j.foodchem.2019.125475

Walia N, Dasgupta N, Ranjan S, Ramalingam C, Gandhi M (2019) Food-grade nanoencapsulation of vitamins. Environ Chem Lett 17(2):991–1002. https://doi.org/10.1007/s10311-018-00855-9

Wandrey C, Bartkowiak A, Harding SE (2009) Materials for encapsulation In: Zuidam NJ Nedovic VA (eds) Encapsulation technologies for food active ingredients and food processing, Springer, The Netherlands, pp 31–100

Wang J, Wang H, Zhu R, Liu Q, Fei J, Wang S (2015) Anti-inflammatory activity of curcumin loaded solid lipid nanoparticles in IL-1β transgenic mice subjected to the lipopolysaccharide-induced sepsis. Biomaterials 53:475–483. https://doi.org/10.1016/j.biomaterials.2015.02.116

Wen Z, You X, Jiang L, Liu B, Zheng Z, Pu Y, Cheng B (2011) Liposomal incorporation of rose essential oil by a supercritical process. Flavour Frag J 26(1):27–33. https://doi.org/10.1002/ffj.2012

Wooster TJ, Andrews HF, Sanguansri P (2017) Nanoemulsions. U.S. Patent Application No. 15/595,232

Wu G, Li J, Yue J, Zhang S, Yunusi K (2018) Liposome encapsulated luteolin showed enhanced antitumor efficacy to colorectal carcinoma. Mol Med Rep 17(2):2456–2464. https://doi.org/10.3892/mmr.2017.8185

Wu J, Liu H, Ge S, Wang S, Qin Z, Chen L, Zheng Q, Liu Q, Zhang Q (2015) The preparation, characterization, antimicrobial stability and *in vitro* release evaluation of fish gelatin films incorporated with cinnamon essential oil nanoliposomes. Food Hydrocoll 43:427–435. https://doi.org/10.1016/j.foodhyd.2014.06.017

Wu JE, Lin J, Zhong Q (2014) Physical and antimicrobial characteristics of thyme oil emulsified with soluble soybean polysaccharide. Food Hydrocoll 39:144–150. https://doi.org/10.1016/j.foodhyd.2013.12.029

Xiong Y, Li S, Warner RD, Fang Z (2020) Effect of oregano essential oil and resveratrol nanoemulsion loaded pectin edible coating on the preservation of pork loin in modified atmosphere packaging. Food Control. https://doi.org/10.1016/j.foodcont.2020.107226

Xue J, Davidson PM, Zhong Q (2015) Antimicrobial activity of thyme oil co-nanoemulsified with sodium caseinate and lecithin. Int J Food Microbiol 210:1–8. https://doi.org/10.1016/j.ijfoodmicro.2015.06.003

Yazgan H, Ozogul Y, Kuley E (2019) Antimicrobial influence of nanoemulsified lemon essential oil and pure lemon essential oil on food-borne pathogens and fish spoilage bacteria. International J Food Microbiol. https://doi.org/10.1016/j.ijfoodmicro.2019.108266

Yoo JM, Kim SY, Cho EA, Cho EH, Choi SJ, Jeong YJ, Ha BJ, Chae HJ (2010) Stabilization of astaxanthin using nanoliposome. KSBB J 25(2):130–136

Zabihi A, Akhondzadeh Basti A, Amoabediny G, Khanjari A, Tavakkoly Bazzaz J, Mohammadkhan F, Hajjar Bargh A, Vanaki E (2017) Physicochemical characteristics of nanoliposome garlic (*Allium sativum* L.) essential oil and its antibacterial effect on *Escherichia coli* O157:H7. J Food Qual Hazards Control 4:24–28

Zamani-Ghaleshahi A, Rajabzadeh G, Ezzatpanah H, Ghavami M (2020) Biopolymer coated nanoliposome as enhanced carrier system of perilla oil. Food Biophys. https://doi.org/10.1007/s11483-019-09621-y

Zambrano-Zaragoza ML, Quintanar-Guerrero D, Del Real A, González-Reza RM, Cornejo-Villegas MA, Gutiérrez-Cortez E (2020) Effect of nano-edible coating based on beeswax solid lipid nanoparticles on strawberry's preservation. Coatings. https://doi.org/10.3390/coatings10030253

Zardini A, Mohebbi M, Farhoosh R, Bolurian S (2017) Production and characterization of nanostructured lipid carriers and solid lipid nanoparticles containing lycopene for food fortification. J Food Sci Tech 55:287–298. https://doi.org/10.1007/s13197-017-2937-5

Zariwala MG, Elsaid N, Jackson TL, Corral López F, Farnaud S, Somavarapu S, Renshaw D (2013) A novel approach to oral iron delivery using ferrous sulphate loaded solid lipid nanoparticles. Int J Pharm 456(2):400–407. https://doi.org/10.1016/j.ijpharm.2013.08.070

Zhang L, Hayes DG, Chen G, Zhong Q (2013) Transparent dispersions of milk-fat-based nanostructured lipid carriers for delivery of β-carotene. J Agric Food Chem 61(39):9435–9443. https://doi.org/10.1021/jf403512c

Zhang Y, Zhong Q (2020) Physical and antimicrobial properties of neutral nanoemulsions self-assembled from alkaline thyme oil and sodium caseinate mixtures. Int J Biol Macromol 148:1046–1052. https://doi.org/10.1016/j.ijbiomac.2020.01.233

Zhao C, Wei L, Yin B, Liu F, Li J, Liu X, Wang J, Wang Y (2020) Encapsulation of lycopene within oil-in-water nanoemulsions using lactoferrin: Impact of carrier oils on physicochemical stability and bioaccessibility. Int J Biol Macromol. https://doi.org/10.1016/j.ijbiomac.2020.03.063

Zhao Q, Ho CT, Huang Q (2013) Effect of ubiquinol-10 on citral stability and off-flavor formation in oil-in-water (O/W) nanoemulsions.

J Agric Food Chem 61(31):7462–7469. https://doi.org/10.1021/jf4017527

Zou LQ, Liu W, Liu WL, Liang RH, Li T, Liu CM, Cao YL, Niu J, Liu Z (2014a) Characterization and bioavailability of tea polyphenol nanoliposome prepared by combining an ethanol injection method with dynamic high-pressure microfluidization. J Agric Food Chem 62(4):934–941. https://doi.org/10.1021/jf402886s

Zou LQ, Peng SF, Liu W, Gan L, Liu WL, Liang RH, Liu CM, Niu J, Cao YL, Liu Z, Chen X (2014b) Improved *in vitro* digestion stability of (−)-epigallocatechin gallate through nanoliposome encapsulation. Food Res Int 64:492–499. https://doi.org/10.1016/j.foodres.2014.07.042

Zuidam NJ, Shimoni E (2009) Overview of microencapsulates for use in food products or processes and methods to make them. In: Zuidam NJ, Nedovic VA (eds) Encapsulation technologies for food active ingredients and food processing. Springer, Berlin, pp 3–31