Chapter 13
Application of Encapsulation Technology in the Agri-Food Sector

Marko Vinceković and Slaven Jurić

1 Introduction Into the Encapsulation Technology to the Agri-Food-Bio Sciences

Encapsulation might be defined as a process of substance (*internal phase*, *payload*, or *payload phase*) insertion into another substance (*membrane*, *shell*, *capsule*, *carrier material*, *external phase*, *wall,* or *matrix*) (Vinceković et al. 2021; Nedović et al. 2011). Throughout the encapsulation process, various sizes of particles can be produced, from a few nm (nanoparticles) to a few mm (microparticles) (Lengyel et al. 2019). The encapsulation technology was first introduced to the area of biotechnology to increase the efficiency of products. The developed technology became huge interest in the other areas like pharmaceuticals and cosmetics industry, as well as agricultural and food industry.

There are several advantages towards using the encapsulation process in agri-food-bio sciences: (i) easier handling (*e.g.* converting liquid ingredients into a powder form, which can be completely free of certain impurities with better rheological and sensory (smell/odor) properties, (ii) immobilization of encapsulated material for various production processes, (iii) better stability of encapsulated material during technological preparation and in the final product (*i.e.* significant reduction of volatiles evaporation, reduced degradation/decomposition and reduction of reaction with other ingredients in the complex matrix of the product), (iv) increase the safety and security (*e.g.* reduced flammability and explosive behavior of volatile compounds and easier handling), (v) improving visible and textural effects (visual signs) in the final product (cosmetic, food and agricultural industry), (vi) tunning the properties of encapsulated material (particle size distribution, structure, solubility in organic and inorganic solvents, color), (vii) time adjustment of the release of

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encapsulated material which may be activated under certain conditions or with the ingredients of a complex product system or by the action of external factors (Jurić et al. 2020a).

In addition to the above advantages, encapsulation processes have certain disadvantages, as (i) increasing the costs of upscaling the encapsulation process, (ii) the industrial production and/or supply chain process are complex, (iii) the final appearance of the product is not in line with customer expectations (visually or sensory does not meet customer criteria) products, and this is especially problematic in the food production sector, (iv) stability problems of prepared nano- and microparticle formulations during storage, transport and application in certain complex system products (Vinceković et al. 2021). Despite these shortcomings mentioned, encapsulation technology is increasingly being advanced and developed and continuously used as a process in the preparation of new products in the fields of agriculture, food technology, cosmetics, and nutraceuticals.

The encapsulation technology applies to the food industry as a useful tool to improve the delivery of bioactive compounds (*e.g.* antioxidants, minerals, vitamins, phytosterols, lutein, fatty acids, lycopene, esters, aromas, colors) and living cells (*e.g.* probiotics, yeast) in real food products (Jurić et al. 2021; Mrkonjić Fuka et al. 2021; Belščak-Cvitanović et al. 2017; Vos et al. 2010). Furthermore, there is an increasing trend towards using encapsulation technology for agricultural purposes to increase the viability and to control the delivery of living microorganisms into the field. These methods proved efficient and superior to the other formulations in terms of living organisms' protection against the harsh environment (Jurić et al. 2020c; Vinceković et al. 2016). The encapsulation process can be applied for the production of particles loaded with biological and chemical agents as an advanced tool for ecological and sustainable plant production. Encapsulation in biopolymer matrices has been recognized as an effective method for the controlled release of agents used for plant protection and nutrition (Jurić et al. 2019, 2020b). In the cosmetic industry encapsulation process have been proposed to increase the stability of the material, to protect it against degradation, and also to direct and control the release of encapsulated material used in cosmetic products (Casanova and Santos 2016).

The stability of encapsulated compounds mainly depends on a combination of environmental and chemical factors (*i.e.* pH, metal ions, light, high temperatures, enzymes, and oxygen) (Mahdavee Khazaei et al. 2014). In Table 13.1 we have outlined some of the recently used stabilization techniques and carriers for encapsulation of natural pigments. Usually, with regards to the encapsulation of various ingredients, research papers deal with the fabrication and development of new production methods but worryingly the research on the inclusion of encapsulated material into *e.g.* real food products is still scarce (Jurić et al. 2020a). Due to the stability issues under environmental conditions during product manufacturing and later storage, the incorporation of particles loaded with active ingredients into final products is still extremely challenging. Even though encapsulation is always advancing and represents an effective way to protect encapsulated material, incorporation of nano- and microparticles into products is still not investigated enough (Jurić et al. 2020a).

Table 13.1 Stabilization techniques and materials used for the protection of water and lipid-soluble natural pigments (Adapted from Jurić et al. 2020a, 2020b, 2020c)

Pigment	Co-pigment/Wall materials	Stabilization technique	Reference
Water soluble			
Anthocyanins	Dairy proteins	Complexation	Chung et al. (2015); He et al. (2016)
	Pectins	Complexation	Lin et al. (2016)
	Whey proteins and pectins	Complexation/physical entrapment	Arroyo-Maya et al. (2016)
	Gum arabic	Complexation	Chung et al. (2016a); Guan and Zhong (2015)
	β-cyclodextrins	Molecular inclusion	Howard et al. (2013); Fernandes et al. (2013)
	Green tea extracts	Complexation	Chung et al. (2016b)
	Ferric ion	Chelation	Tachibana et al. (2014)
	Stearic acid	Lyophilization	Cruz et al. (2015)
	Oleic acids	Lyophilization	Cruz et al. (2016)
	Different fatty acids	Lyophilization	Cruz et al. (2017, 2018); Luo et al. (2017); Yang et al. (2019)
	Montmorillonite	Hybridization	Kohno et al. (2009)
	Methoxyl pectin	Ionic gelation	de Moura et al. (2018)
	Sodium alginate	Ionic gelation	da Silva Carvalho et al. (2019)
	Polyethylene glycol (PEG)	Ionic gelation	Santos et al. (2013)
	Alginate	Ionic gelation	Belščak-Cvitanović et al. (2016)
	Pectin amide	Ionic gelation	Oidtmann et al. (2012)
	Whey protein isolate	Microemulsions	Oidtmann et al. (2012)
	Maltodextrin, pectin amide	Spray drying	Oidtmann et al. (2012)
	Glycerol mono-oleate, soy Lecithin, maltodextrin, poloxamer 338	Spray drying	Ravanfar et al. (2018)
	Supercritical carbon dioxide	Liposomes	Zhao et al. (2017)
Betalains	Sucrose	Co-crystallization	Karangutkar and Ananthanarayan (2020)
	Sodium alginate, sodium alginate-bovine serum	Ionic gelation	Otálora et al. (2016)
	Rapeseed oil, guar gum, xanthan gum	Double emulsions	Kaimainen et al. (2015)
Lipid Soluble			
Carotenoids	Whey protein concentrate, gum arabic	Spray drying	Chuyen et al. (2019)
β-carotene	Wheat gluten nanoparticles, wheat gluten nanoparticle-xanthan gum	Pickering emulsion	Fu et al. (2019)

(continued)

Table 13.1 (continued)

Pigment	Co-pigment/Wall materials	Stabilization technique	Reference
	Maltodextrin, gum arabic, chitosan, gelatin	Spray drying	Bonilla-Ahumada et al. (2018)
	Native and hydrolyzed Pinhao starches	Freeze-drying	da Silva Carvalho et al. (2019)
Lycopene	Gelatin, sucrose	Spray drying	Shu et al. (2006)
	Lecithin, α-tocopherol	Supercritical antisolvent co-precipitation (SAS)	Cheng et al. (2017)
Lutein	Gelatin, gum arabic	Coacervation	Qv et al. (2011)
Chlorophylls	Polycaprolactone	Microfluidic emulsification	Hsiao et al. (2020)
	Gum arabic, maltodextrin	Spray drying	Kang et al. (2019)
	Whey protein isolate	Spray drying	Zhang et al. (2020)

2 Classification of Next-Generation Biopolymer-Based Carriers as Sustainable Materials

Research is nowadays more focused on the investigation of alternative carriers such as biopolymers. Biodegradable polymers are suitable materials for the production of NPs because of their abundance, relative stability, and durability throughout the encapsulation processes. One of the most important advantages of encapsulation in biopolymeric particles is also high food compatibility and safety which is connected with the availability of polysaccharides, proteins, and lipids (Fathi et al. 2021). Biopolymeric carriers are generally easily prepared from natural biodegradable polymers. These types of materials are usually used because they are generally regarded as safe for the consumer and environment. Also, prepared particles have superior properties especially considering controlled and targeted release (Jana et al. 2020). Biopolymeric particles are usually spherical with some deviations. It is possible to distinguish two types of particles, the *reservoir* type, and the *matrix* type. The reservoir type (*capsule*) has a shell around the bioactive component (*filler*). These types can further be divided into a single-core/mono-core or a core-shell type. The release of the payload from reservoirs can be achieved via the application of force (pressure) or under specific conditions which are generally resulting in capsule breakage. Poly- or multiple-core type particles have several reservoir chambers loaded with encapsulated material in a single particle (Vinceković et al. 2021). In the matrix type of particles, the payload is usually dispersed over the biopolymer matrix carrier and it can be in the form of homogeneously dispersed small droplets or it can be adsorbed on the surface.

Currently, various materials of different origins and properties are being used for the encapsulation process either in solid, liquid, or gaseous forms. Materials used in the production of carrier systems can be divided into three groups as proteins, polysaccharides, and lipids (Fig. 13.1). Biopolymer carriers can be prepared in various

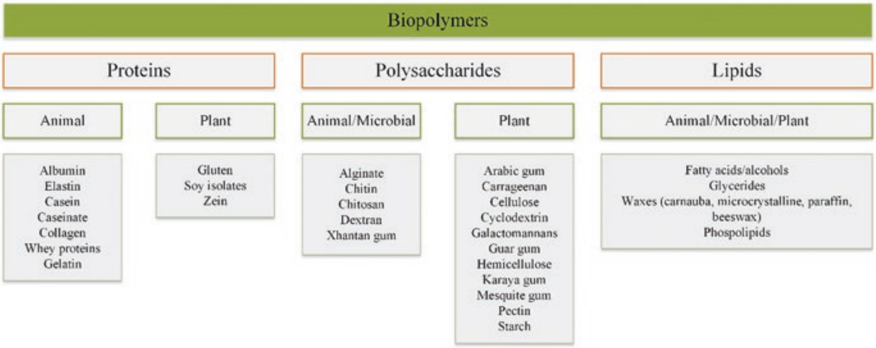


Fig. 13.1 Major natural biomolecules groups which are most often used in the preparation of nanosized carriers

shapes (films, spheres, irregular particles), or structures (compact or porous, amorphous or crystalline, rubbery or glassy) which depends mainly on the type of payload and application (Madene et al. 2006). Encapsulation in biopolymeric carrier systems is continuously developed and mostly advances to improve physicochemical, functional, and release properties while keeping in mind cost-effectiveness and the use of environmentally friendly material throughout the process (Lozano-Vazquez et al. 2015). The chosen material for the production depends on the purpose of encapsulation and final application. Generally, there are a couple of aims that are to be considered when choosing the right material for the encapsulation process: (i) the improvement of shelf life, (ii) type of encapsulation method, (iii) masking of taste or aroma, (iv) easier handling, (v) controlled and/or targeted release, (vi) improvement of appearance. Chosen materials for biopolymeric particle production are required to have several of the following requirements (Desai and Park 2005a). Furthermore, carriers should not react with a component which is to be encapsulated and should have good rheological properties and behavior even at very high concentration. Also, it should not release the encapsulated component during the storage or transport, provide maximal protection against environmental conditions, and should be completely solvent-free or from any other material used during encapsulation under drying or other desolvating conditions. Concerning the economical aspect, encapsulation material should be inexpensive, available in large quantities, and of constant quality (Desai and Park 2005b).

3 Modern Nanocarrier Systems

When considering the use of desired nanocarrier system, few basic points need to be considered. The main point is to take into the account type of used payload, consider its physicochemical stability, consider the overall sustainability of the production process, and possible health risks (Fathi et al. 2021). There are carrier systems that can be considered to be used in agri-food sectors and these include:

(i) *Nanofibers* are used due to their desirable properties for encapsulation of various payload materials. They are usually lightweight with small diameters and have controllable pore structures with a high surface-to-volume ratio (Vinceković et al. 2021).

(ii) *Nanohydrogels* are nanosized networks of chemically/physically cross-linked polymers consisted of chains that are hydrophilic or amphiphilic. They are three-dimensional biocompatible materials with a large amount of water content. For delivery applications, few key properties are necessary: high water content/swellability, biocompatibility, and adjustable chemical/mechanical properties. Hydrogels can retain a large quantity of water or biological fluid without disturbing their basic polymeric chain structure. Hydrogels prepared from natural polymers have drawn huge attention due to their applications in pharmacy, agriculture, medicine, tissue engineering, cancer therapy, and drug delivery (Akram and Hussain 2017; Khoee and Asadi 2016).

(iii) *Nanoemulsions* are kinetically stable liquid-in-liquid dispersions with droplet sizes in the range of 100 nm. They are characterized by high surface area per volume, robust stability, optically transparent appearance, and tunable rheology. Nanoemulsions are applicable in different areas from drug delivery, food production, agriculture, cosmetics, pharmaceuticals, to material synthesis (Gupta et al. 2016).

(iv) *Nanostructured lipid carriers* are delivery systems composed of both solid and liquid lipids as core matrices. These types of carriers have advantages for drug therapy over conventional carriers. These include higher solubility, increased storage stability, better permeability, and bioavailability, decreased adverse effects, prolonged half-life, and tissue-targeted delivery (Nie et al. 2020).

(v) *Bionanocrystals* are especially interesting due to their unique properties and have received considerable attention for the delivery of bioactive compounds. They are biocompatible, rigid, biodegradable, easy to modify, and are renewable (produced from food and agriculture waste) (Koshani and Madadlou 2018). For the food industry, especially are interesting starch, chitin, and cellulose nanocrystalline particles. They are considered promising contenders for the fabrication of reinforced, biodegradable carrier systems (Kasiri and Fathi 2018; Hao et al. 2018).

Despite many advantages to the nanocarrier systems, some problems are in the future to be overcome. These include (i) aggregation and adhesion of particles, (ii) special storage conditions and limited stability time of prepared formulations, (iii) difficulties in encapsulating some payloads of different hydrophilic properties in the same matrix, (iv) difficulties in regulating the polydispersity of particles (Vinceković et al. 2021).

To choose the optimal encapsulation method and the process of production of particles several things are needed to be considered. Mainly the type of material and encapsulated component because this is determinant when regarding pore size, payload size, molecular weight, solubility in the carrier, the volumetric size of the carrier, and complex interactions between the payload and the carrier since this will govern the release mechanisms. Knowledge of this can significantly increase efficiency, loading capacity, and release properties which are the most important parameters (Panyam et al. 2004).

4 Encapsulation Technology in Agriculture – Present and Future

The encapsulation technology is widely used in different sectors from medicine, agriculture, food processing through the cosmetics and pharma industries. The scientific investigation in agricultural science technology and development in the last several years have concluded the huge necessity to set up a new type of microparticles (microspheres/microcapsules) as a delivery system of biological agents (fungi, bacteria, microalgae) and chemical agents (micro-and macronutrients, esters, peptides, amino acids, hormones, pesticides, etc.) (Vinceković et al. 2016; Jurić et al. 2020a, 2020b, 2020c; Slattery et al. 2019; Pereira et al. 2019; Rodríguez Nogales et al. 2020; Tsuji 2001).

One of the most important properties of the prepared microparticle formulations (microspheres/microcapsules) is the protection of active ingredients from external conditions and their decomposition and loss of activity in a particular environment. It can also improve their bioavailability and regulate the time release of ingredients over a longer period. Also, it brings the possibility of longer storage without loss of their activity. All setup properties depend on several important factors of encapsulation technology in agricultural application: (i) various types of wall materials and their concentration, (ii) encapsulation method/encapsulation process – microparticle production, (iii) pH and temperature, (iv) particle size (especially important for the method of application in agriculture (plant protection/nutrition)), (v) type and amount of encapsulated ingredients/additives and their interaction, as well as interaction with the carrier material. All these factors have a significant influence on the microparticle loading capacity, encapsulation efficiency, swelling degree, the strength of the membrane, and the type of release mechanism of bioactive components from microparticles (Li et al. 2019).

Present scientific investigation of microparticle formulations is focused on the preparation of a complex biopolymer-based network containing several bioactive components (synergistic effect). With this intensive research, new insights were gained connected to the complex processes and mechanisms of inter-and intramolecular interactions in biopolymer-based microparticles (microspheres/microcapsules). Inter- and intramolecular interactions are influencing the structural properties of microparticles loaded with active agents (biological and chemical) which in turn have an impact on their overall properties, especially on tunning their release mechanism from microparticle formulation in a specific environment. With this knowledge, it is possible to prepare a new generation of microparticle formulations with the desired properties for different types of application in the agricultural production in the open field, greenhouse, hydroponics, or foliar approach of agroecological plant nutrition or protection and functional food production (higher level of plant metabolites) (Jurić et al. 2020a, 2020b, 2020c; Vinceković et al. 2019).

Besides the use of microparticles in agriculture, nanoparticles are also extensively utilized. Nanocapsules are vesicular systems consisted of a polymeric porous membrane that encapsulates an inner liquid core at the nanoscale. Some of the preferentially used nanoparticles are:

- Polymeric nanoparticles have superior biocompatibility and a minimal impact on non-targeted organisms. Polymeric types of nanomaterials are widely used in agriculture are polyethylene glycol, poly(epsilon-caprolactone), poly(lactide-co-glycolides), and poly (γ-glutamic acid) (Chand Mali et al. 2020; Clemente et al. 2014; Grillo et al. 2013; Ranganathan et al. 2019; Xu et al. 2013; Govender 1999).
- Silver nanoparticles are very effective against different phytopathogens (pesticide activity) with low toxicity and also in some cases, they are showing plant growth promotor properties. They are efficiently used for site-targeted delivery of important agrochemical products and diagnosis purpose tools in case of prior detection of plant diseases (Sadak 2019).
- Nano alumino-silicates, used as an effective pesticide (for different insects) in agriculture. They have very good properties: non-toxicity, biocompatibility, low costs, and environment-friendly nature (Singh et al. 2021; Mittal et al. 2020).
- Titanium dioxide nanoparticles (TiO_2) are one of the forms of titanium in the environment. TiO_2 nanoparticles are widely used for plant protection and environmental remediation because of their photoprotective and photocatalytic properties (Lyu et al. 2017).
- Carbon nanomaterials (graphene, graphene oxide, carbon dots, fullerenes, carbon nanotubes, fullerenes, carbon nanoparticles, and carbon nano-horns) have beneficial and stimulatory effects on plants *in vitro* or culture conditions. They are used to improve the seed germination process (Mukherjee et al. 2016; Husen and Siddiqi 2014).

Most nanotechnology products utilized in agriculture are used for plant protection and nutrition (nano herbicides, nano pesticides, nano fertilizers, and nanosystems for disease protection). All these systems explore the possible use of nanotechnology primarily in the process of controlled delivery of active ingredients that could be used as pesticides, herbicides, or fertilizers, but also secondary to improve the safety of the products which are applied in the process of plant protection and nutrition. Because of that, their group name is nanoagroparticles (Baker et al. 2017). In Table 13.2 we have presented examples of the application of colloidal delivery systems for essential oils in agriculture.

Viruses, fungi, and bacteria infections are causing huge economical losses in agricultural production. The preparation of nanomaterials enriched with certain components which are having specific antimicrobial properties against phytopathogenic fungi (*Colletotrichum gloeosporioides, Fusarium oxysporum, Fusarium*

Table 13.2 Examples of application of colloidal delivery systems for essential oils in agriculture (Adapted from Fathi et al. 2021)

Field of application	Essential oil delivery system	Preparation procedure	Claimed advantages
Organic farming	Carvacrol in alginate-whey protein biopolymeric particles	Emulsification and extrusion	Targeted release in chicken jejunum and ileum (Zhang et al. 2014)
Pest control	*Aegeratum conyzoides*, *Achillea fragrantissima*, and *Tagetes minuta* EOs nanoemulsions	High pressure homogenization	Higher toxicity against eggs and adults of beetle *Callosobruchus maculates* than free oils (Nenaah et al. 2015)
	Zanthoxylum rhoifolium EO in biodegradable polycaprolactone nanospheres	Nanoprecipitation of the pre-formed polymer	Significantly higher reduction of *Bemisia tabaci* eggs and nymphs compared with control (Christofoli et al. 2015)
	Carum copticum EO in myristic acid–chitosan nanogels	Self-assembly	4–8-fold higher fumigant toxicity against *Sitophilus granarius* and *Tribolium confusum* than the free oil (Ziaee et al. 2014)
	Geranium and bergamot EOs in poly(ethylene glycol) nanoparticles	Self-assembly	Higher toxicity against *Tribolium castaneum* and *Rhizopertha dominica* than free oils (Werdin González et al. 2014)
	Artemisia arborescens EO in solid lipid nanoparticles	Hot high-pressure homogenization	Reduced volatility with respect to emulsions (Lai et al. 2006)
	Lippia sidoides EO in chitosan/cashew gum nanoparticles	Spray drying of nanoemulsion	Mortality rate of *St. aegypti* larvae correlates with EO loading (Abreu et al. 2012)
Pest luring	Geraniol in chitosan/gum arabic nanoparticles	Ionic gelation method	Improved EO stability and luring effect toward whitefly *Bemisia tabaci* (de Oliveira et al. 2018)
Repellant textile	Citronella EO in chitosan/gelatin microcapsules	Complex coacervation	Higher repellant effect and lasting protection from insects compared to textiles sprayed with EO in ethanol (Specos et al. 2010)

solani, Dematophora necatrix, etc.) can be used in the plant disease protection process. Prepared cobalt and nickel ferrite nanoparticles ($CoFe_2O_4$ and $NiFe_2O_4$) are successfully tested for antimycotic activity against three plant-pathogenic fungi: *Fusarium oxysporum*, *Colletotrichum gloeosporioides,* and *Dematophora necatrix* (Sharma et al. 2017). Copper nanoparticles with chitosan and celluloses showed antifungal and antibacterial properties against *Escherichia coli, Staphylococcus* *aureus*, *Alternaria solani, Fusarium oxysporum, Klebsiella pneumoniae, Pseudomonas aeruginosa, Aspergillus niger, Aspergillus flavus, and Candida albicans.* Besides plant protection, copper nanoparticles are also used in plant nutrition (Rai et al. 2018). Copper is a micronutrient that can be found in high concentrations in chloroplasts. Almost 70% of the total Cu is found in chloroplasts. Cu has an important role in the process of synthesis of chlorophyll, other pigments and has a crucial role in the process of protein and carbohydrate metabolism (Mengel et al. 2001).

Despite the significant advantages of encapsulation technologies in the process of nano- and microparticle production, the preparation process still has several significant obstacles that must be addressed in the coming years to be able to achieve production in larger quantities:

(a) insufficient number of methods used in the characterization of micro- and nanoparticle formulations,
(b) the balance between biosafety and compatibility of wall materials,
(c) various types of active ingredients release mechanisms,
(d) stability during long-term storage at variable environmental conditions and temperatures.

Due to the abovementioned, it is necessary to conduct further research that will focus on increasing the stability of nano- and microcapsule formulations, control the uniformity of formulation sizes and release mechanisms of bioactive components in certain time intervals, testing their effectiveness on certain phytopathogenic fungi and bacteria and testing their action as new green formulations with 3 in 1 effects (plant protection, plant nutrition, and time-release mechanism). It can be concluded that from the above scientific research, technologies of encapsulation and production of nano- and microparticle formulations will more effectively promote the development in the agroecological agriculture and functional food production process.

5 Implementation of Encapsulated Material Into Final Food Products

There is a significant gap in the research with regards to the implementation of encapsulated natural pigments in real food products. Usually, with regards to this topic, research papers deal with bioactive compounds encapsulation procedures but the research on their inclusion in real food products is worryingly scarce and a couple of available examples are listed in Table 13.3.

It is important to observe the behavior of encapsulated bioactive compounds in food matrices and their influence on the sensory characteristics of food products. This would significantly advance the knowledge of ingredient behavior when considering implementation during food production.

Table 13.3 Examples of application of stabilized natural pigments in real food products (Adapted from Jurić et al. 2020a, 2020b, 2020c)

Encapsulated compounds	Compound donor	Stabilization method	Material	Functional food	References
Anthocyanin	Barberry (*Berberis vulgaris* L.)	Spray drying	Gum arabic, maltodextrin, gelatin	Jelly	Mahdavi et al. (2016)
	Black bean (*Phaseolus vulgaris* L.) coat	Molecular inclusion	β-cyclodextrin	Sport beverage	Aguilera et al. (2016)
	Grape (*Vitis vinifera* L.) skin	Spray drying	Maltodextrin	Apple puree	Lavelli et al. (2016)
	Sour cherry (*Prunus cerasus* L.) pomace extract	Freeze-drying	Whey and soy proteins	Cookies	Tumbas Šaponjac et al. (2016)
Betalains	Barbary fig (*Opuntia ficus-indica* L.)	Ionic gelation	Calcium alginate/Gelatin	Gummy candy	Otálora et al. (2019)
	Barbary fig (*Opuntia ficus-indica* L.)	Spray drying	Soluble fiber [(1–3)(1–4)-*β*-D-glucan	Extruded cereal	Ruiz-Gutiérrez et al. (2017)
	Beetroot (*Beta vulgaris* L.)	Freeze-drying	Maltodextrin	Chewing gum	Chranioti et al. (2015)
	Red beet (*Beta vulgaris* L.) extract diluted with dextrin	Thin-film hydration-sonication technique	Lecithin liposome	Gummy candy	Amjadi et al. (2018)
Carotenoids	Yellow bell pepper (*Capsicum annuum* L.)	Ultrasonic homogenization, kneading	β-cyclodextrin	Isotonic beverage	Lobo et al. (2018)
	Saffron (*Crocus sativus* L.)	Freeze-drying	Maltodextrin	Chewing gum	Chranioti et al. (2015)
Chlorophylls	Alfalfa (*Medicago sativa* L.)	Emulsification + Freeze-drying	Canola oil, glycerol monostearate, gelatin, agar	Gummy candy	Raei et al. (2017)

When considering the application of encapsulated ingredients into final food products the matrix can significantly affect its release behavior and particles physicochemical properties. Diffusion of ingredients may be affected by the presence of proteins, carbohydrates, fatty acids, pH, water activity, packaging material, and trace metals. Furthermore, physicochemical stress factors like food processing, preservation, storage, food ingredients, etc. may start the degradation and collapse of the encapsulation system making it inefficient.

There are a couple of examples (Table 13.3) that have proven to have problems when the implementation of encapsulated bioactive compounds like anthocyanins into food products have negative effects on the shape, size, and uniformity of products (*e.g.* cookies, and other dough-based products). Furthermore, protein-based coatings (encapsulation systems) might induce significant changes in the structure of dough-based products (proteins absorb water resulting in increased hardness) while the presence of an additional particulate phase can increase the fragility of dough-based products (hindering the formation of a continuous starch network).

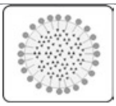
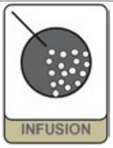
The main applications of encapsulated ingredients can be classified into four groups (Table 13.4). (1) Direct mixing with liquid foods or mixing with the food ingredients before food preparation; (2) washing the product surface with carrier systems in an aqueous dispersion; (3) infusion in porous food matrices; (4) coating with a biopolymeric layer incorporating the active ingredients delivery systems. Details about the strategies for the utilization of different colloidal systems for active ingredients like essential oils (EO) alongside the examples of application in food products are listed in Table 13.4 (Fathi et al. 2021).

Published research mainly deals with the fabrication procedures and the work on implementation into food products is scarce (even often contradicts the *in vitro* results). Thus it is important to understand the issues related to the application of encapsulated bioactive compounds (or other ingredients like microorganisms) into various food matrices. It is also necessary to investigate the behavior of carrier systems (*i.e.* protein-based) in complex food matrices alongside the influence on the sensory characteristics of final food products (Jurić et al. 2021).

6 Future Remarks

Encapsulation is becoming essential for the sustainable and economic development of various products, from agri-food to nutraceuticals. Respectively, it can resolve some problems regarding the stability of payload during industrial processing and storage. Even though still there is a significant gap when considering using this technology for a large scale production due to the limitations. Advancing the encapsulation methodology and technology these limitations could be minimized significantly. Advanced nanocarrier systems are becoming popular due to the low-cost materials necessary for their manufacturing especially when introduced to industrial-scale production.

Table 13.4 Strategies of the utilization of different colloidal systems for essential oils (EO) delivery, together with examples of application in food products (Adapted from Fathi et al. 2021)

	 **Nanoemulsions**	 **Liposomes**	 **Biopolymeric nanoparticles**
Advantages	*Active barrier with controlled release of antimicrobial, low amount needed (surface treatment), low impact on organoleptic properties*	*High efficiency of delivery through the biological membranes, additional loading of hydrophilic molecules*	*High food compatibility, several natural polysaccharides and proteins available*
Disadvantages	*Need for surfactant in formulation, high costs of nanoemulsion production*	*Limited loading of bioactives, high costs of phospholipids and of fabrication*	*Formation of particles in aqueous systems requires chemical/physical modification of hydrophilic polymers, or use of solvents for hydrophobic polymers*
	Shelf life extension of milk and quality preservation by encapsulation of thyme EO (Ben Jemaa et al. 2017) Microbial stabilization of orange and pear juices by encapsulation of carvacrol (Donsì et al. 2011) Microbiological stabilization of chicken pâté by encapsulation of oregano EO (Moraes-Lovison et al. 2017)	Microbial stabilization of tofu by clove EO encapsulation (Cui et al. 2015)	Shelf life extension in bakery products by encapsulation of thyme EO by complex coacervation (Gonçalves et al. 2017)
	Microbial stabilization of fresh lettuce by washing with oregano EO nanoemulsions (Bhargava et al. 2015) or of spinach leaves by carvacrol or eugenol nanoemulsions (Ruengvisesh et al. 2015)	–	–
	Enhancement of organoleptic properties and extension of the shelf life of trout fillets by infusion of nanoemulsions of rosemary, laurel and thyme EOs (Ozogul et al. 2017)	Preservation of minced beef by *Zataria multiflora* EO liposomes (Khosravi-Darani et al. 2016)	Reduction of lipid oxidation and microbial growth by infusion in meat patties of chitosan nanoparticles containing cinnamon EO (Ghaderi-Ghahfarokhi et al. 2017)

(continued)

Table 13.4 (continued)

COATING	Shelf life extension of rucola leaves coated with chitosan containing lemon EO nanoemulsions (Sessa et al. 2015) Microbial stabilization of green beans (Severino et al. 2014a, 2015) or broccoli florets (Severino et al. 2014b) by modified chitosan coatings containing citrus EO nanoemulsions Preservation of fresh-cut cheese by encapsulation of Oregano EO (Artiga-Artigas et al. 2017) Microbial stabilization of bread slice by an edible coating containing clove bud or oregano EO nanoemulsions (Otoni et al. 2014)	Shelf life extension and quality improvement of banana slices by a mucilage coating containing rosemary EO liposomes (Alikhani-Koupaei 2015)	Microbial stabilization of beef cutlet by spraying with a chitosan-myristic acid nanogels containing clove EO (Rajaei et al. 2017) Enhanced antimicrobial and antioxidant activity of cinnamon EO on pork by encapsulation in chitosan nanoparticles (Hu et al. 2015)

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