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## *Food Nanotechnology Applications to the Beverage Industry*

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### 11.1 Introduction

Consumer demand for food products that are not only wholesome, safe, and convenient but also provide a healthy dietary proposition is on the rise. As a consequence of this market driver, there are significant efforts in research, development, and innovation in the “functional foods” space. Functional foods are the foods considered to be a part of a normal diet and, in addition to providing basic caloric value, offer potentially enhanced nutritional attributes such as improved well-being and physical, psychological, and behavioral performances (Roberfroid, 2000). This definition is increasingly broadening, as most foods are now designed to provide added value to the consumer. Functionalization of a food matrix is generally made possible by adjusting the potency (concentration) of bioactive components naturally present in the product or by adding such components as bioactive ingredients at concentrations proven to be efficacious.

In the developed world, the busy lifestyles and calorie-rich diets of citizens have resulted in an increased incidence of lifestyle and diet-related chronic diseases, with growing public health care costs. The increased population’s understanding of the linkages between dietary choices and well-being and the government recommendations and regulations for healthier food choices have grown the need for the development of functional foods, which have now become a part of public health prevention approaches (Corbo et al., 2014). It is therefore important to continue to improve our ability to design food matrices that can deliver benefits beyond those of simple nutrition, and we need to understand how the components recognized to be bioactive can be maintained at concentrations that will be biologically significant at the time of consumption and point of delivery. One of the basic factors affecting bioefficacy is the ability of the bioactive compound to be soluble and maintain its stability during processing and storage. For example, in a water-based food system, inclusion of hydrophilic food components may be relatively straightforward, since soluble components can be easily dispersed in the continuous phase. However, processing and storage conditions may still affect their bioefficacy, for example, because of heat treatments or chemical, enzymatic, or light-induced degradation. On the other hand, the inclusion of nonpolar

components in an aqueous system can be achieved by the addition of a less polar phase, where the nonpolar components can be solubilized. In this case, the lipophilic compound is preencapsulated in a separate phase. In food emulsions, the lipophilic molecules are solubilized within the oil droplets, which are emulsified in a continuous, aqueous phase with the aid of surface-active material. Emulsification often allows for improved physicochemical properties and appearance of the product and improved storage stability of the lipophilic bioactive, aiding in preserving biological functionality as well.

In addition to emulsion droplets, many other colloidal structures have been used as delivery platforms for food bioactives. These colloidal systems, particles with diameters in the micrometer or nanometers range, are designed to remain in suspension, and they are increasingly utilized to encapsulate, stabilize, and deliver molecules with a technological or biological functionality. Among examples of colloidal systems with food applications, it is possible to include liposomal dispersions, microemulsions, protein particles, solid lipid nanoparticles, nanostructured lipid carriers, and biomolecule conjugates. Many of these systems have diameters below 100 nm, and they are often defined as nanodelivery systems. The application of nanoparticles in food has shown a great potential for the creation of innovative functional foods.

Functional beverage products can be included as a subcategory of functional foods, as they possess some unique challenges. On the one hand, they represent a great opportunity to innovate and meet the market demand for novel sensory experiences and convenience; however, they require to have a homogeneous appearance, stable physical and chemical characteristics, and a long shelf life. At times, similar beverages can be found in concentrated, diluted, or powder forms, with clear expectation for the consumer to have a similar sensory experience or similar biological functionality. Their appearance is very critical to quality as well; transparency, cloudiness, or lack of phase separation are the features that often require significant technological solutions. Products such as vitamin waters require the presence of delivery systems to protect bioactive molecules from oxidation; however, ideally, such colloidal structures should not scatter light, to maintain the optimal optical properties of the product (Mohammadi et al., 2014). Another example is the addition of active components such as omega-3 fatty acids to beverages. These compounds are prone to oxidative deterioration. Nanoencapsulation of eicosapentaenoic acid (EPA) and docosahexaenoic acids (DHA) in sodium caseinate–gum arabic complexes has the potential to stabilize these acids against oxidation, improving the ability of fortifying fruit juices with omega-3 fatty acids (Ilyasoglu & El, 2014).

A variety of products can be considered examples of functional beverages, including dairy drinks, plant-based beverages, meal replacers and supplement, fruit juices, and sport and energy drinks. Fortified dairy beverages account for a large percentage of the functional beverage category (Özer & Kirmaci, 2010). These drinks may include probiotics, prebiotics/fibers, polyphenols, peptides, sterol/stanols, minerals, vitamins, and fish oil emulsions or be whey-based and may contain fruit (i.e., smoothies). Inclusion of components with recognized biological functionality in the beverage product can easily enhance the nutritional value as well as the purchase occasion. The functional beverages category is experiencing significant market growth and innovation opportunities, also from the technological stand point, as innovative solutions are needed to enhance both sensory characteristics and the overall appeal of the product, in addition to ensuring bioefficacy of the components present. Nearly 30% of the beverages launched worldwide in 2016 claimed themselves as functional beverages and included functionalities such as vitamins, antioxidants, and protein fortification, as well as products improving energy, alertness, or gut health (Butler, 2018).

Applications of nanotechnology are of great interest in beverage systems, as nanoparticles show a great potential to be utilized as delivery systems to improve the bioefficacy of the bioactive molecules present in the formula (Gülseren et al., 2012b).

In this review, potential nanotechnological applications in beverages are summarized, with specific emphasis on delivery systems used in these applications and potential product groups, including dairy-based drinks, vegetable- and fruit-based beverages, sports and energy drinks, and alcoholic beverages. Finally, potential influence of these products on human health is reviewed based on *in vitro* and *in vivo* findings from the literature.

Over the last two decades, applications of nanotechnology were shown to provide enormous potential for innovation. Table 11.1 summarizes a series of patents published in recent years on food nanostructures and their applications.

TABLE 11.1

Patents of Application and Potential of Nanotechnology in Beverages in the Last 10 Years

Description	Encapsulated Ingredient	Publication Date, Country	Publication Number
Nanolipid particles incorporated in food products as beverages	Ethanol	November 23, 2017, USA	US2017335260A1
Gelled mixture of alginate and denatured protein that provide resistance to thermal and acidic conditions	Probiotic bacteria	October 18, 2012, USA	US2012263826A1
Hangover-alleviating beverage with added liposomes	Fat-soluble components of turmeric	April 4, 2018, Korea	KR20180033862A
Spherification based on sodium alginate and calcium lactate to incorporate in beverages	Product incorporating calcium ions	July 28, 2017, Mexico	MX2016002000A
Microencapsulation technology applied to formulate beverage granules	<i>Lycium ruthenicum</i> Murray anthocyanin	May 31, 2017, China	CN106721849A
Passion fruit flavor incorporated in beverages	Passion fruit vinegar	May 31, 2017, China	CN106721708A
Method for encapsulating one or more materials to be delivered in small capsules in beverages	Not specified	May 25, 2017, Japan	JP2017086078A
Preparation method and application of a chitosan nanoemulsion in beverage formulation	Blueberry anthocyanin	October 26, 2016, China	CN106038484A
Methods to prepare emulsions to be incorporated in ready-to-drink and liquid concentrate beverages	Not specified	September 14, 2016, China	CN105935120A
Protein-polysaccharide conjugates as nanocapsular vehicles, which, when added to a beverage, disperses to provide a clear solution	Biologically active compounds	November 15, 2012, USA	US20120288533A1
A complex coacervate delivery system that encapsulates lipophilic nutrients to include in beverages (pH 1.5–5.0)	Fish oils high in omega-3 fatty acids	July 21, 2016, USA	US2016206561A1
Two-phase beverage comprising an aqueous phase and encapsulated fruit pulp	Fruit pulp	May 13, 2010, USA	US20100119662A1
Flavor encapsulated particles incorporated in beverages	Flavor	December 24, 2009, USA	US20090317521A1
Oil-encapsulated phytosterol microparticles incorporated in beverages	Phytosterols	September 15, 2011, USA	US20110223312A1
Gelatin capsules encapsulating an aroma material that may be applied to product packaging	Aroma	March 7, 2013, USA	WO2013032631A1
Nutrient salts encapsulated with a water-insoluble chitosan-stearic acid complex to incorporate in beverages	Nutrient salts	January 19, 2012, USA	US20120015004A1
Microencapsulated delivery system incorporated onto a substrate or filter material such as those used in drip coffee makers or tea bags	Flavor- or aroma-masking agents, medicinal additives, fragrances, vitamins, colorants, homeopathic and herbal remedies, appearance and characteristic modifiers, and other ingredients	April 16, 2009, USA	US20090095164A1

(Continued)

TABLE 11.1 (Continued)

Patents of Application and Potential of Nanotechnology in Beverages in the Last 10 Years

Description	Encapsulated Ingredient	Publication Date, Country	Publication Number
<b>Complex coacervate delivery system for water-insoluble flavors that are released once product is ingested, e.g., beverages at pH range 1.5–5.0</b>	Water-insoluble flavorant	July 28, 2010, China	CN101790325A
<b>Protein-polysaccharide macromolecular complex product containing encapsulated ethyl alcohol and/or other spirits</b>	Ethyl alcohol	October 17, 2013, USA	US20130273212A1
<b>Encapsulated phospholipid oil-in-water emulsion that can be incorporated into a beverage</b>	Not specified	February 24, 2016, Australia	EP2986132A1
<b>Isolated casein micelles useful for encapsulation and delivery of compounds in beverages</b>	Hydrophobic or poorly-water-soluble biologically active compounds	December 17, 2009, USA	US20090311329A1

Source: Espacenet ([https://worldwide.espacenet.com/searchResults?ST=singleline&locale=en\\_EP&submitted=true&DB=&query=beverage+encapsulated+](https://worldwide.espacenet.com/searchResults?ST=singleline&locale=en_EP&submitted=true&DB=&query=beverage+encapsulated+)) Words: beverage AND encapsulated.

The size range below 100 nm is regarded as the domain for nanostructures, especially since, in this range, these structures tend to have novel properties (Singh et al., 2017). These properties might include improved solubility, dispersibility, toxicity, and optic and thermodynamic characteristics (Singh et al., 2017). Such changes do not take place immediately at 100 nm, and depending on the system in question, the improvements can be observed below or above this limit, as the properties will be structure- and material-specific (Kreyling et al., 2010).

Novel food applications with promising value will arise from the development of food nanostructures (Sanguansri & Augustin, 2006). The presence of nanostructures may alter the food matrix, compared with if the same components were present in isolation, and this could mean changes to the microstructure or rheological or functional attributes. In general, these structures show assembly (i.e., aggregation) and disruption (i.e., digestion) properties quite different from those of the single components. Furthermore, the physicochemical characteristics are enhanced compared with macroscale dispersions (Weiss et al., 2009). Based on the exploitation of these alterations, it may be possible to manufacture products superior to those commercially available today (Sanguansri & Augustin, 2006).

Nanotechnology in food product development will lead to new texture, taste, other sensory attributes and experiences, improved stability during shelf life, thermal or oxidative stability, and oral bioavailability of bioactive compounds (Ezhilarasi et al., 2013). One of the most exciting applications of nanotechnology is nanoencapsulation. The ability to protect valuable biomolecules in nanostructures could improve the bioefficacy of the food matrix, as well as the ability to target and control the delivery of the active compounds during consumption and digestion.

## 11.2 The Potential of Nanotechnological Applications in Beverages

In the last few decades, approaches based on nanotechnology were one of the main innovation drivers in the category of functional beverages (He & Hwang, 2016). Although the safety of nanoparticle systems has been a subject of debate (Livney, 2015; Singh et al., 2017), it is important to point out that those based on biological material and designed to closely mimic nature, both for composition and structure, have been demonstrated to be safe. For example, casein micelles (Haratifar et al., 2014), liposomes (Mohammadi et al., 2014), and whey protein nanoparticles (Gülseren et al., 2012a) are systems already present in nature, and their safety as delivery systems has been demonstrated in the studies listed here.

The safety of nanoparticles containing synthetic or inorganic materials or characterized by novel structures with unique composition may have to be discussed separately.

So far, nanotechnological principles have been applied to “the characterization, fabrication, and manipulation of nanostructures or nanomaterials” (Pathakoti et al., 2017). It can be argued that the preparation, inclusion, and process-based tailoring of nanostructures in a food matrix represent, so far, the main activities in the field of food nanotechnology. However, it is important to point out that proven improvement of bioefficacy or proven value is critical to the adaptation of the technology in food products. In food beverages applications, nanotechnological approaches have been mostly focused on the enhancement of the nutritional and/or sensory characteristics of the products. Encapsulation in emulsions, liposomes, hydrogels, and protein and/or polysaccharide nanostructures have been reported with the purpose of utilization in beverages (Mohagheghi et al., 2011; Mohammadi et al., 2014; Matalanis & McClements, 2013).

To enhance the nutritional attributes of beverages, bioactive ingredients, including, but not limited to, phenolic compounds, minerals, vitamins, fibers, unsaturated fatty acids, enzymes, antimicrobials, and antioxidants, have been studied as model systems for incorporation in beverages nanodelivery systems. Indeed, the addition of a compound recognized by the consumer as beneficial to his/her health and well-being has been one of the main drivers of innovation in the beverage industry (Corbo et al., 2014; Patel et al., 2018), as regulations are limiting possible health—functionality-related claims. It is also important to point out that in the future, this drive will be increasingly linked to personalized performance nutrition (Kapsak et al., 2011). For example, a large beverage manufacturer has recently launched a portable pod-containing liquid and powder ingredients that create a personalized drink based on individual preference and lifestyle (Drinkfinity, 2018). The technological challenges are clear, as such products need to have stable delivery systems, both under concentrated and diluted conditions. Using nanotechnology, it may be possible to generate beverage products with a bioactive content stable during processing and storage (Jafari & McClements, 2017; Bromley, 2013). However, as previously mentioned, the assembly and stabilization of the nanostructures are rather difficult, and the low solubility of these compounds, as well as their rapid degradation during processing and storage, makes the bioefficacy of the encapsulated material a real challenge (Gülseren et al., 2014).

In addition to the design and processing stability, it is becoming increasingly critical to prove the stability and targeted delivery of these nanostructures during gastrointestinal (GI) transit, digestion, and absorption (Ting et al., 2014; Speranza et al., 2017). Since foods contain the essential macro- and micronutrients for our metabolism and physiological functions, it is very critical to understand how bioactive compounds are affected by digestion and absorption processes and what portion of these compounds could reach certain tissues in the body (Rein et al., 2013). As all the processing parameters and environmental conditions can affect stability and bioefficacy before consumption, the mechanical forces that take place in the GI system, the presence of digestive fluids, and their chemistry, as well as the changes occurring in the physical and chemical properties of the matrix during digestion, have the potential to alter the bioactive stability and, as a consequence, its bioavailability and bioefficacy (Zhong & Shah, 2012).

The residence time in the GI tract as well as interactions with the other food components determine the metabolic fate of food components in the system. For example, the consumption of a slice of chocolate cake with or without an acidic drink has the potential to alter the gastric pH values temporarily, which in turn will affect the digestibility of these products and the absorption of their components. Based on these data, it is quite clear that the macro- and microstructural attributes of foods and beverages and their physicochemical characteristics determine the extent of component stability and absorption of bioactive components (i.e., their bioavailability) (Jafari & McClements, 2017).

Consequently, the enrichment of beverages with active compounds is primarily geared toward the promotion of health and wellness or performance improvement (Bromley, 2013). As mentioned previously, the use of nanotechnology to encapsulate bioactive compounds brings additional benefits compared with traditional means of encapsulation, owing to the improved light scattering properties, the increased surface area of nanoparticles, and the unique structures that may result in improved stability (Ezhilarasi et al., 2013; Gülseren et al., 2014), absorption, synergistic effects (Moreno et al., 2005) during digestion, or bioefficacy (Guri et al., 2013) (see [Table 11.1](#)).

Currently, a variety of nanoencapsulation applications are being utilized in food research and food production. Owing to the presence of small particles in the system, their surface-area-to-volume ratio is quite large, which facilitates the dispersion of high concentrations of active materials in the system. Particle size may also affect the kinetics of digestion or targeted delivery in the intestinal tract (Ezhilarasi et al., 2013). In addition, the physical properties of the nanoparticles, for example, charge, size, and density, may affect their mobility in the mucus layer of the intestine, with obvious consequences on the delivery of the bioactive (Mackie et al., 2012; Li et al., 2017). As the size of particles incorporated into beverage systems decreases, owing to increased surface area, rapid digestion and easier penetration through mucus and immediate cellular uptake may occur. In sum, nanoencapsulation can be utilized toward improvement and optimization of bioactive uptake.

During transit in the GI tract, there are several metabolic paths for the absorption of nanoparticles, such as fluid-phase endocytosis (nonspecific), receptor-mediated endocytosis, and phagocytosis (Berrocal et al., 2000; Saltan et al., 2011). All the processes are affected by the size, composition, and perhaps structure and shape of the nanoparticles (Vácha, et al., 2011). As nanoparticles may successfully pass from specific zones in the GI tract, without the degradation of the encapsulated matter, the chances of physiological benefits being realized at targeted regions become more likely (Jafari & McClements, 2017).

Various nanoencapsulation systems and their utilization in foods have been investigated in detail. In this section, some examples will be summarized for systems that might be appropriate for utilization in beverages. For example, macromolecular Maillard conjugates made from the reaction of proteins and carbohydrates have demonstrated not only excellent emulsifying properties, owing to the presence of hydrophilic sugar groups that further stabilize emulsions through steric effects, but also their unique structure has been shown to have the potential as a nanoencapsulation system. The usage of such conjugates, for example, has enabled the encapsulation of volatile oils and flavor compounds (Shah et al., 2012). These systems are also available in spray-dried forms, so that the products may have an extended shelf life, and the volatile oils and flavor compounds may be dispersed in aqueous systems without negatively affecting their appearance (Shah et al., 2012).

Another interesting example is the case of phenolic compounds, which often, when added to food matrices, may affect sensory properties, since, at relatively low concentrations, they impart an astringent or bitter taste (Kranz, 2010). Encapsulation of these compounds in nanostructures will not only allow for the fortification of beverages at concentrations considered nutritionally significant but will also help in preserving the original sensory characteristic of the product (Li et al., 2008). This is of particular importance in beverages applications.

Compounds with low aqueous solubility might be present in foods, but as already mentioned previously, their bioavailability would essentially be limited. Their presence in complex systems often ensures their ability to be dispersed in the beverage, digested, and absorbed by the intestinal cells (Sabouri et al., 2018). This once again opens room for the development of nanoencapsulation systems that might solubilize the water-insoluble materials in a less polar phase, disperse them in water, and facilitate absorption in our intestinal tract (Guri et al., 2013; Chen et al., 2014). Demonstrating an improvement in the bioefficacy of these systems is a challenge (Arranz et al., 2016).

In addition to the physical stability, nanoparticles may affect visual characteristics or mouthfeel. Turbidity and/or color are affected by the interactions of nanoparticles with light (Zhong & Shah, 2012). At sufficiently low particle sizes, it is possible to manufacture optically transparent emulsions (Rao & McClements, 2011); by the same token, by fine tuning the structure of the suspended colloidal particles, it is possible to control the extent of “cloudy” appearance (Rao & McClements, 2011). The presence of nanoparticles in beverages also has the potential to influence viscosity and mouthfeel.

There are two major approaches for the design of nanoparticle systems that can be utilized in food or other applications: top-down and bottom-up approaches. In the top-down approaches, bulk materials are reduced continuously in size until a smaller target size is achieved, whereas bottom-up approaches bring molecules together to generate a larger assembly in the nanometer scale (Saratale et al., 2018). While homogenization and grinding (e.g., media milling) can be defined as top-down methods, manufacture of macromolecular complexes of biopolymers is a bottom-up approach. As will be detailed in the following sections, both approaches have a potential for being utilized in the generation of novel beverage formulations.

### 11.3 Delivery Systems, Technological Aspects

A multidisciplinary approach is needed to design food matrices that can perform in the chosen conditions, during manufacturing, storage, consumption, and digestion (Fasinu et al., 2011). With the increased awareness of consumers for particular components beneficial to health, new beverages containing biological molecules with perceived health benefits are increasingly needed. Principles of technologies used in the pharmaceutical and nutraceutical fields for encapsulation and delivery are extrapolated to food product development; in particular, the application of nanotechnology has been shown to be able to provide value-added benefits in the design of food matrices (Salvia-Trujillo et al., 2017). The multidisciplinary collaborations between drug delivery scientists, food engineers, colloid scientists, and food product developers have helped to overcome some of the challenges related to developing beverages that can not only be appealing to consumers but also be safe, stable throughout the shelf life of the product, and with benefits beyond simple nutrition (McClements & Li, 2010, Fathi et al., 2013, 2014, Salvia-Trujillo et al., 2017).

It is important to point out that much is yet to be understood of how the complexity of the structures present in food behaves during digestion and absorption in the GI tract and that it is not always clear if and when synergies occur due to the consumption of a particular matrix, assembled to a certain structure, compared with other structures or with the consumption of the biological molecules in isolation.

The formulation of functional beverages imparting biological benefits is ruled by a number of criteria that have to be met:

1. Targeted assembly and structure optimization during processing
2. Overall stability during shelf life
3. Consumer acceptance (appearance, taste, and sensory attributes)
4. Known and controlled behavior during GI transit and optimal breakdown during digestion
5. Targeted delivery at the biologically significant concentrations
6. Imparting the perceived benefit to the consumer

One of the most common applications of delivery systems in beverages has been the fortification of vitamin D in milk and orange juice (Tangpricha et al., 2003; Biancuzzo et al., 2010). Inclusion of bioactive compounds such as vitamins, phytochemicals, antioxidants, mineral, prebiotics, and probiotics as means for enhanced health benefits have been followed, and delivery systems have been designed to protect such components and promote their solubility.

Stability of the encapsulating structures is closely related to their thermodynamic behavior; thus, emulsions, microemulsions, micelles, and protein structures are colloidal particles that may tend to break down with time due to creaming, flocculation, sedimentation, aggregation, or Ostwald ripening if not due to chemical degradation or phase changes (McClements, 2012). All these events are strongly correlated to the particle structure, size, and charge; overall composition; particle–particle interactions; and environmental conditions. Hence, it is imperative to understand the effect of these factors on stability in detail, to control the properties of the delivery systems (Raikos & Ranawana, 2017). These properties become important when they affect consumer acceptance. This is particularly relevant to the design of beverages, where phase separation, turbidity, or visual creaming needs to be controlled carefully.

When designing functional foods, there are a few fronts to consider: choosing the right beneficial compounds; protect their stability, so that they will be present at concentrations nutritionally significant at point of delivery; developing the right matrix, as this may also ensure synergistic effects; and protection during processing, storage, and digestion. Utilization of nanotechnologies in the development of food beverages is further challenged by the fact that the highly active compounds need to be protected in a suspended form, and all the ingredients need to be generally regarded as safe (Singh et al., 2017) or highly regulated. Inclusion of active ingredients in colloidal delivery systems will affect chemical, physical, or microbial stability and sensory attributes (turbidity, color, flavor, astringency, bitter notes, etc.) and will lead to packaging design challenges, because of the appearance of the sensitivity to barriers to light or oxygen.

Different attempts have been made to overcome issues with instability and performance by obtaining particles with nanoscale dimensions, such as micro- and nanoemulsions, biopolymer encapsulation, liposomes, coacervates and complexes, and inclusions, among others (Weiss et al., 2006., McClements, 2012, Anandharamakrishnan, 2014; Corbo et al., 2014). Nanoparticles used in beverages are generated through different methods but should be biocompatible and biodegradable and pose no harmful effect on the host (Guri et al., 2013., Corbo et al., 2014).

One of the utmost conventional systems to improve the protection of bioactive species is the delivery of lipophilic molecules by using emulsions. Nature has already provided unique examples of naturally occurring nanostructures in foods. Milk is an example of emulsion ideally designed to deliver proteins, fats, and minerals to nurture the offspring (Watzke & German, 2007) or mixed micelles and vesicles present in the GI tract, solubilizing lipids during digestion (Singh & Horne, 2009). These remarkable examples show how a proper design of the delivery system is principal to achieve the desired activity of the bioactive ingredient in the body. An emulsion is a mixture of two or more immiscible liquid phases stabilized by amphipathic compounds, to create stable systems where coalescence, flocculation, or creaming is not taking place (Yang et al., 2017). Based on the particle size of the dispersed phase, emulsions might be microemulsions or nanoemulsions.

A few different emulsion categories have been introduced such as simple single emulsions, oil-in-water (O/W) emulsions, water-in-oil (W/O) emulsions, or more complex structures like double emulsions such as water-in-oil-in-water (W/O/W) emulsions and oil-in-water-in-oil (O/W/O) emulsions. Based on the nature of the particles, if the fats exist as crystal in normal room or body temperature, they are called solid lipid nanoparticles (SLNs). These structures have been shown to be able to enhance the potency and dose efficiency of lipophilic bioactives (Guri et al., 2013). The size of such systems can be controlled using homogenization, ultrasonic, cavitation, or microfluidization techniques. It has been proposed that it may be possible to prepare submicron-sized droplets with improved stability, starting with conventional emulsion droplets, containing a volatile compound, and, through evaporation, shrink their size (Ghosh & Coupland, 2008).

Polymer-based materials have been used in nanomedicine (Swider et al., 2018). Recently, similar approaches have been suggested for the development of delivery systems for beverages (Alessa et al., 2014). Thus, proteins, biopolymers, polysaccharides, and lipids (with different chain lengths) have been used as protective shell layers, while entrapping the bioactive structure to ensure nonaltered functionality and safe delivery (Anandharamakrishnan, 2014). Manipulation of the colloidal properties of these structures result in control of color, turbidity, and their overall stability. Whey protein isolate nanoparticles were prepared by desolvation in ethanol solution. Particle size ranged from 10 nm to 100 nm, with better stability at low pH and no changes in particle size; however, heating leads to particle aggregation (Gülseren et al., 2012). In addition, polylactic-co-glycolic acid has been used to encapsulate a bioactive peptide, and its stability was proven in an acidic environment such as apple juice (Alessa et al., 2014). Nanosized self-assembled structured micelles have also been suggested as food-grade delivery systems (Sanguansri & Augustin, 2006). The principle of utilization is the creation of minute micelles, which can be used as carriers of hydrophobic components, such as phytochemicals, minerals, and vitamins, and while upstanding the gastric digestion, they can be effectively absorbed in the gut (Vance et al., 2015).

In the case of bacterial encapsulation, larger particles are needed. It has been reported that microencapsulation of *Lactobacillus acidophilus* ATCC 43121 in alginate beads has been successful in preserving the activity (Kim et al., 2008). It is imperative in preserving the functionality of the microorganisms during harsh industrial processing such as high-temperature treatment (pasteurization or ultra-high pasteurization), homogenization, shear forces, and during shelf life. Extrusion of the probiotics in the fruit beverage media has been achieved through extrusion, using chitosan-alginate mixtures (Gandomi et al., 2016).

Spray drying has been successfully applied in the formulation of the drinks and beverage applications, either by molecular encapsulation (Speranza et al., 2017) or complexation with other ingredients (Sansone et al., 2011). Utilization of these techniques could assure a higher concentration of the active components, which may hinder the undesirable sensory attributes such as aroma, flavor, appearance, and bitterness, for consumer acceptance and increased activity (Corbo et al., 2014).

### 11.4 Delivery Systems, Biofunctionality Aspects

Once stability has been achieved across processing, storage, and throughout shelf life, the encapsulation of the bioactives will be challenged during physiological digestion (Figure 11.1).

The biological fate of the bioactive components is related to the fraction of the ingredient that survives the GI transit; gets absorbed, metabolized, or transported through epithelium; and reaches the target site, often by being transported in the blood (Ting et al., 2014). It is important to point out that many bioavailability studies have not taken into consideration complex *in vitro* systems, the potential synergies or challenges of a food matrix, and the interactions between the delivery system or of the bioactive molecules with the mucus (Figure 11.2).

It is proven that the transfer of these biologically active structures in the gut will face a slow absorption and therefore bioactivity caused by low solubility and challenges of oxidation and denaturation in gastric juices, enzymes, and pH conditions (McClements et al., 2016). Hence, in overall harsh gut environment, they will face challenges due to low solubility and denaturation in gastric juices, enzymes, pH conditions (McClements et al., 2016).

Considering the high volume of published research in the nanoencapsulation of food and food beverages, some considerations regarding *in vitro* and *in vivo* studies are given as follows.

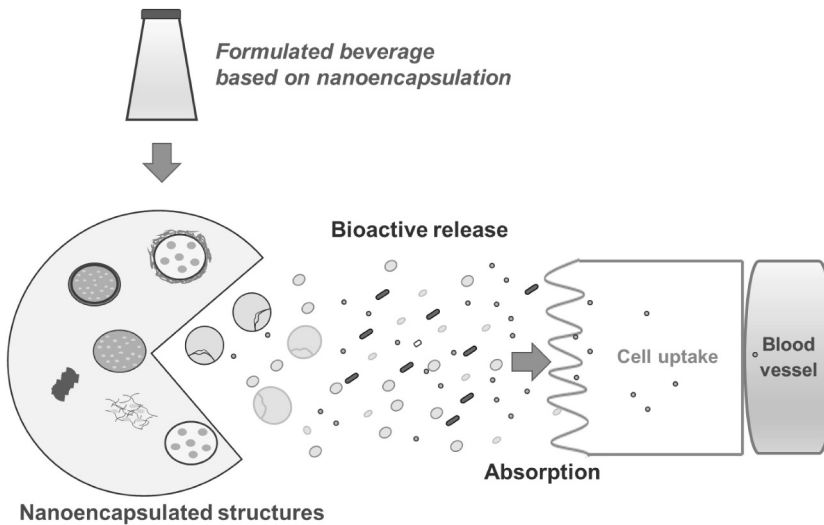


FIGURE 11.1 Designing proper structures for increased bioavailability in the gut.

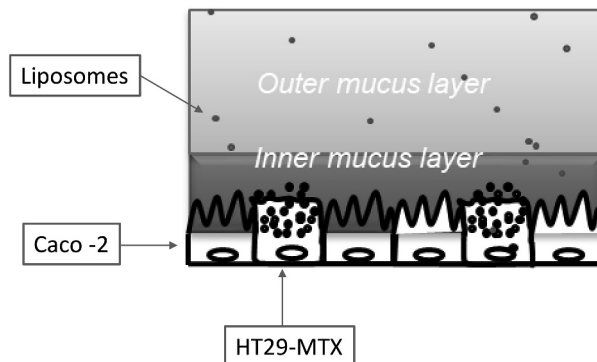


FIGURE 11.2 Schematic illustration of the liposome uptake on mixed cocultures of Caco-2 and HT29-MTX.

When preparing functional foods, it is imperative to study the mechanism of the main functional ingredient delivered through the designed matrices. Since nanostructures may vary from those fully mimicking nature to some highly functional, novel physical structures, their behavior in the food matrix and later in the human gut, digestion, uptake, and overall functionality needs to be studied. Hence, a few reports are present in the literature that uncover some of the details on the physicochemical attributes, stability and encapsulation properties, and performance during digestion of nanodelivery systems. As a mechanistic understanding of their behavior is critical to design optimization and for demonstrating their value added, most studies adopt the *in vitro* approaches as the initial tool in the early development stage, to be able to fine tune the mechanisms of stability and delivery.

Several *in vitro* approaches have been employed. Often, these methods are suited to the type of bioactive present, the matrix, and the expected functionality. The approaches vary in the literature, but it is important to point out that a valid study requires a multidisciplinary approach and an overall look at the behavior of the matrix throughout the GI transit.

Some of the approaches available in the literature screening methods include the following:

1. Physicochemical characterization of the delivery system, its stability, encapsulation efficiency, and the changes occurring during digestion.
2. Biological activity testing at various levels (antioxidant potential, anticancer, antimicrobial, and immunomodulatory) before and after encapsulation and during storage, changes in the environmental conditions, and GI transit.
3. Bioaccessibility, bioavailability (cellular uptake, *in vivo* animal trials, and clinical studies), and bioefficacy.

Safe delivery of phytochemicals, for their unique properties beneficial to human health, has been widely researched. Such molecules are well known for their numerous beneficial activities in the body such as antimicrobial, neurocognitive function, anticancer, and anti-inflammatory; nevertheless, their usage in food, especially in the beverages, is limited. Attributes such as solubility, dispersibility, bitterness, flavor, oxidation, and critical concentration to exert the biological activity are some of the concerns that need to be addressed to successfully incorporate these compounds for the benefit of common health (Shah et al., 2012). Their stability and the potential of use have been comprehensively reviewed (Harbourne et al., 2013; Da-Costa-Rocha et al., 2014; Shahidi & Ambigaipalan, 2015). These compounds have been used as model systems in the studies of the delivery matrix, as their bioefficacy can be studied by using cell culture models, at the various stages of the development and design (Arranz et al., 2016). Polyphenols are also quite difficult to quantify when present in complex matrices, and often, this may result in conflicting interpretations about their bioavailability. By testing the bioefficacy of the delivery matrix, it has been possible to demonstrate that the complexes are uptaken by the intestinal cell even if their quantification is a challenge (Sabouri et al., 2018). Encapsulation of tea polyphenols in milk liposomes was shown to be effective using cancer cell models (Gülseren et al., 2012b).

It has been demonstrated that polyphenols are complexed with the naturally present protein assemblies composed of caseins (casein micelles). These complexes show the ability to protect polyphenols during digestion and result in polyphenols being still biologically active when absorbed by human intestinal cells (Haratifar et al., 2014). Other authors have also demonstrated that grape polyphenols-fortified yoghurt drinks preserved the antioxidant capability (Karaaslan et al., 2011).

Often, other protective compounds are added in the delivery matrices to ensure bioefficacy at the targeted site. The oxidation rate of omega-3-fortified dairy beverages can be controlled by the addition of oregano oil extract or oregano essential oil as part of the delivery system (Boroski et al., 2012). Overall, both oregano extract and oil preserved the oxidative stability of the beverage, without compromising the sensory properties and physical stability (Boroski et al., 2012). Rosemary extract is well recognized as a functional ingredient and used in bulk oils and emulsions (Hernández-Hernández et al., 2009, Arranz et al., 2016), but applications in liquid beverages have yet to be developed.

Screening for bioactivities is usually carried out using target cell culture models. In addition to human intestinal cells such as HT-29 and Caco-2 model, anticancer activity is studied on other target cell types, such as human cervical adenocarcinoma HeLa cells, lung carcinoma A549, and hepatoma HepG2.

For example, screening of the bioactivity of a selenium-enriched green tea widely used in China was characterized by testing different extracts, and higher activities were found in the ethanolic extracts (Li et al., 2008). These studies on the extracts in isolation clearly show that despite an understanding of the biological activity of the extract *per se*, very little is known of the stability of these extracts when consumed in a food matrix.

Food safety, microbial spoilage, and physical and chemical stability for prolonged periods of times, sometimes at temperatures above room temperature, are a challenge when developing beverages. Heat stability of the delivery systems is often necessary, especially when designing beverages processed under aseptic conditions. Low pH is usually preferred in case of beverages, as it helps in preserving microbial safety. In case of beverages at low pH, encapsulation of the bioactive ingredients may pose challenges owing to the effects of pH and storage on physical properties, affecting appearance (turbidity and precipitation) or flavor (Shah et al., 2012). Nanoparticles of 80-nm diameter made with polylactic-co-glycolic acid containing bioactive peptides were tested in apple juice (Alessa et al., 2014), and the authors showed that neither the integrity and functionality of the encapsulated peptide nor the particle size and the sensory attributes were affected, up to 60 days' storage.

Of course, designing the structures to ensure stability and consumer acceptance at point of purchase is not sufficient when developing beverages that must deliver dietary benefits. The physical, chemical, and biological efficacy changes during GI digestion are key to delivering products with value to consumers. In the last decade, a great deal of research shed light on the importance of thorough understanding of digestion process, and with unified efforts from scientists across the world, a consensus protocol of *in vitro* digestion is now available as a guideline (Minekus et al., 2014). This method has been widely tested and further improved through more interlaboratory studies, warranting a better comparability and consistency of the research outcomes from different research groups (Egger et al., 2016). Since then, numerous studies have contributed to the knowledge related to digestion, release, and absorption and to providing guidelines for developing micro- and nanoencapsulation methods and *in vitro* digestion protocols to accurately measure *in vitro* bioavailability of targeted compounds. Studies have shown increase in oral bioavailability as well as increased bioaccessibility and stability in well-designed food matrices during GI digestion. More work is needed to better understand synergies and the effect of structure of the delivery system on bioefficacy of the functional foods and beverages; however, it is now possible to derive some general principles, and methodological approaches are more standardized.

For example, delivery systems have been characterized during their GI transit, using *in vitro* digestion models, but their bioefficacy was then tested using intestinal cell absorption and transit models, such as Caco-2 monolayers and cocultures of Caco-2 and HT-29 MTX, mucus-producing cells (Guri et al., 2013, Arranz et al., 2016, Li et al., 2017). The effect of different protein type at the interface of emulsions encapsulating rosemary extract was studied (Arranz et al., 2017), and no differences were reported on the uptake of two different protein-stabilized emulsions; however, a higher retention of the particles on the mucus layer was noted in the case of positively charged oil droplets (lactoferrin emulsion) (Arranz et al., 2017).

The effect of the interactions between the mucus and the delivery system must be considered, to better understand possible barriers to the release of absorption of the bioactives.

The characterization, absorption, and uptake of solid lipid nanoparticles containing tea polyphenols were tested on cocultures mucus containing (Caco-2 and HT-29 MTX) (Guri et al., 2013). Recent work has been published on the effect of nanodelivery systems such as liposomes on the rheological properties of the mucus layer, by using drop tensiometry techniques (Li et al., 2017). The research demonstrated that milk proteins complexed with polyphenols changed the viscoelastic properties of mucus produced by HT-29 MTX cells. Composition of the nanodelivery systems may therefore have an impact on the interactions; however, it is still to be determined if these rheological changes have a significant effect on the uptake of the encapsulated bioactive (Li et al., 2017).

A number of studies have been carried out to improve the delivery of probiotics in food matrices. The work has resulted in the enrichment of a number of food products with probiotics, for example, in dairy or fruit juice category, after the development of encapsulation methods to preserve the activity and *in vivo* studies to demonstrate their effectiveness. Encapsulation of the probiotics in beverages requires their ability to withstand industrial processing (high pressure, temperature, and shear) conditions,

as well as a preserved viability during their shelf life (Speranza et al., 2017). Utilization of probiotics in the fruit beverages has been successful, with surviving rates of minimum  $10^6$ , which is seen as a limit for their ability to survive in the GI tract (Bhat et al., 2015). Although such delivery systems are not in the nanoscale dimension, learnings from those approaches may be needed in the future, as more applications related to micro-RNA (mi-RNA) vesicles and phages therapies may become of interest (Munagala et al., 2016; Malik et al., 2017). When encapsulating biological structures, both mechanistic understanding and *in vivo* efficacy and toxicity studies will be needed to respond to regulatory requirements.

The emergence of nanotechnology applications for delivery of health benefits in beverages has opened a myriad of opportunities for innovation. However, much work is needed to prove the safety of the ingested nanostructures, as well as the efficacy and value addition of such sophisticated systems. The potential of the undesired effects of any nanostructures that may accumulate in the cells or in the bloodstream, as well as the benefits/risks associated to the consumption of large volumes of fortified beverages with encapsulated compounds, still remains unclear. In addition, work will need to be carried out to understand if the consumption of such beverages will affect gut microbiota. For example, studies have shown that gut microbiota transforms phenolic compounds present in juices into bioactive metabolites contributing to the intestinal homeostasis and simulative growth (De Prisco & Mauriello, 2016).

The *in vitro* trials are the bases to predict the behavior of the encapsulated ingredients in the host. They are fundamental in terms of predictability and further extrapolation into *in vivo* studies, which will be the ultimate proof of the value obtained by designing nanodelivery systems instead consuming the compounds in isolation. However, *in vivo* human intervention trials will occur only when adequate information has been gathered from *in vitro* and *in vivo* animal studies and when a financial or economical benefit is in sight (Bhat et al., 2015).

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## 11.5 Examples of Performance Beverages

The market for functional/performance beverages is growing and is an active sector of the food industry. Commercially available functional beverages could be grouped as dairy-based beverages, plant- or fruit-based beverages, and sport nutrition beverages. Despite the variety of the products available on the market shelf, the number of commercial beverages containing encapsulated functional ingredients is limited. Therefore, this section describes encapsulation examples, with reference to nanotechnology, whenever applicable. It is clear from the applications currently available that most products with encapsulated bioactives use very simple system, mostly still in the microscale. However, much can be learned from these applications when developing nanoscale structures for use in beverage matrices. The main barrier to innovation using nanotechnological approaches is cost, as the design sophistication comes hand in hand with some capital investment and a higher ingredient cost, especially when trying to mimic nature and use clean label ingredients in the beverage formulations. This added cost will need to be justified by a proven additional value related to the use of nanotechnology, compared with simpler delivery systems.

Perhaps the most important value added is the biological activity that can be preserved or enhanced. For example, products containing probiotics are well recognized by consumers, and nanodelivery systems in the future may be developed to carry genetic material (i.e., specific phages or mi-RNA) specifically targeted to therapeutic or prophylactic functions. The application of nanotechnology may also bring an added sensory experience not possible with other encapsulating means, for example, the release of an active component on shaking and a particular texture obtained during consumption. Another successful example is that of vitamin waters, where the delivery systems need to have specific light-scattering properties to make the product more or less cloudy. A typical example of a sensory experience is that of “Bubble teas,” a Taiwanese tea-based drink invented in early 1980s made with toppings such as chewy tapioca balls added to a variety of drinks, ranging from juices such as smoothie type to milk teas. These types of sensory experiences have proven to add value to the consumer but, in many cases, are still limited to fresh consumption and not shelf-stable products.

### 11.5.1 Dairy-Based Drinks

Dairy-based products account for approximately 43% of the functional beverage market, and a large percentage of these are fermented products (Özer & Kirmaci, 2010). Dairy-based functional beverages are optically opaque; therefore, the presence of multiphase particles in suspension is not a barrier to innovation. When lipophilic molecules must be delivered, emulsion droplets are employed as carriers. The environmental conditions during storage (such as pH, ionic strength, and concentration of other components, e.g., polysaccharides) and the processing steps are critical factors affecting the stability of these systems. It is important to point out that nanostructures may also be built at the interface of the emulsion systems. For example, it has been recently described that epigallocatechin-gallate (tea polyphenol) forms complexes with sodium caseinate at the interface of emulsions, and such complexes can be employed to deliver this bioactive in dairy-based beverages (Sabouri et al., 2015). Other approaches have also been shown effective in incorporating polyphenolic compounds in dairy products (Karaaslan et al., 2011; Seo et al., 2011; Giroux et al., 2013). Some successes have also been reported for the incorporation of iron in milk beverages. According to Lee et al. (2004), ascorbic acid and iron can be microencapsulated by using polyglycerol monostearate and then incorporated in milk at a ratio of 5:1 polymer to ascorbic acid. Authors also demonstrated that the sensory perception was well maintained in milk fortified with 100-ppm ascorbic acid. Other examples of encapsulation in dairy beverages are related to the use of polysaccharides such as chitosan in the form of nanocapsules (Seo et al., 2011). Nanoparticles could also be used to cover oil–water interfaces, in Pickering emulsions (Chevalier & Bolzinger, 2013), including chitosan nanofibers (Baklavari et al., 2018). Hesperetin, a flavanone used as a potent antioxidant, has been incorporated in nanostructured lipid carriers and applied to milk beverages (Fathi et al., 2013). Higher encapsulation efficiency and smaller size were described for nanostructure lipid carriers compared with solid lipid nanoparticles. In this case, the added benefit is clear, as hesperetin cannot be added to milk directly, as it would result in adverse sensory attributes. Nanoencapsulation of hesperetin has demonstrated that this technological approach offers a solution to increase solubility, reduce bitterness, and prevent color change in dairy beverages. A similar approach using lipid nanoparticles was employed to fortify milk with vitamin D<sub>3</sub>, with no effect on sensory properties. Furthermore, the study demonstrated by using *in vitro* simulated digestion that the use of lipid nanoparticles could extend the release duration of vitamin D<sub>3</sub> (Kiani et al., 2017).

As previously mentioned, much can be learned from the efforts to encapsulate probiotics and maintain their viability in dairy matrices. Oral administration of probiotics and the harsh conditions of the upper intestinal tract cause huge losses of viability owing to the acidic pH of the stomach and presence of bile salts in the intestine. Therefore, encapsulation of probiotic bacteria is usually employed to protect the probiotics during the GI tract transit and provide controlled release of probiotics along the intestinal tract. Mortazavian et al. (2008) formulated a yogurt drink containing microencapsulated *Lactobacillus acidophilus* LA-5 and *Bifidobacterium lactis* Bb-12 in calcium alginate that improved the viability after exposure to simulated GI conditions and 42 days of storage at 4°C (4–5.5 log cycles increased).

Perhaps the most significant examples of nanostructures in dairy beverages are those present in nature, such as the mi-RNA vesicles, the lipoprotein structures, and the milk phospholipid vesicles. A better understanding of these natural structures and their reason for being present in milk have tremendous potential for the development of the next generation of bioactive nanoparticles. Indeed, in this case, not only the material entrapped but also the composition and structure of the nanoparticles impart health benefits beyond nutrition, related to GI health and development of the immune system (Sun et al., 2013; Baier et al., 2014; Gallier et al., 2015).

### 11.5.2 Plant and Fruit Juices-Based Beverages

Although dairy-based products are predominant in the functional beverages' category, plant- and fruit-based products are becoming increasingly available in the marketplace. The main drivers for innovation are dietary restrictions, such as lactose intolerance, allergies, and sensitivities to certain components, or simply just the interest in novel and premium beverage options. In general, developers of such products

often resort to using encapsulation to impart functional properties in the formulation. Fruit juices with added probiotics have been developed (Granato et al., 2010; Sun-Waterhouse, 2011). For example, in 2016, a multinational (Tropicana, USA) launched Essentials Probiotics®, a line of juices that contains *B. lactis* HN019. Bravo® (Skånemejerier, Finland) line of juices incorporated *L. paracasei* 8700:2 and *L. plantarum* HEAL 9 strains of probiotics. Survival of probiotic strains in the formulated products during storage is critical, and encapsulation is employed to improve the viability.

Apart from probiotics, food researchers in functional foods also looked at the fortification of juices beverages with bioactive molecules. Zardini et al. (2018) produced solid lipid nanoparticles and nanostructure lipid carriers containing lycopene, by high-shear homogenization and ultrasound methods, that were incorporated in an orange drink. Solubility of lycopene was improved; however, the acceptability of the final product was significantly lower, as orange color was reduced, compared with control orange drink. Functionality of incorporated bioactives could be compromised if further thermal processing steps follow formulation of drinks. Encapsulation of hesperidin in cellulose acetate phthalate capsules reduced its degradation after pasteurization compared with nonencapsulated hesperidin added to orange juice (Afkhami et al., 2018).

Plant proteins are also becoming interesting matrices to formulate functional drinks (Molina et al., 2012). These proteins are naturally assembled in large aggregates, and they may show potential for the development of functional carriers. The colloidal properties of the plant-protein-derived nanoparticles are still largely unknown; only one study is available on soy beverage extract (Ringgenberg et al., 2012). As the interest of consumers for plant protein increases, the research findings will allow for innovation to occur in this sector.

A particular challenge of plant-based beverages is to improve the sensorial attributes of the final product. Most often, beverages have poor mouthfeel, with watery, gritty, or sandy perceptions. Particular polymers may interact with plant proteins, causing the formation of nanosized aggregates with unique properties that may respond to some of the challenges in innovation, including an improvement in mouthfeel and sensory attributes.

### 11.5.3 Sport and Energy Drinks

Sport drinks are specifically formulated to cover the needs before or after exercise and to improve performance or help in better recovery. Commonly, to prevent dehydration, beverages provide carbohydrates, electrolytes, vitamins, or other minor nutrients, and usually, they do not contain a source of caffeine (Heckman et al., 2010). Energy drinks, contrary to sport-type drinks, are designed for a specific age range of population and usually contain caffeine. This wide beverage category is growing, as the demand is now larger than just the sport and nutrition space, but it is more related to performance nutrition and well-being (Corbo et al., 2014).

Although there is an extensive number of sport and energy drinks in the market, application of nanotechnology is opening opportunities for novelties to better address consumer demands. Traditionally, these types of drinks are formulated by blending ingredients in water and then forming the final beverage, concentrate or shot. Utilization of delivery systems, typically emulsions or nanoparticles, could improve the delivery of bioactives, nutrients, or preservatives. Therefore, Rivera et al. (2010) patented microencapsulation of citrus phytochemicals to mask their bitter taste once incorporated in sport drinks. Casein-maltodextrin conjugates could be used as emulsifiers for acidic beverages, are soluble at low pH, and result in transparent solutions, features that open their potential application as protein-soluble additives for sport drinks (Shepherd et al., 2000). Cholecalciferol and ergocalciferol, D-group vitamins, are bioactives with special interest in athletes' diet and reduce bioavailability. Khalid et al. (2017) have described that the application of encapsulation in medium-chain triglycerides in water emulsion effectively entrapped both vitamins; however, in many cases, shelf life is still a challenge. Matoušková et al. (2012) presented an alternative controlled release of caffeine encapsulated in liposomes and polysaccharide particles, chitosan and alginate, and its potential application in energy drinks. As a commercially available encapsulated bioactive ingredient in the market, we can find Esolv®, patented by Virun (California, USA). Esolv® is a water-soluble formulation of astaxanthin (lipophilic antioxidant marine carotenoid) deodorized and encapsulated into micelles as bioactive supplement for energy and sport drinks.

Nanotechnology applied to alcoholic beverages has an excellent potential in the formulation of alcoholic functional drinks. Very little is published in this area, as most of the work in the past has been focused on improving the stability of cream liqueurs. In these products, Ostwald ripening is one of the factors affecting stability (Radford et al., 2004), since ethanol increases the solubility of oil in the aqueous phase. As the dividing line between sports nutrition, performance beverages, and energy drinks with and without alcohol becomes blurrier, more challenges will occur in development to ensure multiple functionality and stability, and nanotechnology will provide solutions for innovation and growth in this category.

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## 11.6 Conclusions

In the recent years, we have experienced a growth in the market for beverages proposing functionalities beyond those of simple nutrition, owing to an increased consumer demand for products that would provide dietary choices leading to improved health, lifestyle, and well-being. However, to provide such benefits through beverages is quite a challenge, as sophisticated micro- or nanostructures need to be designed as delivery matrices. In beverages, these structures need not only show proven biological efficacy, but they must also be disrupted in a specific area of the GI tract to target a specific function. Furthermore, they need to be stable during processing and storage and, above all, not have any detrimental effects in terms of visual or sensory appeal. Finally, in many cases, they have to be colloidally stable, both in concentrated and diluted systems, and keep the encapsulated substances stable during the life time of the product.

It is necessary to understand the effects occurring during the assembly of such structures and their disruption during digestion and, ultimately, to have a mechanistic understanding of the principles linked to the delivery of the biological function via these structures. In addition, the application of engineered structures in food, and in beverages, requires that the consumer's demand for a clean label, and increasingly for personalized needs related to lifestyle, ethical choices, and dietary recommendations, are satisfied. Ideally, an understanding of how to optimize the assembly during processing would allow to make significant advances in the field.

Nanostructures are a great opportunity in beverages, as they possess some of the physical and chemical characteristics to deliver stability and appealing sensory properties to the products, while providing the necessary targeted functionality during digestion in the GI tract. There are several nanoparticles providing these functions in nature, such as liposomes, protein nanoassemblies, polymer aggregates, micro-RNA vesicles, and micellar structures. As we continue to improve our understanding of how to build such nanostructures, we also need to improve our knowledge on structure disintegration during digestion, so that our abilities to engineer the right structures by using bottom-up approach also improve. It is also important to note that more research is also needed to understand when such nanostructures bring a synergistic matrix effect that can be replicated by consuming the components in isolation. More in-depth characterization of the nanoparticles in food and beverage category is needed as a critical step to address both the benefits and the possible shortcomings (e.g., toxicity and differences in digestion behavior) of nanoparticle components in biological systems (Singh et al., 2017). This will pave a way for data-driven regulatory policies, as well as a better understanding of the value added by using nanotechnology in food product development.

## ACKNOWLEDGMENTS

E Arranz receives funding from Enterprise Ireland and the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement no. 713654.

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