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Title: A step forward on micro- and nanotechnology in beverage industry

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Abstract

The use of micro- and nanotechnology in the beverage industry had a remarkable growth in recent years, and is expected to have a major impact on the beverage market in the near future because it may offer many potential benefits for consumers and manufacturers. The dimensions and physicochemical properties exhibited by materials at micro (10^{-6} m) and nano (10^{-9} m) scale allow their inclusion in various beverages processes, leading to novel material functionalities and applications, showing great advantages than those at the macroscale. Due to their small size, micro- and nanosystems can enhance solubility, bioavailability and sensorial properties (e.g., mask unpleasant flavors), as well as prevent undesirable physical and chemical reactions and bioactive compounds degradation. This has led to the development of novel and high performance systems using bio-based materials for beverage industry in several fields such as: encapsulation of bioactive compounds (e.g., lipids, vitamins, peptides, antioxidants and probiotics), safety (e.g., detection of contaminants and microorganisms) and processing (e.g., improvement of texture, color, flavor and aroma). The increasing number of publications and patents prove the fast growth of this topic in beverage industry, confirmed by the significant number of companies using micro- and nanotechnology in the development of their products. This chapter will provide an overview of the latest evolutions and expectations of forthcoming developments involving the use of bio-based micro- and nanosystems to improve beverage safety, sensory and nutritional quality. Examples of commercially available beverages products containing bioactive micro- and nanosystems will be also provided, together with a revision of the main challenges for their industrial use and future trends, the potential health effects and risks for human consumption, and the regulatory and safety issues involved.

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1. Introduction

Beverage industry is constantly challenged to address the consumer's demands for safe, nutritious, appealing, heathier and functional products. Today's consumer trend is for the consumption of natural, fresh or minimally processed products. Therefore, food researchers are looking for novel technologies or natural compounds to be used in beverages (Rocha et al., 2017, Xu et al., 2017, Raikos, 2017), to i) improve their nutritional value and sensorial attributes (e.g., aroma, taste, flavor and texture) (Given, 2009); ii) increase their shelf life by adding natural preservatives (Nunes, 2016), developing active packaging (Ferreira et al., 2014), or improving clarification procedures (Gassara et al., 2015); and iii) develop novel functional beverages (Nualkaekul et al., 2012).

Therefore, providing the consumer with better-quality beverages products, either through the improvement of their protective packaging (e.g., keeping products safe, with original nutritional value and organoleptic quality) or through the enrichment of their matrices (e.g., assuring the level of bioavailable nutraceuticals) is a current challenge.

The use of micro- and nanotechnology in food industry, and in particular for beverage products, can be a suitable solution to address these challenges (Balassa et al., 2015; Benshitrit, Levi, Tal, Shimoni, & Lesmes, 2012). The global beverage market is estimated to reach at least $1.9 trillion by 2021, and is expected to grow ca. 3.0 % from 2016 to 2021. Therefore it is imperative to use innovative technologies to address the current issues found in beverage industry, as well as to allow the development of new products (e.g., beverages enriched with nutraceuticals) to face the consumer needs.

Micro- and nanotechnology have finding growing applications in the beverage industry, once these approaches allow the development, processing and application of structures and systems with tailor-made properties, by controlling shape and size at the micro- (10^{-6} m) and nanometer (10^{-9} m) scale (Joye and McClements, 2014, de Souza Simões et al., 2017).

Microsystems had their main focus of research efforts in the 1980s, while the nanosystems have been development and explored more recently. The real dimensions characteristic of micro- and nanosystems still under discussion, but some authors have defined as 100 nm the upper size limit for nanoscale (Sekhon, 2010, Singh, 2016, McClements and Xiao, 2017). The size of nanosystems is highly dependent on the materials and processes used to create them and can range from 20 nm (surfactant micelles) to 100 nm (lipid, protein, or carbohydrate-based nanosystems) (McClements and Xiao, 2017).

At this scale range, it is possible to create materials displaying different behaviors and novel physicochemical and functional properties than those in the bulk state exhibiting higher sizes (de Souza Simões et al., 2017, Madalena et al., 2016). This is mostly due to the large surface area-to-volume ratio observed at lower scales, but also to the effect of physical and chemical interactions established between materials at micro- and nanoscale, which significantly impact the overall properties of those systems (Cerqueira et al., 2014).

Therefore, the size of materials added to beverage products may either change its functional performance in beverages such as the encapsulation features (e.g., loading, retention and release), and the behavior though the gastrointestinal (GI) tract (e.g., transport, degradation, interactions and penetration); or impacts the bulk physicochemical and sensorial properties of beverages (e.g., rheology, optics and stability) – Figure 1 (Joye and McClements, 2014).

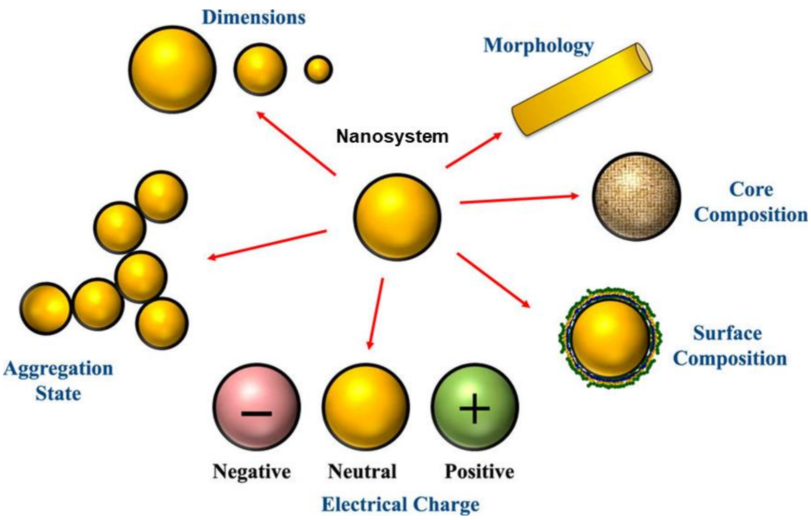

Figure 1. Nanoparticles in food and beverages products vary in particle characteristics, such as dimensions, morphology, composition, aggregation state and charge. Adapted from Mcclements and Xiao (2017).

These features can be explored to engineer micro- and nanosystems for a variety of purposes in beverages such as: i) improving the sensorial attributes (e.g., beverages with enhanced mouthfeel or built-in triggered release of colors and flavors); ii) masking unpleasant taste and odors or retaining the product's taste; iii) mimicking fat droplet functionality; iv) improving nutraceuticals storage stability; v) extending shelf life of volatile flavors (which can evaporate when they come in contact with the atmosphere); vi) boosting sugar perception; vii) altering optical properties; encapsulation and controlled release of bioactive ingredients (e.g., antioxidants, omega-3 fatty acids, probiotics, vitamins, polyphenols); and viii) enhancing safety and security (e.g., micro- and nanosensors to better tracking and tracing of contaminants, nanotracers and nanocomposites to improve the properties of packaging materials) (de Vos et al., 2010, Ramos et al., 2017, Chung et al., 2013, Cerqueira et al., 2014, Rocha et al., 2017, Chaudhry et al., 2010). The application of micro- and, in particular, nanotechnology in the beverage industry may allow the production of high quality beverages in terms of thermal stability, solubility and oral bioavailability (Augustin and Oliver, 2012). These are key fundamentals towards achieving a better and healthy life.

Currently, the major challenges concerning the usage of micro- and nanosystems for beverage applications are the replacement of non-food grade ingredients by food grade and generally recognized as safe (GRAS) alternatives (de Souza Simões et al., 2017, Kwak, 2014).

Food grade micro- and nanosystems can be fabricated from a range of different ingredients, including lipids (e.g., vegetable oils, phospholipids and triacylglycerol), proteins (e.g., whey, soy and egg proteins) and polysaccharides (e.g., chitosan, alginate, gum arabica and pectin), isolated or associated (Aditya et al., 2017, Ramos et al., 2017, de Souza Simões et al., 2017) These bio-based materials are usually in the liquid, semi-solid (gelled), or solid (i.e., crystalline or amorphous) state at ambient temperatures, depending on their composition and processing conditions. They can be used as the primary building blocks to fabricate controlled delivery micro- and nanosystems due to their ability to form gels, particles/capsules or emulsions, and to their bonding capacity (usually through electrostatic interactions) with bioactive compounds (Ramos et al., 2017).

The selection of the most suitable bio-based material needs an understanding of the bioactive compound characteristics to be encapsulated, as well as of the nature of the food matrix, in which such compounds will be incorporated.

Distinct approaches have been used to design micro- and nanosystems, intended the improvement of even the development of novel functional properties in beverages products, using “bottom-up” or “top-down” techniques (Anandharamakrishnan, 2014b). The former is based on the manipulation of atoms and molecules significantly smaller than the recognized nanoscale size i.e., 100 nm (self-assembly); while the latter applies mostly physical means (e.g., shredding, homogenization, co-extrusion) to reduce systems until the desired size (micro- or nanoscale). These approaches allow the development of micro- and nanosystems exhibiting different properties (e.g., thermal resistance, stability, permeability and controlled release, and delivery performances), and thus distinct functionalities. With appropriate physical, chemical and biological techniques, naturally occurring food molecules and structures can be also designed to display unique roles for novel ingredients and products (Martins et al., 2015, de Souza Simões et al., 2017).

This chapter provides an overview of the most promising food grade micro- and nanosystems (including the bio-based materials and the major fabrication techniques employed in their production) and highlights some of their most important applications in beverage safety and processing. Examples of products commercially available containing micro- and nanosystems are provided, together with a review of the main challenges for their widely commercialization. The potential health effects and risks for human consumption, and the regulatory and safety concerns are also addressed.

2. Micro- and nanotechnology for encapsulation

In an era of continuous technological advances, small-scale technologies (micro- and nanosystems) take the lead when it comes to offering the food industry a number of new approaches for improving the quality, shelf life, safety, and healthier foods. Nonetheless and as opposed to this demand, there is also an endless concern of consumers and regulatory agencies for natural products – with no risk of potential adverse effects (toxicity issues). In particular, there is a distress about the direct incorporation of engineered nanosystems into foods and beverages, such as those used as delivery systems for flavors, colors, preservatives, nutrients, and nutraceuticals, or even those used to modify food and beverage products and/or packaging proprieties (i.e., optical, rheological, or flow properties) (McClements and Xiao, 2017).

It seems important to underline that nanosystems may be intentionally added to food and beverages (such as particle-based delivery systems), or they may inadvertently find their way into food and beverages (such as particles in packaging materials that leach into the beverage matrix) (Yada et al., 2014). In this chapter the nanosystems will be considered only as typically systems whose composition, size, shape and interfacial properties are specifically designed to achieve one or more functional attributes in the matrix.

In order to trailing the double-dealing between innovation and its fears, the authors focused on the properties and potential safety of ingested nanosystems in beverages, since they are most likely to cause health concerns and the target of consumers major anxiety. In this point chapter will review the most recent advances and expectations of forthcoming developments comprising the use of bio-based micro- and nanosystems (from hydro and lipophilic character) to improve beverage safety, sensory and nutritional quality, assuring their safety and even revealing some market products.

2.1. Capsules

Microencapsulation or nanoencapsulation are techniques that have been widely explored in both food and pharmaceutical industries. The benefits of these systems can be the reduction of production costs, the increase stability of bioactive compounds and of physical proprieties of the food matrix, to mask the bitter taste, and to improve the release properties of some compounds in food industries (such as specific ingredients, nutrients or nutraceuticals) (Dias et al., 2015, Koo et al., 2014). This ability as delivery systems for bioactive compounds is one of the most widely investigated, since capsules are well-known as hollow vesicular structures that can incorporate bioactive compounds by surrounding them with a biopolymer layer, isolating bioactives from the environmental conditions (de Souza Simões et al., 2017).

Nowadays, micro- and nanocapsules are exploited in beverage, bakery, meat, poultry and dairy products. The challenge of microencapsulation is in selection of the most suitable parameters for producing highly effective microcapsules. In this sense, many factors may affect the quality of such capsules, including the preparation techniques, types of core material and of wall material (Peanparkdee et al., 2016).

The research care in this selection of the core, wall material and microencapsulation technique affects the capsules properties, including morphology, and clearly compromises the success in its development (Gharsallaoui et al., 2007). The morphology of microcapsules can be described as: mononuclear, poly/multinuclear, matrix, multi-wall and irregular, as described in Figure 2.

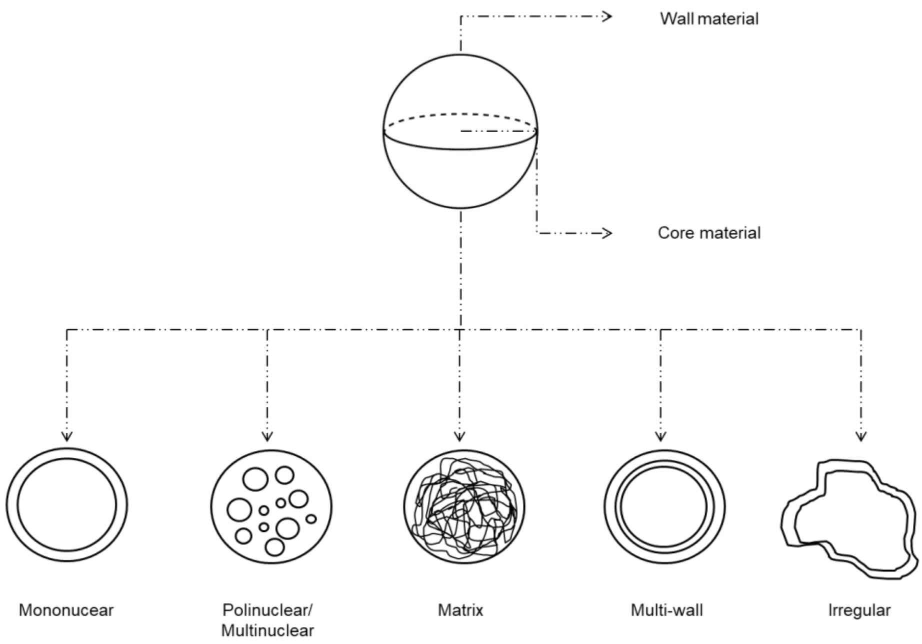

Figure 2. Microcapsules types of morphology. Adapted from Peanparkdee et al. (2016).

There are also a large diversity of available techniques that can be successfully employed in the production of micro- and nanosystems for encapsulation of bioactive compounds, intended for beverage applications (i.e., capsules, hydrogels, emulsions, micro- and nanoemulsions, solid lipid nanoparticles, nanostructured lipid carriers and liposomes) – Figure 3. The success depends on the nature of the bioactive compound, and the encapsulating bio-based material (including their molecular weight, polarity, solubility, particle size distribution, encapsulation efficiency and shape) (de Souza Simões et al., 2017).

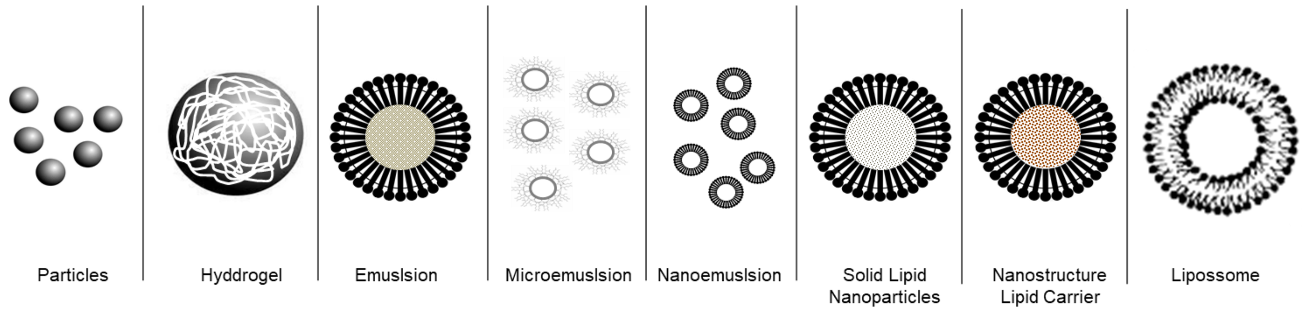

Figure 3. Micro and nanosystems as delivery carriers for bioactive compounds encapsulation. Adapted from de Souza Simões et al. (2017).

The capsules can be easily produced (by distinct but no complex methodologies), exhibiting high storage stability of entrapped bioactive compounds. In addition, these systems allow a controlled release of such compounds through a complete disintegration of their structure or altering their porosity in response to external stimuli (i.e., changes in ionic strength, pH or temperature).

Burin et al. (2011) evaluated the stability of anthocyanin, which was encapsulated within different carrier agents in an isotonic soft drink system. Anthocyanins are water-soluble pigments obtained from plants used as colorants in foods and drinks, due to their high colorant power, low toxicity and high water solubility (Ersus and Yurdagel, 2007). Beyond important antioxidant and anticarcinogenic properties, anthocyanins are unstable pigments and can be decomposed to colorless compounds by many factors including pH, temperature, light, oxygen and food matrix components (Wang and Xu, 2007). In this sense Giusti and Wrolstad (2003) used microencapsulation to increase the stability of anthocyanins and for this purpose the spray-drying technique was used to encapsulate these compounds originated from Cabernet Sauvignon grapes. They concluded that the obtained microcapsules presented uniform particle sizes and a spherical surface. Moreover, a combination of maltodextrin and gum Arabic resulted in increased protection of the anthocyanin pigments (Giusti and Wrolstad, 2003).

2.2. Hydrogels

Hydrogels are commonly defined as a three-dimensional (3D) network of hydrophilic polymeric molecules that may be associated by forming covalent or non-covalent (e.g., hydrogen bonds, van der Waals interactions and physical entanglements) interactions (de

Souza Simões et al., 2017). These polymer 3D networks are prepared by gelation processes, mainly through aggregation of polymeric chain groups through intermolecular bonds, which are mainly composed of crosslinked natural polymers (e.g., alginate, chitosan and gelatin) or synthetic macromolecules (e.g., polyethylene glycol and polyvinyl alcohol) (Marchesan et al., 2013).

The continuous polymerization increases the extent of the ramification (i.e., increase in size of the polymer chain groups) and, consequently, decreases its solubility, which it is called “sol”. In other way, the transition between the aggregation of polymeric molecules and the continuous cross-linking is called “sol-gel transition”, or gelation, and the critical point where the gel is formed is denominated by “gel point” (Ramos et al., 2014). In order to produce hydrogels, bioactive compounds or cells are premixed in an aqueous solution (sol) and applied to a matrix site, to form a hydrogel depot through a sol-to-gel transition mechanism. This sol-gel transition can be generated by changing the environmental conditions including pH, temperature, light and ionic strength. In this sense, pH-sensitive hydrogels shrinkage under gastric conditions but only swells under intestinal conditions, which means that this bioactive delivery system may be used to protect a compound from the harsh conditions of the human stomach, releasing its content in the small intestine, so that nutrient absorption can occur (de Souza Simões et al., 2017).

Hydrogel in the presence of water has the ability to swell ca. 30 times their initial size, and it is able to hold a large amount of water while maintaining its network structure (Ramos et al., 2017). Other proprieties such as: appearance, texture, responsiveness and water-holding capacity are essential characteristics that may be determined by the strength, number and morphology of the structural units and presence of hydrophilic moieties (i.e., hydroxyl, carboxyl, ethers, amines and sulphate groups) (Davidov-Pardo et al., 2015).

2.3. Lipid-based systems

Lipid nanoparticles are currently present in different commercial food matrix, and are now being studied in several other products. Beverages are the focus of this lipid based-systems since soft drinks, fortified waters, fruit juices and dairy drinks, may contain already small oil droplets dispersed in water that falls into the nanoscale range (d < 100 nm) (Piorkowski and

McClements, 2014). Nonetheless, lipid nanoparticles are also being developed as colloidal delivery systems to encapsulate, protect and release hydrophobic bioactives, such as colors, flavors, antimicrobials, antioxidants, nutrients and nutraceuticals (Livney, 2015). Lipid based systems are crucial for compounds that present poor water solubility, due to their intrinsic physicochemical properties, diversity and biocompatibility (de Souza Simões et al., 2017). Also lipid-based systems can be designed to be optically transparent (which is desirable for clear foods and beverages), and they can increase the physical stability of the product (since small particles are less susceptible to gravitational separation and aggregation). These systems may be classified into: emulsions, solid lipid nanoparticles, nanostructured lipid carriers and liposomes. Nonetheless the most common applications in beverages are the emulsions, specifically nanoemulsions due to some advantages revised below. Solid lipid nanoparticles, nanostructured lipid carriers and liposomes are less applied and for that reason will be summarized together in the section “other lipid-based systems”.

2.3.1. Emulsions

Emulsions are formed by two immiscible phases in which one (i.e., dispersed phase) is spread in small droplets in a solution (i.e., continuous phase) forming a stable phase combination (de Souza Simões et al., 2017). Bioactive compounds can be incorporated into the dispersed phase and protected in the continuous phase from external environmental conditions (Sagalowicz and Leser, 2010). These systems can be classified as (i) oil-in-water (O/W), (ii) water-in-oil (W/O), (iii) liquid-in-liquid or (iv) solid-in-liquid emulsions. The characteristics and stability of the emulsion depends on the type of emulsifiers/surfactants, the interface between phases, the composition, the surfactant-to-oil ratio, the presence of co-solvents and co-solutes, and the homogenization conditions (Livney, 2015).

Conventional emulsions are usually opaque under multiple scattering techniques, but in other way nanoemulsions (i.e., typically ranging from 10 to 100 nm), are optically transparent and considered more appropriate as delivery systems for controlled release of bioactive compounds in beverages (Fathi et al., 2012). Nanoemulsions are composed by very small droplets, so they can be added to transparent or slightly turbid products, such as most of the fortified waters, soft drinks and fruit juices. These small size droplets in nanoemulsions also contributes to their higher stability to gravitational separation and particle aggregation than conventional emulsions, which are two of the major frequently instability phenomena faced by commercial beverage products (Rao and McClements, 2013). Recently, there has been considerable attention in the utilization of nanoemulsions as delivery systems to encapsulate lipophilic flavor compounds among others such as essential oils (e.g., ω-3-rich oils), polyphenolics (e.g., curcumin), antioxidants (e.g., quercetin), antimicrobials (e.g., thymol) and vitamins (e.g., vitamin A) (Sagalowicz and Leser, 2010). Hydrophilic and amphiphilic bioactive components may also be incorporated within the oil droplets, the continuous phase or the interfacial region of the oil-in-water nanoemulsions, depending of their nature (Berton-Carabin et al., 2013).

Emulsions can be prepared by high pressure valve homogenizers, microfluidizers and sonicators, which are high-energy techniques that require special equipment. However low energy methodologies can be also employed, which are mainly dependent on the intrinsic physicochemical properties of surfactants and oily phases (i.e., phase inversion and solvent demixing methods) (Silva et al., 2012)

One of the most important challenges facing by the food and beverage industry is to produce food grade nanoemulsions from label-friendly components. For instance, the surfactants that have been commonly used to fabricate very small droplets in nanoemulsions are synthetic ionic or non-ionic surfactants (e.g., sodium dodecyl sulfate and Tweens) (Rao and Mcclements, 2012). However, it is possible and increasingly common the preparation of food grade nanoemulsions using more label friendly surfactants, such as sucrose monoesters, which breakdown into a sugar and a fatty acid within the stomach (McClements and Rao, 2011).

Previous studies determined whether flavor oil nanoemulsions with fine droplets and high physical stability could be produced using food grade co-solvents and co-surfactants. The obtained data from this study would then enable the rational production of food grade delivery systems for application in transparent beverage products (Rao and McClements, 2013)

Curcumin and catechin microcapsules prepared elsewhere (Aditya et al., 2015) using W/O/W emulsions were developed aiming the prevention of the degradation of both bioactive compounds into beverage products. The biological activities of curcumin and catechin are superior when they are used in combination. In the food sector, these two bioactive compounds are used to develop functional food and drink products owing to their activity in preventing several diseases such as cancer, obesity, infection and cardiovascular ailments (Aditya et al., 2015). Nonetheless these two compounds are unstable and easily degraded in the presence of oxygen, alkaline pH and high temperature. In this study, it was found that the stability of curcumin and catechin, when encapsulated, either separately or in combination, increased when added into a model beverage system (Aditya et al., 2015).

In another study, it was also showed that the encapsulation of lemon oil (used as bioactive compound) with maltodextrin, using the spray-drying technique, increased its stability (Kausadikar et al., 2015). Lemon oil has a sharp, fresh smell and for this reasons, it is mainly used as a flavoring agent in food and beverages. However, the high levels of unsaturated and oxygen-functionalized compounds in this oil impact oxidation during storage. Thus, the microencapsulation technique used here to address this problem showed that the encapsulated lemon oil exhibited a good odor/taste profile and appearance during 6 months of storage for tested conditions.

2.3.2. Other lipid-based systems

Solid lipid nanoparticles (SLNs) are prepared by using common lipids like sunflower and palm oils, and are simply O/W emulsions in which the lipid phase has been totally or partially solidified by a solid lipid or solid lipid mixture (Gao and McClements, 2016). SLNs have some limitations, such as limited loading capacity and premature release of the entrapped compounds, which are associated with the low solubility of the bioactive compounds in the molten lipid and the high water content of the dispersions. This turns the system unstable during the storage. Moreover when the lipid matrix are composed by similar molecules (i.e., tristearin or tripalmitin), a perfect crystal are formed with few imperfections and the bioactive compounds are incorporated between the lipid layer and the crystal (Tamjidi et al., 2013).

Nanostructured lipid carriers (NLCs), were created to surpass the major drawbacks of SNLs, exhibiting a higher loading capacity and a sustained bioactive compound release due to the low crystallinity index (Gutiérrez et al., 2013). NLCs are a combination among lipids in the liquid and solid state, where the overall solid content can be up to 95 % of the total weight.

Though, in the food industry, the use of NLCs has some limitations such as the relatively low purity of the bio-based materials employed in comparison with those of the pharmaceutical industry. On the other hand, the different pH values, osmotic pressure and ionic strength of food matrices can lead to agglomeration and flocculation of NLCs, when added to food and beverages products (Liu et al., 2012).

Liposomes are most frequently used in the pharmaceutical and food industries for encapsulation of aqueous solution within a membrane of phospholipids. Liposomes are microscopic vesicles composed of phospholipid bilayers surrounding aqueous compartments (de Souza Simões et al., 2017). Encapsulation into liposome systems can protect bioactive compounds from adverse environmental and chemical conditions, including the presence of enzymes or reactive chemicals, and exposure to extreme pH, temperature and high ion concentrations (Foged et al., 2007).

This delivery system is fabricated through combining surfactants and water, under low shear forces. The capacity to encapsulate hydrophilic, hydrophobic and amphiphilic bioactive compounds turns them suitable carriers to be applied in the food and beverage sector (Foged et al., 2007). Nonetheless, the high cost associated to their production, low loading capacity, fast release rates and relatively high instability, during storage, still limiting their widely application (Dima et al., 2015).

3. Micro- and nanotechnology for beverage safety

Food safety and quality are relevant matters that have captured the attention of consumers, food players, governments and organizations because food is a crucial part of human life, and food industry is huge business in constant evolution. Therefore, the absence of contaminants in food products is fundamental either for consumer’s health or for the continuous growth of this industry. Contaminants are chemical, physical and biological elements that can inadvertently enter on food products during its processing, handling and distribution (Kuswandi et al., 2017). Chemical contaminants, including the pesticides (Sun et al., 2012), heavy metals (Soldatkin et al., 2012), antibiotics (Shrivastav et al., 2017), melamine (Zhu et al., 2016) and nutrients, are the most commonly found in beverages and food products, and can originate from natural sources, environmental pollution or be formed during whole food chain. Physical (e.g., radioactivity, light, noise and thermal discharges) and biological (e.g., toxins (Zhang et al., 2017) and pathogenic bacteria (Thakur et al., 2015)) contaminants are also important factors affecting the quality and safety of food and beverages, which may have potential health effects and risks for human consumption. Regarding the biological contaminants the main foodborne illness outbreaks are provoked by *Campylobacter* spp., *Salmonella* spp., *Listeria monocytogenes*, *Escherichia coli*, *Staphylococcus aureus*, and *Bacillus cereus* (Kuswandi et al., 2017).

Micro-, and in particular, nanotechnology can be explored as innovative and a high potential tool to detect, measure, monitorize or remove these contaminants, thus being crucial in the preservation of food quality and safety, which are fundamental for food industry.

3.1. Detection of contaminants or adulterants and microorganisms

A rapid detection of contaminants in food products is a crucial step because it allows a fast decision-making, which is of extreme importance to maintain the public health. In this sense, the use of sensors has been proposed to monitor and receive information about food contamination. Sensors provide information in the form of variation of energy, (e.g., thermal, mechanical, optical, electrical, magnetic, or biochemical) into another form of energy. The progression over the past few years in nanotechnology field allowed the development of innovative and more accurate sensors, known as nanosensors (Dahman, 2017). Normally, to be considered a nanosensor, it must fulfill at least one of these parameters: i) the sensitivity of the sensor, ii) the interaction confinement between the sensor and the substance; and iii) the size of the sensor, have to be on the nanometer scale (Dahman, 2017).

In this context, the major advantages of nanosystems are: i) the high level of sensitivity; ii) the specificity potential and possibility of detect multiple analytes; and iii) the control in real time and *in situ*. These features are conceivable due the large number of sites accessible for molecular interactions promoting from the high surface to volume ratio of nanosystems (Bueno et al., 2017). Comparing to other sensors at micro- and macroscales, nanosensors are small and lightweight, have a large reactive surface area, greater selectivity, better sensitivity and faster detection (Dahman, 2017). Hence, nanosensors have been attainment more marketing attention at an early stage, when employed to detect and measure chemical and biological properties at industrial level, and more recently, as remarkable tool for solving safety and quality issues. Generally, nanosensors can be categorized based on four criteria: i) nature of interaction between the sensing component and the analyte; ii) method used to detect this connection; iii) type of the recognition constituent (e.g., biological or inorganic); and iv) transduction structure (Bueno et al., 2017).

In food and beverage industry, nanosensors can be used to detect contaminants on packaging or during processing, distribution and storage. Detection of food contamination is crucial for human health care, and for monitoring the global trading of contaminated food and beverage products. Therefore, it is necessary further research and investment in the improvement of existing nanosensors (chemical and biosensors) or even in the development of innovative ones, with faster and more accurate detection functionalities, as they have demonstrated to be an enormously viable alternative to conventional analytical techniques such as chromatography and spectroscopy, most frequently used in contaminants detection (Kuswandi et al., 2017).

Melamine is a chemical adulterant frequently used in food and beverage industries and due its high nitrogen level is illegally added to various foodstuffs as milk beverages in order to increase its protein content. Recent advances in analytical methods using nanosensors for melamine contamination incidents detection are in progress. For example, a ratiometric sensor based on conjugated polyelectrolyte-stabilized silver nanoparticles was developed for determination of melamine in milk beverage products, through fluorescent and colorimetric sensing (Zhu et al., 2016). Another recurrent chemical contaminant that has been extensively used in cattle industries and consequently found in milk beverages is the erythromycin antibiotic. However, considering the potential harms for human health due to the presence of erythromycin residues in milk, various countries have fixed a maximum residual limit. Food and Drug Administration (FDA) approved some antibiotics for use in lactating dairy cows, but it was established an Acceptable Daily Intake (ADI) in μg/kg bw/day for human exposure to total drug residues in milk and milk products. For erythromycin, the hazard value (HZ) is between $15 \leq HV < 40$ μg/kg bw/day (FDA, 2015). A recent method to accurate detect erythromycin has been created employing a fiber optic core covered with a silver coating and with a layer of erythromycin imprinted nanoparticles. The sensor was applied in milk beverages and showed various advantages such as fast response time (less than 15 s), low cost and highly selective (Shrivastav et al., 2017).

Concerning biological contaminants, the pathogens that may be present in food and beverage products are frequently detected and identified by using conventional, yet specific, inexpensive and sensitive microbiological and biochemical methods. These techniques can be used to have a qualitative and quantitative evidence of specific pathogenic microorganisms, but usually requires a considerable period of time (can vary from a few hours to a couple of days) to produce the results (Koedrith et al., 2014). There are numerous recognized benefits of using nanosensors to guarantee the microbial food safety, such as the low cost of analysis due to less sample volumes needed, the use of few reagents, the reduced time of analysis required, the possible of multianalyte analysis, and the use of safer devices with low environmental risks associated (Grumezescu and Oprea, 2017). Hence, the use of nanosensors has showed great potential to detect biological contaminants (e.g., toxins and pathogenic microorganisms) in beverages and thus they have been increasingly explored. There has been a growing attention in developing new techniques based on nanomaterials to detect pathogens such as *S. aureus* and *E.coli*. In this sense, a colorimetric sensor film, made from polyaniline nanoparticles were synthesized and proposed by Thakur et al. (2015) for detection of bacterial growth using *E.coli* as proof of concept. The films, developed by these authors, exhibited a visible color change, from blue to green, when the bacterial growth was detected. In this case, the sensor showed two important advantages, it is generic (since no specific antibodies or receptors were needed), and have potential to verify the safety of beverages in real time (Thakur et al., 2015). In another study conducted by Lai et al. (2015), a nanoprobe-based mass spectrometry was developed to detect *S. aureus* in aqueous samples. In this case, a peptide DVFLGDVFLGDEC (DD) that recognizes *S. aureus* was used, as the reducing agent, and the protective group to generate DD-immobilized gold nanoparticles (AuNPs@DD) from one-pot reactions. The generated AuNPs@DD can selectively attach to the pathogen and the complexes (target bacteria with AuNPs) were directly evaluated by surface-assisted laser desorption/ionization mass spectrometry (SALDI-MS), which allows obtaining a low limit of detection (in the order of a few ten cells). Apple juice mixed with *S. aureus* was used, as proof of concept, to validate the suitability of this method for application in beverage products (Lai et al., 2015).

As described before, mycotoxins are also a biological contaminant that can be present in beverages. Mycotoxins are secondary metabolites, naturally produced by fungal species such as ochratoxin and patulin, which can be present in small amounts in foodstuffs (Grumezescu and Oprea, 2017). A surface plasmon resonance (SPR) assay of ochratoxin A using AuNPs was explored by Yuan et al. (2009) and it proved to be rapid and highly sensitive for the detection and quantification of ochratoxin A in wine, grape juice and apple juice. This approach relevels to be a relevant and accurate tool for detecting this teratogenic and carcinogenic toxin in food and beverage matrices (Yuan et al., 2009). For the determination of patulin in apple juice, a phosphorescent nanosensor based on a surface molecularly imprinted polymer capped Mn-doped ZnS quantum dots has been recently developed and presented a high selectivity and adsorption capacity (Zhang et al., 2017).

In summary, the use of nanosensors, as suitable and promising tool to detect the presence of contaminants in beverage products, is gaining a growing importance and popularity over traditional methods, because of their higher portability and specificity, lower cost, faster response versus time, and allows a continuous real-time signal monitoring.

3.2. Removal of chemicals or pathogens

The shelf life of several beverages has been accomplished by thermal treatment, being the temperatures of pasteurization between 72 and 82 °C. However, thermal treatment could reduce the quality and freshness of the product. Therefore, antimicrobial compounds have been used to prevent or eliminate microbial contamination (Speranza et al., 2017). There are several compounds that exhibit antimicrobial activity, such as metal ions and their oxides (e.g., silver, copper, zinc, magnesium, palladium and titanium) or natural antimicrobial agents (e.g., essential oils, bacteriocins, among others) (Srividya et al., 2017). However, these compounds are chemically reactive species that can originate undesirable effects when incorporated into a food matrix like beverages, causing alterations on the physical stability or integrity of the food product, as well as a reduction in the biological activity of antimicrobials. Therefore, the entrapment of antimicrobial compounds may represent a suitable solution to solve this challenge, thus improving the quality and safety of foods. In this context, the use of nanosystems can be interesting because they can control the release of compounds entrapped into, protecting them from adverse conditions (e.g., undesired temperature, pH, or presence of enzymes), enhancing their stability and also reducing the quantity required to achieve the desired antimicrobial effect (Speranza et al., 2017).

The bioactivity of nanosystems is dependent on multiple factors, including the particle size, shape, concentration, charge and sensitivity of microorganism to nanosystem action (Srividya et al., 2017). The antimicrobial effect is size-dependent, for instance Panáček et al. (2006) showed that the action of silver nanoparticles raised with the decrease of the nanoparticle diameter, which is likely due to a larger surface area of interaction that improves the binding capacity to the microbial cell (Panáček et al., 2006). On the other hand, the shape of the particles is correlated with the reactivity of nanosystems, thus spherical and rod-shaped silver nanoparticles demonstrated to have less antimicrobial effect against *E. coli* compared to triangular particles (Pal et al., 2007). The charge is also an important feature, Imani et al. (2012) showed that the opposite charge between the surfaces of microbial cells (which is negative) and the CuO and AgO nanoparticles (which are positive) allows electrostatic interactions, and thus a higher effect upon the *Clostridium botulinum* cells. In this way, the large contact area causes an oxidative effect on the surface molecules of the microorganisms, causing their unviability (Imani et al., 2012). Lastly, microorganisms display different sensitivity to nanoparticles due to their morphology. For instance, the antimicrobial action of silver nanoparticles is higher on Gram-negative (e.g., *E. coli*) than Gram-positive (e.g., *S. aureus*) bacteria (Santos et al., 2013).

Micro- and nanosystems can be used directly into food systems, where the bioactive compounds are released and act, or they can be incorporated in packaging materials, where the bioactives migrate progressively from the package to the food matrices, performing their activity. Some active delivery systems incorporating antimicrobial agents have been already developed and used into beverage products. Thymol nanoemulsions have been developed combining gelatin and lecithin, as base encapsulating materials, and used in milk and cantaloupe juice. These nanoemulsions were more effective than free thymol, showing a high inhibition of *E. coli* O157:H7 and *L. monocytogenes* (Xue et al., 2017). In another study, the encapsulation of isoeugenol using spray-dried emulsions enhanced the efficacy of this antimicrobial compound against Gram-positive and Gram-negative bacteria in carrot juice (Nielsen et al., 2016). On the other hand, antimicrobial active packaging incorporating antimicrobial micro- and nanoparticles into polymer films, has been also investigated by Palomero et al. (2016), who shows that antimicrobial agents can act by direct contact or migrate slowly and progressively into the package. Antimicrobial packaging materials are usually composed by antimicrobial micro- or nanosystems incorporated into inert ceramic, glass or zeolites matrix, or included in plastic polymers like nylon polyamide (Palomero et al., 2016). For example, nanocomposite low-density polyethylene films containing Ag and ZnO nanoparticles were performed by melt mixing in an extruder. Fresh orange juice was storage in these packages at 4 ºC and the shelf life of this product was extended up to 28 days (Emamifar et al., 2010). Other films also comprising Ag were obtained by depositing, via plasma, an Ag-containing polyethylenoxide-like coating on a polyethylene layer. This packaging system was capable of inhibiting *Alicyclobacillus acidotrerrestris* (a spore-forming bacteria already recognized as a cause of spoilage in acidic beverages) in an apple juice (Del Nobile et al., 2004).

Another problem in food industry is the penetration of oxygen through the food and beverage packaging, because it is responsible for oxidative rancidity of fats, loss of vitamins including vitamin C, browning of food products, alterations in flavor and growth of aerobic spoilage microorganisms (Grumezescu and Oprea, 2017). Therefore, the disposal of oxygen is imperative in the beverage field because allows overcoming some difficulties in the distribution associated with the oxidation of sensitive components present in beverages (Palomero et al., 2016). In this sense, functional nanoparticles have been used to produce oxygen scavenger films. For instance, polyolefin nanocomposite films containing an iron modified kaolinite have been studied by Busolo and Lagaron (2012) to verify their potential as oxygen scavengers in active food packaging. These films exhibited a significant oxygen scavenger activity by two means: i) active performance, i.e., trap and react with molecular oxygen; and ii) passive performance, i.e., impose a difficult diffusion path to the permeant (Busolo and Lagaron, 2012). Another system that showed good oxygen scavenging capacity was a gelatin film contained α-tocopherol-loaded nanoparticles and iron chloride (Byun et al., 2012).

Therefore, micro- and nanotechnology have showed a great potential, and it is currently becoming increasingly important, in food safety, particularly for prevention or inhibition of spoilage and pathogenic microorganisms, thus extending the shelf life time of beverages.

4. Micro- and nanotechnology for beverage processing

In recent year's innovation in encapsulation and particular in nanotechnology have allowed food industry to overcome processing difficulties related with the addition of ingredients, trough reducing the impact of their incorporation on the beverage texture, taste, and color (Ezhilarasi et al., 2013, Zhu et al., 2016). Encapsulation is a process to entrap bioactive compounds into particles, which may be used to retain flavors in food products or to allow a controlled release, thus improving bioactive compounds bioavailability. This enables that some sensitive compounds can be used in industrial process, preventing the loss of flavors, vitamins or essential oils (Estevinho and Rocha, 2017, Zuidam and Shimoni, 2010). Food flavor can be defined as sensorial impression of food that is created during food consumption. The incorporation of a flavor in a beverage product can improve the sensorial attribute of a product, and thus the consumer satisfaction, while their encapsulation may allow either their stabilization during storage and manufacturing process, which is a current challenge, or their controlled release, thus maintaining it for long time period (Estevinho and Rocha, 2017, Trifković et al., 2016). Therefore, the encapsulation technology may be used to mask bad tasting, increase the solubility and stability of some food ingredients (in particular those with poor water solubility or high reactive), thus increasing their bioavailability and consequent effectiveness. Other approaches have been used in food and beverage industry such as the adopted by Senomyx (which works in the development and commercialization of novel flavor ingredients), which produce bitter blockers at nanoscale able to trick the tongue by activating the taste receptors, thus reducing the bitterness naturally inherent of some foods, or by activating the sweet or salty enhancers (Wenner, 2008).

For flavor nanoencapsulation, the spray drying technique is the most frequently use since present a vast number of advantages such as the low cost of the process, the large variety of carrier materials (e.g., arabic gum, maltodextrin, modified starch), the ability to retain volatile compounds, and the capacity to large-scale production. For the large majority of thermally-sensitive materials or flavors encapsulated at industrial scale, spray drying is the process frequently chosen. This process produces a dry powder from a liquid, and is based on the dissolution and emulsification or dispersion of the active compound in an aqueous solution containing the carrier material. The solution is them submitted to an atomization process in a hot chamber (usually through a hot air), thus resulting in water evaporation and in the promptly production of a powder (Zuidam and Shimoni, 2010, Trifković et al., 2016). During this process there are some parameters that should be taken in account, such as the temperature, the feed rate, the viscosity and the surface tension of the solution. For instance, at the same temperature the size of the produced particles increases by increasing the feed rate, the viscosity, or the surface tension of the solution to dry. The particles produced by this method ranges between 10-50 µm, and the separation of the particles from the hot air is made by a cyclone (Estevinho and Rocha, 2017). Some of the flavors that can be encapsulated resorting to a spray drying are rosemary and mandarin essential oils, D-limonene, Cardamom oleoresin and L-Menthol (de Barros Fernandes et al., 2014, Bringas-Lantigua et al., 2011, Krishnan et al., 2005, Fisk et al., 2013, Soottitantawat et al., 2005).

Nanoencapsulation has an important role in the development of functional foods, once allow the addition of many bioactive compounds and nutrients, which could not otherwise be added (Zhu et al., 2016). One example of nanotechnology application in beverages is the development of oat chocolate and oat vanilla nutritional drink mixes. These drinks were produced for dairy drinks free of gluten and soy to address children's nutritional disorders and are composed by Sunactive® Fe that is an enzymatically modified lecithin stabilized by iron pyrophosphate colloidal particle. These nanoparticles, which range from 10 to 300 nm, increase the bioavailability of Fe (Aydogan-Duda, 2017, Zuidam, 2012). The formulation Sunactive® Fe has been also used in other products such as in fruit juice. This product, commercially produced by Jamba Juice Hawaii and known as “Daily Vitamin Boost”, is a fortified juice containing 22 essentials vitamins and minerals (Farré and Barceló, 2012). Other commercially available product developed by BASF resorting to nanotechnology is LycoVit. This product use a synthetic lycopene, which has red color and potent antioxidant activity, in soft drinks an juices (Ijabadeniyi, 2012). Nano Tea is a nutraceutical product using nanoparticles with size of 160 nm that has antioxidant activity and acts as an immune booster and antiaging agent. The process of producing this product encompasses crushing the tea in a crusher to 80 meshes, followed by airflow collision crushing, and finally crushing into nano powder with particles below 100 nm (QU LAI, 2003). Aquanova is a manufacturing company that developed a beverage product called NovaSol, which uses nanolipid carriers (i.e., micelles) to encapsulate bioactive compounds and natural colorants (e.g., vitamins, omega-3 fatty acids, coenzyme Q10, isoflavones, flavonoids, carotenoids, phyto extracts and essential oils), enhancing their stability in foodstuffs (Silva et al., 2012). The use of nanotechnology in food and beverage products has a great potential of applications and benefits for human health, however the products commercial available for consumption are scarce and limited to the examples presented above. This field still requiring a huge investment in research and development and therefore several projects are on-going. In this regard, the most promising developments for incoming years, but at early stage research, are presented below.

Wang and co-workers (2016) developed an innovative functional drink from natural ingredients, including both hydrophilic and hydrophobic vitamins and mineral salts, resorting to nanotechnology. The authors designed a nanoemulsion of ca. 250 nm composed by a mixture of peppermint oil (previously dissolved in propylene glycol together with Vitamin D3 and E) with sodium caseinate, and complexed with pectin (where vitamins B3, B6, B12 and C are previously dissolved) to be incorporated into a drink. The resulting functional drink was able to retain the antioxidant activity of encapsulated nutrients during storage (Zhu et al. (2016). In another study conducted by Bovi et al. (2017), it was demonstrated that a nanoemulsion of buriti oil can be incorporated in isotonic beverages. The purpose of use buriti oil in beverages is to replace artificial coloring agents by natural dyes, since it is rich in carotenoids and already in use by food industry (Bovi et al., 2017). Khoozani et al. (2014) studied the activity of calcium carbonate nanoparticles added to acidic drinks to prevent tooth erosion once the frequent consumption of this kind of drinks can cause dental erosion. This study demonstrated that the use of these nanosystems at 0.06 % in soft drinks can reduce or prevent tooth erosion (Khoozani et al., 2014). Other study conducted by Min et al. (2015) also showed that the addition of nanosystems, composed by hydroxyapatite, to sports drink have prevented dental erosion (Min et al., 2015). Several other works showed the potential of active nanosystems, in particular of nanoemulsions, in preventing the microbiological spoilage on beverage products. Ghosh et al. (2014) designed an antimicrobial O/W nanoemulsion eugenol-loaded to preserve fruit juice against microbial spoilage. This formulation demonstrated a significant reduction on the heterotrophic bacteria population in orange juice (Ghosh et al., 2014). Joe et al. (2012) developed an active nanoemulsion composed with sunflower oil, as base encapsulating material, and surfactin as entrapped bioactive compound to preserve apple juice. This formulation showed to be successfully employed in apple juice with a significant reduction of bacterial and fungal populations (Joe et al., 2012). In turns, Donsì et al. (2011) used terpenes, as bioactive compounds, entrapped into nanoemulsion based sunflower oil, to delay or completely inactivate the microbial growth in orange and pear juice (Donsì et al., 2011), whereas Char et al. (2016) showed that using capsul®, a modified maize starch emulsion contained carvacrol, as bioactive compound, successfully inactivated *E. coli* in apple and orange juices.

García-Ruiz et al. (2015) demonstrated the high inhibitory spectrum potential of two innovative silver-based biocompatible nanoparticles against *E. coli*, *S. aureus*, *Oenococcus oeni*, *Lactobacillus casei*, *Lactobacillus plantarum*, *Pediococcus pentosaceus*, *Acetobacter aceti* and *Gluconobacter oxydans*, that can be successfully applied to control the microbial growth in winemaking. Mirhosseini and Afzali (2016) studied the antibacterial activity of suspensions of magnesium oxide nanoparticles in combination with nisin against *E. coli* and *S. aureus* in milk. The use of such nanoparticles is reported as being a potent biocompatible, low cost and thermostable antibacterial agent with no toxicity (Krishnamoorthy et al., 2012, Jin and He, 2011).

On the other hand, Kin et al. (2014) used nanoemulsions to encapsulate lycopene as antioxidant compound, in order to prevent their degradation when added to complex beverage matrices, thus promoting health benefits for consumers upon ingestion (Kim et al., 2014). Saldanha do Carmo et al. (2017) showed that using cyclodextrins-limonene inclusion complexes can improve the aroma and shelf life of beverages products (Saldanha do Carmo et al., 2017).

Tao et al. (2017) developed an O/W microemulsion encapsulated with steppogenin to improve its solubility and stability when added to apple juice. This bioactive compound is of particular importance once inactivates the tyrosinase, which is the enzyme responsible for the browning in juice fruits, which leads to huge losses in beverage industry (Tao et al., 2017). Habibi et al. (2017) demonstrated that the fortification of pomegranate juice with microencapsulate omega-3 fish oil is possible using the complex coacervates of gelatin–gum Arabic. The microencapsulation approach allowed to enrich juice and delayed the omega-3 fatty acids oxidation. Micro- but in particular nanotechnology promote innovation in the beverage industry, thus allowing the development of more natural and healthier products through the fortification with new proprieties; while permit either controlling microbial processes in fermentation or the microbial spoilage in beverages. Preventing the oxidation, retaining flavors, changing colors, or tricking the tongue to provide a pleasant perception of what we drink, are some of the possible applications of this technology that the beverage industry will certainly apply in near future.

Table 1. Commercial beverages products containing nanosystems. Adapted from Farré and Barceló (2012), Ijabadeniyi (2012), and Talegaonkar et al. (2016).

Product name	Manufacturer	Nano Content	Purpose	References
Oat chocolate and Oat Vanilla - Nutrional Drink Mixes	Toddler Health	Particles of iron with 300 nm (Sunactive® Fe)	Increase bioavailability of iron	(Zuidam, 2012)
Daily Vitamin Boost - fortified fruit juice	Jamba Juice Hawaii	Particles of iron with 300 nm (Sunactive® Fe)	Provide 22 essentials vitamins and minerals	(Farré and Barceló, 2012)
Nano Tea	Shenzen Become Industry & Trade Co.	Particles with 160 nm	Immune booster, antiaging, and antioxidant agent	Patent Nº 0100033.3
Synthetic lycopene	BASF	<200 nm synthetic lycopene - LycoVit 10%	Colorant (provide red color) and potent antioxidant agent	(Ijabadeniyi, 2012)
NovaSol®	Aquanova®	Capsules ranging from 30–40 nm	Increase the potency and bioavailability of active ingredients	(Silva et al., 2012)

5. Products, market and future trends

Global food challenges for humans in the 21st century are rapid population growth, population health and its maintenance, food supply and safety, and sustainable use of resources. Advances in science and technology are fundamental to archiving economically viable solutions to such challenges (Sun-Waterhouse and Waterhouse, 2016). The application of micro- and nanotechnology in food and beverage industry have a huge potential for adding value to the food chain by altering the food industry in areas as food production, processing, analysis and packaging, thus allowing future populations to attain target nutritional outcomes or health benefits (Sun-Waterhouse and Waterhouse, 2016).

During the last decade, it has been possible verifying a growing trend for “healthy” foods and beverages in many parts of the world and the advances in scientific research in this field support the evidence that diet may fulfill nutritional necessities and exert a beneficial role in some diseases. The idea of health-promoting foods is not new: Hippocrates wrote 2400 years ago “Let food be thy medicine and medicine be thy food” (Corbo et al., 2014).

The research and development in the functional foods field have increased over the past few years and has passed from a tendency to a reality in the food and beverage industry, as a response to a growing consumers' demand for more and more nutritional and healthy food products. In order to accomplish this evolutionary step, the information gathered by researchers and industrial food workers was essential in the field of micro- and nanosystems. The development and application of these techniques can be found during all steps of the food chain. The investment towards the development of novel approaches to scale up the application of micro- and nanoencapsulation to a large range of processes and products is expected to increase in upcoming years (Momin, Jayakumar and Prajapati, 2013; de Souza Simões et al., 2017).

Several critical causes have been known as the main factors that promotes the diffusion of functional foods, namely: the health deterioration owing to busy lifestyles, poor or deficient consumption of convenience food products and scarce exercise; increased incidence of self-medication; growing awareness linking diet to health due to more information available by health authorities and media on nutrition; and a loaded and competitive food market (Granato et al., 2010). Nowadays, the variety of functional foods comprises products such as baby foods, baked goods and cereals, dairy foods, confectionery, ready meals, snacks, meat products, spreads and beverages (Corbo et al., 2014; Perricone et al., 2015). In particular, beverages are the greatest active functional foods category owing to i) convenience and possibility to satisfy consumer needs for packaging contents, size, shape, and appearance; ii) ease distribution and better storage conditions for refrigerated and shelf-stable products; and iii) great opportunity to incorporate desirable nutrients and bioactive compounds (Sanguansri and Ann Augustin, 2010; Wootton-Beard and Ryan, 2011; Tiwari et al., 2012; Corbo et al., 2014).

Materials at micro- and nanoscale exhibit different physical, chemical and biological properties, which may enhance the features of such materials or even display new functionalities and applications in comparison with those at large scales (Durán and Marcato, 2013; Kwak, 2014; de Souza Simões et al., 2017).

The term “nanofood” describes food that has been produced, processed or packaged using nanotechnology approaches, or to which engineering nanosystems or nano-ingredients have been deliberately added (Sekhon, 2010). Nanofood has been part of food processing for centuries, since many of the food structures are naturally present at the nanoscale. The purpose of nanofood is to enhance food nutrition, favor, quality and safety, while reducing the costs. The major benefits of nanofood are the use of additives promoting health and foodstuffs with extended shelf life or novel flavor and odor varieties. So far, the warnings and concerns about nanofoods produced via the deliberate addition or manipulation of molecules are growing; however they have not reached a tipping point in terms of public attention. Instead, nanotechnology is being used in more than 100 food products, food packaging and contact materials currently on the shelf. Already in 2004 more than 180 nanotechnological developments at different stages of implementation in food industry are known. In March 2006, more than 200 foodstuffs marked as “nano” by their producers were present at the world market. Of them, 59 % are linked to the Health and Fitness, while only 9 % to the food and beverages field (Popov, Filippov and Khurshudyan, 2010).

There are several food products currently commercially available containing nanosystems or nano-ingredients that were deliberated added. The list of products still growing, however only the most commercially known are presented below: Canola Active Oil (Shemen, Haifa, Israel), Nanotea (Shenzhen Become Industry Trading Co. Guangdong, China), Fortified Fruit Juice (High Vive.com, USA), Nanoceuticals Slim Shake (assorted flavors, RBC Lifesciences, Irving, USA), NanoSlim beverage (NanoSlim), Oat Nutritional Drink (assorted flavors, Toddler Health, Los Angeles, USA), and 'Daily Vitamin Boost' fortified fruit juice (Jamba Juice Hawaii, USA) and nanocapsules containing tuna fish oil (a source of omega 3 fatty acids) in "Tip-Top" Up bread (Enfield, Australia) (Sekhon, 2010). Various functional compounds, such as vitamins A and E, isoflavones, phytosterols, lycopene and lutein are available (NutraLease, 2011a). Another company called Aquanova has produced novel beverage solutions with healthy functional compounds rich in co-enzymes, vitamins and natural colorants. The novel encapsulated beverages are also stable under various environmental conditions with the standardized additive concentrations. A listing of food and beverage products containing "nano" is provided by the Nanotech Project in its Nanotechnology Consumer Products Inventory.

The global market for the application of nanosystems into food products is projected to reach US$10.1 billion by 2024, driven by the increasing need for higher bioavailability of nutrients, growing number of possible applications, and recent technological and scientific advances. Despite the significant developments and innovation in other areas, nanotechnology stills a niche in the food industry. However, the market is growing with food manufacturers and research groups actively endeavoring to apply advances in nanotechnology to the food industry (Global Industry Analysts 2017). At the same time, it is still early to say that nanotechnology has already been introduced in food industry. The initiation of this process can be dated back to 2000, when Kraft Foods installed the first nanotechnological laboratory and NanoteK Consortium composed by 15 universities in multiple countries and national research laboratories (Popov, Filippov and Khurshudyan, 2010).

Currently, the U.S. is considered the largest market worldwide for nanoencapsulation for food products, as stated by the recent market research report on Nanoencapsulation for Food Products. This is possible due to the higher number of companies involved in nanotechnology developments and applications achieved, mostly in recent years, which have pushed developed markets such as the U.S. to the top of the food and beverages nanosystems market. Asia-Pacific ranks as the fastest growing market worldwide, with a CAGR of 7.3 %

through the analysis period (Global Food Encapsulation Market 2018). Information regarding the current global market size and the number of companies involved in the nanofood sector varies. This reflects the difficulty in obtaining the exact information due to commercial and environmental sensitivities. Several of the major food and beverage companies are reported to have (or have had) an interest in nanotechnology. These include Altria, Nestle, Kraft, Heinz and Unilever, as well as small nanotech start-up companies (Stain et al., 2012). Moreover, it has been extensively anticipated that the amount of companies employing nanotechnologies to food and beverages products will widely increase in the near future. Taking into consideration the potential rapid evolution in this field, together with and the global setup of international food companies, it possible to predict that more and greater nanofood products will appear on the EU markets within the next few years.

Like any other sector, the food and beverage industry are driven by innovations, competitiveness and profitability. The industry is, therefore, always seeking new technologies to offer products with improved tastes, flavors, textures, longer shelf life, and superior safety and traceability. Other pressures, such as the grown public health consciousness among consumers, and tighter regulatory controls, have also led the industry to focus their action in finding new ways to reduce the amount of salt, sugar, fat, artificial colors and preservatives in their products, and to address certain food-related ailments, such as obesity, high blood pressure, diabetes, cardiovascular diseases, digestive disorders, certain types of cancer (e.g., bowel cancer) and food allergies. The requirements for food packaging have also altered with time, to stronger but lightweight, recyclable, biodegradable and functional packaging materials. "Smart" labels have been created to monitor food quality, safety and security during transportation and storage. Other "newer" societal and technological pressures are further influencing the food industry, such as the need to control pathogens and certain toxins in food, to reduce the amount of packaging and food waste, and to minimize the carbon footprint in the life cycle of food products and processes. In this context, the advent of nanotechnology has raised hopes that it can address many of these needs of the industry (Chaudhry et al., 2008; Stain et al., 2012).

6. Potential Health effects and Risks

The main route for micro- or nanosystems to access the gut and delivery the encapsulated bioactive compounds (e.g., vitamins, antioxidants, nutrients, among others) is through oral ingestion of food and beverage systems. After digestion of foodstuffs, it is expected that the micro- and nanosystems transport the bioactives entrapped into, through the gastrointestinal (GI) tract and delivery it, in a controlled manner – in response to external stimuli (e.g., change in temperature or pH, or enzymatic action) – in specific sites of action. The uptake of micro- and nanosystems in the GI tract and the subsequent delivery of bioactive compounds depends on several factor such as their i) contact with the gut epithelium; ii) diffusion and accessibility through mucus; and iii) absorption and translocation processes (Martins et al., 2015). In the case of microsystems, due to their higher size, it is expected that the release occurs in the gut, where gut wall ensure the passage of the bioactive compounds, but prevent larger (macro- and microsystems) or foreign materials. In turns, nanosystems, due to their sub-cellular size, can penetrate the gut and deliver the bioactives through the bloodstream, thus assuring a higher bioavailability (de Souza Simões et al., 2017, Martins et al., 2015). The resulting increase in absorption and bioavailability of certain nano-bioactives may lead to a different nutrient profile in the organism or to a greater absorption of some nano-additives (e.g., preservatives), which may have some negative implications in human health such as toxicity to the liver and other vital organs due to over intake, improper metabolism or prolonged clearance of e.g., fat soluble vitamins, which could lead to hypervitaminosis or vitamin poisoning (Chaudhry et al., 2010, Zhong and Shah, 2012). Currently, there are a number of knowledge gaps in relation to the GI fate and toxicity of most types of food grade nanosystems above mentioned. Therefore, there is crucial to better understand their GI fate, after their ingestion when incorporated into beverage products, and to characterize their potential toxicity. This should be performed firstly through *in vitro* experiments (do not raise ethic issues, and are simple and less expensive) and then through *in vivo* tests (to properly understand the behavior of nanosystems and of bioavailability of bioactive compounds under real conditions) (de Souza Simões et al., 2017). The safety assessment of nanosystems is not a simple procedure, since it is not possible to make a general recommendation about the safety. Instead, the safety should be assessed on a case-by-case basis depending on the nanosystems-base material and the characteristics of the foodstuff matrix they are added to, because distinct nanosystems may have different mechanisms of action (McClements and Xiao, 2017).

As referred before, very limited information exists regarding to the fate of nanosystems after absorption, or of their possible toxicity, which is most likely due i) to the fact that nanosystems vary significantly their physiochemical and structural characteristics (Figure 1) when incorporated into foodstuff matrices, thus influencing their GI fate and proclivity to produce toxicity; and ii) to the challenges in detecting bio-based nanosystems within complex biological matrices composed by identical bio-based materials (e.g., proteins, polysaccharides and lipids), through current analytical techniques. Regarding this last point, novel and more accurate analytical methodologies and techniques are required to better detect and isolate nanosystems from complex matrices and to allow their extensive characterization (Tran and Chaudhry, 2010). This has been a limiting step in the scientific advancement in this area and as such should be the focus of high-level research and development efforts in the near future.

7. Safety and regulatory considerations

The beverage industry is continuously finding innovative yet affordable products, to meet the increasing consumer demands for more nutritious, healthy and tasty beverages. In this regard, novel and emergent technologies have been used in an attempt to address many of the industry needs. Nanotechnology, which have been widely used for a long time in the pharmaceuticals, personal care and cosmetics, is gaining popularity and growing interest in beverage industry, once have allowed a whole new array of possibilities, as mentioned before (Augustin and Oliver, 2012). In fact, it has been well predicted that nanotechnologies will have a great impact on the materials development, production, processing, as well as on the technologies used by the beverages and related sectors (Chaudhry et al., 2010, Singh, 2016). However, as happened for novel and emergent technologies, nanotechnology applied to beverages is also expected to face its safety challenge before finding the consumer's acceptance. The innovative characteristics and functionalities of nanosystems have an unpredictable influence in the human body due to possible toxic effect. Nanoscale materials can penetrate though the gut epithelium, reaching the bloodstream and accumulate in vital organs, thus may negatively impact the normal function of the organism (Martins et al., 2015). In addition, studies encompassing the stability and behavior of nanosystems in beverage products are very limited and thus the uncertain about the potential long term impacts are very high (Coles and Frewer, 2013, Handford et al., 2015).

In this sense, the use of nanosystems in beverages intended the human consumption must be done with clarity on its health and safety impacts. Therefore, new studies and measurement tools are wanted to ensure the full safety of products, as well as consumer perception and acceptance evaluations should be performed to realize what the market really needs for its successful approval and use in the beverage industry (Anandharamakrishnan, 2014a).

Concerning the legislation, guidances for risk assessment and regulatory principles on the use of nanotechnology or related terms (e.g., nanosystems, nanomaterials, engineered nanomaterials) in beverage and food products, there is a huge gap of standardized information among different countries (Gergely et al., 2010, Amenta et al., 2015). There was several attempts worldwide to regulate the manufacture and safe application of nanosystems and nanotechnology either by legislation or by recommendations and guidances (van der Meulen et al., 2014), but, until now, the European Union (EU) was the unique international organization that has adopted a clear regulatory definition of "nanomaterial". The EU through the Commission Regulation (EU) report No 1363/2013 published the definition of nanomaterials as "*A natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50 % or more of the particles in the number size distribution, one or more external dimensions is in the size range 1 nm - 100 nm. In specific cases and where warranted by concerns for the environment, health, safety or competitiveness the number size distribution threshold of 50 % may be replaced by a threshold between 1 and 50 %. By derogation from the above, fullerenes, graphene flakes and single wall carbon nanotubes with one or more external dimensions below 1 nm should be considered as nanomaterials*" (EC, 2013). Regarding food contact materials and risk assessment, the regulation (EU) nº 10/2011 on plastic materials and articles intended to come into contact with food mention that "*authorizations which are based* *on the risk assessment of the conventional particle size of a substance do not cover engineered nanoparticles."* Therefore, nanomaterials' risk should be evaluated on a case-by-case basis (EC, 2011).

In countries outside the EU, this regulation takes place in an implicit form that works only as a guidance to provide regulated industries with greater certainty toward the use of nanotechnology (Amenta et al., 2015). For instance, in US, the Food and Drug Administration (FDA) has not established yet, a regulatory definition of nanotechnology, instead, released a framework based in two points for considering whether products contains nanomaterials or otherwise involves the application of nanotechnology: i) *"whether a material or end product is engineered to have at least one external dimension, or an internal or surface structure, in the nanoscale range (approximately 1 nm to 100 nm)*"; or ii) "*whether a material or end product is engineered to exhibit properties or phenomena, including physical or chemical properties or biological effects, that are attributable to its dimension(s), even if these dimensions fall outside the nanoscale range, up to one micrometer (1,000 nm)*", These considerations should be used to new products but also when any processing alter the size, shape, characteristics or effects of an regulated product or any of its components (FDA, 2014).

More detailed information about the regulatory aspects of nanosystems/nanomaterials/nanotechnology in the food sector, in EU and non-EU countries, can be found elsewhere (Amenta et al., 2015). The authors' note that beverages available for consume are composed by carbohydrates and proteins whose molecular size falls in the nanoscale dimension. Moreover, food proteins, which are globular particles between 10 and 100 nm in size, and linear polysaccharides, displaying one-dimensional less than 1 nm in thickness, are true nanosystems and are not known to have any safety issues. Therefore it is crucial to understand and clarify why the concerns related with nanomaterial safety implications are only associated to nanostructures that are deliberately added to foodstuffs. This is likely due to the limited information or absence of scientific information on the impacts of nanomaterials use on human and animal health or on the environment (Anandharamakrishnan, 2014a). In this sense, future studies are urgent in this field.

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