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Nanoencapsulation in the food industry: manufacture, applications and characterization

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ABSTRACT

Particle encapsulation is a standard process in the food industry that consists of encapsulating particles in a protective layer, covering, or containment material to protect a sensitive ingredient or nucleus from adverse reactions. This consists of encapsulating small particle cores in a protective wall with the aim to preserve organoleptic and physico-chemical properties of the original products as well as to improve the palatability of volatile odorous ingredients. Encapsulation of flavors and aromas is a rapidly expanding process in the food industry. Many aroma compounds must to be converted into solid products before its use as flavoring agents. Nano and microencapsulation technology is a very promising area in food industry which will have a great impact on a wide variety of products including functional foods, packaging, preservatives, antioxidants, flavors and fragrances. Spray Drying is a widely used technique to eliminate water and other solvents from solutions, emulsions and suspensions. Spray drying is a rapid, convenient and low cost method in comparison to other techniques as lyophilization. This technology is one of the most common encapsulation methods used in the food industry because of its advantages, such as the wide availability of equipment, large-scale production, simple continuous unit operation, ease of manipulation, and low process cost.

Keywords: *nanocapsules****,*** *nanoencapsulation, nanotechnology, nanoparticle, food industry, spray drying, production techniques.*

INTRODUCTION

The word “nano” comes from Greek and means “dwarf”. A nanometer is a thousandth of a thousandth of a thousandth of a meter (10^{-9}m). One nanometer is about 60,000 times smaller than a human hair in diameter, or the size of a virus, a typical sheet of paper is about 100,000 nm thick, a red blood cell is about 2,000 to 5,000 nm in size, and the diameter of DNA is in the range of 2.5 nm (Sekhon, 2010).

Nanotechnology (NT), which is a broad interdisciplinary area of research, development and industrial activity involves the manufacture, processing and application of materials that have one or more dimensions of the order of 100 nanometers (nm) or less (Chaudhry *et al.*, 2008). The global market impact of nanotechnology is widely expected to reach 1 trillion US $ by 2015, with approximately 2 million workers (Roco & Bainbridge, 2001).The idea of nanotechnology was for first time introduced in 1959, by Richard Feynman, a physicist at Caltech. He never mentioned “nanotechnology,” but he suggested that it will eventually be possible to precisely manipulate atoms and molecules. The term Nanotechnology was first used in 1974 by late Norio Taniguchi and refer to the ability to engineer materials precisely at the scale of nanometers. This is in fact its current meaning, “Engineer Materials” is usually taken to comprise design, characterization, production and application of materials, and the scope has now-a-days been widened to include devices and systems, rather than just materials (Kour *et al.*, 2015). A nanoparticle is defined as the small object that acts as a whole unit in terms of transport and properties (Chellaram *et al.*, 2014).

Nanotechnology is the engineering of functional systems at the molecular scale, it deals with the application, production and processing of materials with sizes less than 1000 nm. It is also explained as the control of matter on an atomic and molecular scale, with at least one characteristic dimension measured in the nanometer range. Nanoscience is a multidisciplinary field that brings together researchers from chemistry, physics, pharmaceutics and biology, among others.

The integration of biotechnology, nanotechnology and information technology has opened up new opportunities. Food nanotechnology has its history from Pasteurization process, introduced by Pasteur to kill the spoilage bacteria (1000 nanometers), who made the first step of revolution in food processing and improvement in quality of foods (Chellaram *et al.*, 2014). Despite this, in the last two decades, the "nano-world" has caught the eye of the food industry creating a new range of materials and processes aimed for improving not only the organoleptic characteristics of food, but also to contribute with other features like their nutritional characteristics, their safety and packaging, among others. The food and beverage sector is a global multi trillion dollar industry. All the major food companies are consistently looking for ways to improve production efficiency, food safety and food characteristics. Extensive research and development projects are ongoing with the ultimate goal of gaining competitive advantage and market share (Cushen *et al.*, 2012). A nanomaterial is defined as an "insoluble, bio persistent and intentionally manufactured material, with one or more external dimensions, or an internal structure, on the scale from 1 to 100 nanometers" as detailed in the recent EC Cosmetics Regulation (Commission, 2009). The understanding of taste receptors and flavour perception is leading to the development of an ''electronic tongue'' for describing the taste attributes of food. Indeed, the manipulation of substances so close to the molecular level has blurred the boundaries between a numbers of traditional food science disciplines.

Nanotechnology is thus defined as the design and fabrication of materials, devices and systems with control at nanometer dimensions (Ramsden, 2005). Encompassing nano-scale science, engineering and technology, nanotechnology involves imaging, measuring, modeling and manipulating matter at this scale. The size of vital biomolecules such as sugars, aminoacids, hormones and DNA is in the nanometer range. Every living organism on earth exists because of these nanostructures (Kour *et al.*, 2015). Applications with structural features on the nano-scale level have physical, chemical and biological properties which makes nanotechnology beneficial on various levels.

Nano-scale control over food molecules may lead to the modification of many macro-scale characteristics, such as texture, taste, other sensory attributes, processability and stability during shelf life (Cushen *et al.*, 2012; Sekhon, 2010). The main developments of nanotechnology, in food science, involve altering the texture of food components, encapsulating food components or additives, developing new tastes and sensations, controlling the release of flavours, and/or increasing the bioavailability of nutritional components (Chaudhry *et al.*, 2008b). Nanofood is also related to the improvement of food color, prolongation of shelf life and preservation, detection of germs and antibacterial characteristics, and intelligent packaging materials. In addition, nanofood includes not only the processed food category, but also entire areas from cultivation to packaging (Kour *et al.*, 2015).

Encapsulation is a technique by which the sensitive ingredients are packed within a coating or wall material. The wall material protects the sensitive ingredients against adverse reaction and controls release of the ingredients (Bakowska-Barczak & Kolodziejczyk, 2011). In addition, encapsulation process can convert liquids into powders, which are easy to handle.

Microencapsulation (ME) is the envelopment of small solid particles, liquid droplets or gases in a coating (1–1000 um). ME can be successfully applied to entrap natural compounds, like essential oils (EOs) or vegetal extracts containing polyphenols with well-known antimicrobial properties (Nazzaro *et al.*, 2012). This aspect represents an important starting point for industries, which can try out new natural and safe materials or systems of packaging capable to prolong the shelf life of foods, such as highly perishable fresh foods (vegetables, fruits, meat, etc.), without lessening their characteristics in terms of quality and hygiene. ME can be considered as a real resource for food packaging also to mask unpleasant flavors and odors, or to supply barriers between the sensitive bioactive materials and the environment (represented by food or oxygen). Many of the EOs have antimicrobial properties against several foodborne pathogens and can be potentially used in different food matrices, including meat products (De Martino *et al.*, 2009). However, limits to their use are linked to the aroma that can be unpleasant for consumers, or having poor water solubility and volatility. This technique is generally achieved in two steps. Firstly, an emulsion of the volatile compound is made in an aqueous dispersion of a wall material which also functions as the emulsifier. Then, the microencapsulated emulsion must be dried under controlled conditions so as to diminish the loss of the encapsulation. In food biotechnology, capsules can be also used to entrap or enclose microorganisms by segregating them from the external environment with a coating of hydrocolloids, such that the cells are released in the appropriate gut compartment, at the right time. The main purpose of probiotic encapsulation is to protect cells against an unfavorable environment and to allow their release in a viable and metabolically active state in the intestine (Nazzaro *et al.*, 2012). The size of the capsules is an important parameter that affects the sensory properties of foods. Special attention is needed to design carrier matrices and technology in order to keep pace with the increasing consumer interest in health issues, food safety and environmental consciousness.

The use of microencapsulated food additives is already well established. A variety of other microencapsulated food ingredients and additives are available for use in a range of food products. In this context, the nanoencapsulation of food ingredients and additives appears to be a logical extension of the technology into an already existing application area to provide protective barriers, flavor and taste masking, controlled release, and better dispersability for water-insoluble food ingredients and additives.

Nanoencapsulation (NE) is defined as a technology to pack substances in miniature and provides final product functionality that includes controlled release of the core. NE technologies have the potential to meet food industry challenges concerning the effective delivery of health functional ingredients and controlled release of flavor compounds (Kour *et al.*, 2015). Food applications of nanotechnology for target delivery of bioactives (e.g. omega-3 fatty acids, carotenes, vitamins, coenzyme Q10, plant polyphenols, etc.) are in their infancy and the use of pharmaceutical products made with non-food-grade ingredients is not acceptable for incorporation into foods (García *et al.*, 2010). Research in food-grade encapsulants is needed in order to enable the delivery of desirable bioactives through the food supply.

The applications of nanotechnology in the food sector are new emergent, but they are predicted to grow rapidly in the coming years. However, nanotechnology-derived foods are also new to consumers and it remains unclear how public perception, attitudes, choice and acceptance will impact the future of such applications in the food sector (Chaudhry *et al.*, 2008b). The food industry is also looking out for new technologies to improve the nutritional value, shelf life and traceability of their food products. They are also aiming to develop improved tastes, reduce the amount of salt, sugar, fat and preservatives, address food-related illnesses, develop targeted nutrition for different lifestyles and aging population, and maintain sustainability of food production, processing and food safety (Sekhon, 2010).

A number of new processes and materials derived from nanotechnology can provide answers to many of these needs, as they offer the ability to control and manipulate properties of substances close to molecular level. It is, therefore, not surprising that one of the fastest moving sectors to embrace new technologies, such as nanotechnology, to realise the potential benefits, is the food industry.

Worldwide view related to research & development

The global food and beverage industry is growing at 3.5% a year and is expected to be worth more than US $ 7 trillion in the next years. Key trends for new product development are in health, convenience, naturality and sustainability. New foods based on fruits and vegetables fulfill many of the demands of the premium consumer.

Despite the explosion of growth in this area, food nanotechnology is still a lesser-known subfield of the greater nanotechnology spectrum, even among professional nanotechnologists (Duncan, 2011).

Worldwide sales of nanotechnology products to the food and beverage packaging sector increased, but compared with other areas of research where nanotechnology is being applied, active food ingredients nanoencapsulation seems delayed in time. This may be due to the nature of the processes used in the food industry, or the costs.

Clearly this phenomenon is changing. The increasing scientific interest on nanoencapsulated based food can be clearly seen in Figure 1, which shows the rising number of published articles using the keywords "nanoencapsulation" and “food” in Scopus database.

More than 70% of the total amount of papers published on the subject refer to basic research, and the most explored topics are related to the controlling stability, protection of food materials, enhancing activity/properties (flavor, taste, etc.) and containers functionality. Less than 10% of the total amount of publications is related to changes on release patterns or patents. The latter may means that the industrial interest in these processes is very recent.

From the academic point of view, the number of publications should be analyzed using a criterion that allows assessing their quality as well. The impact factor can be used as a (rather subjective) measure of quality. Since it is obtained by calculating the average of the times an article published in a certain journal is referenced, it is therefore assumed that the higher the impact factor is, the higher the visibility of the journal, and the greater the number of researchers who will intend to publish in that journal. Resulting from that competition, there is a correlation between the quality and impact of the publications in a journal with its impact factor. There are two indicators for scientific journals (journal metrics): Scimago Journal & Country Rank (SJR), and Scopus Source Normalized Impact per Paper (SNIP). The journal metrics show that articles about food nanoencapsulation are more frequently published in journals with intermediate impact factor.

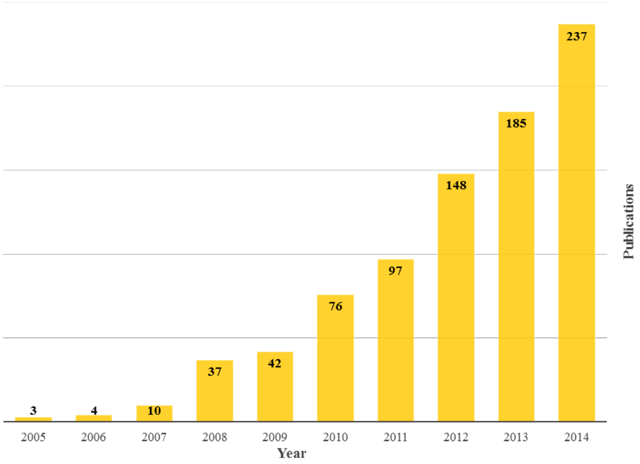

Figure 1. Number of publications involving the keywords "nanoencapsulation" and “food” in Scopus database

It is not surprising that the highest number of research articles are published in - and proceeds from - highly industrialized and high population countries (figure 2A).

On the other hand, Brazil has a unique position in the world. It is one of the few countries that can be one of the most important producers of food, fiber and biofuel and at the same time maintain its mega biodiversity endowment and vital ecosystems services properly running (Martinelli & Filoso, 2009).

It is important to note that over 50% of the publications come from only 4 countries. The intermediate level of the publications and the reduced range of countries that publish may indicate the recent interest in this subject.

Moreover, in figure 2B are described the type of publications where it is possible to emphasize that there are a greater number of research papers indicating a high academic interest.

Comparing other areas of application of nanotechnology, the use of this tools could be restricted or limited by the problems associated with production costs, for instance, in drug delivery systems the cost of an innovative process can be "absorbed" by the price of the medicine, while in a food product that is impossible or difficult.

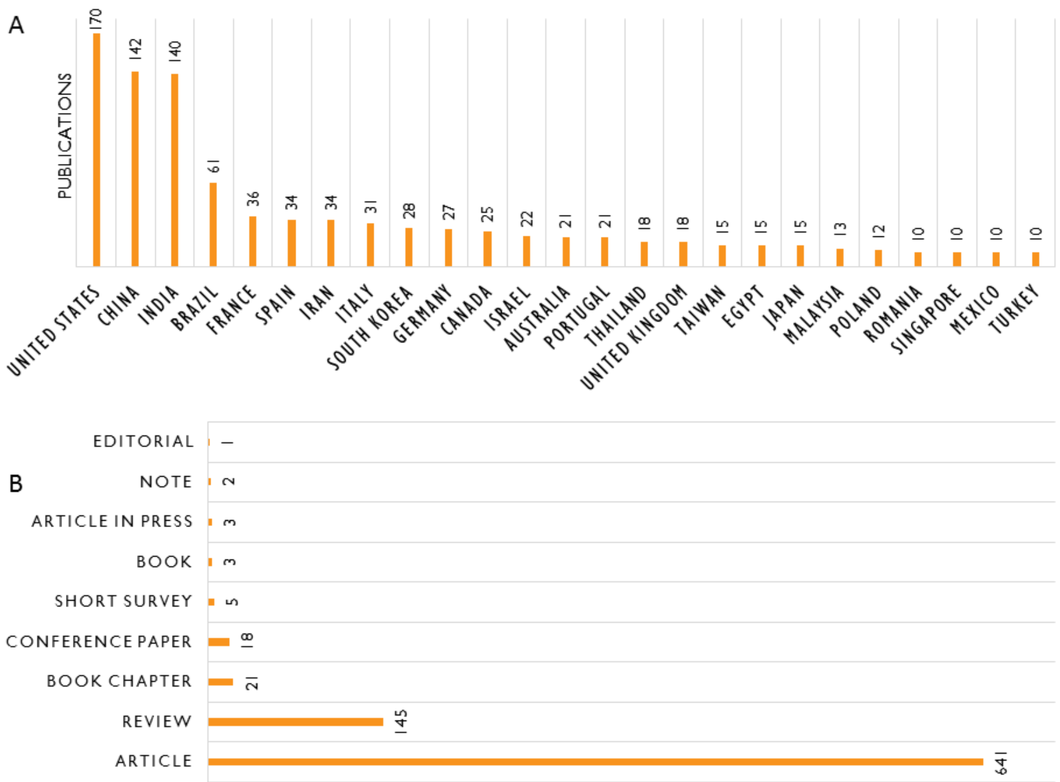

Figure 2. A- Geographical distribution of publications involving the words "nanoencapsulation" and "food". B- Type of publication.

Nanoencapsulation

The term nanoencapsulation describes the application of encapsulation on the nanometer scale with films, layers, coverings, or simply microdispersion. The encapsulation layer is clearly of nanometer scale forming a protective layer on the food or flavor molecules/ingredients. Often the active ingredient is in the molecule or nano-scale state. The major benefit is that the homogeneity imparts, leading to better encapsulation efficiency, as well as physical and chemical properties.

The protection of bioactive compounds, such as vitamins, antioxidants, proteins, and lipids, as well as carbohydrates, may be achieved using this technique for the production of functional foods with enhanced functionality and stability (Sekhon, 2010).

The major benefits of nanotechnology for food ingredient microencapsulation are (Khare & Vasisht, 2014):

- An increase in surface area may lead to the improvement in bioavailability of flavors and food ingredients: This is especially important for flavor ingredients that have low solubility and/or low flavor and odor detection thresholds.

- Improvement in solubility of poorly water soluble ingredients: For example, omega-3 fish oil solubilization using a micelle-based system.
- Optically transparent (important in beverage application): Nanoemulsions and microemulsions that have oil droplet sizes of less than 100 nm are optically transparent.
- Higher ingredient retention during processing (volatile organic carbon reduction) during spray drying.
- Closer to true molecular solution (homogeneity in system properties, such as density): For example, molecular inclusion complexes based on amylose and cyclodextrins.
- Higher activity levels of encapsulated ingredient, e.g., antimicrobials in nanoemulsion/ microemulsion forms.

The production of nanomaterials is often performed in two phases, a first step where the particle is formed in an aqueous or organic solvent and an optional second step, in which the solvent is removed and particles agglomerate with each other.

PRODUCTION TECHNIQUES

In general, the production of nanoparticles can be performed by both the “top-down” and the “bottom-up” techniques, and nanocapsules are not an exception. For the former approach, the nanonization is achieved by the application of energy, while for the latter; the aggregation of molecules, monomers, ions, or even atoms is controlled physico-chemically to form the nanocapsule (Fig. 3).

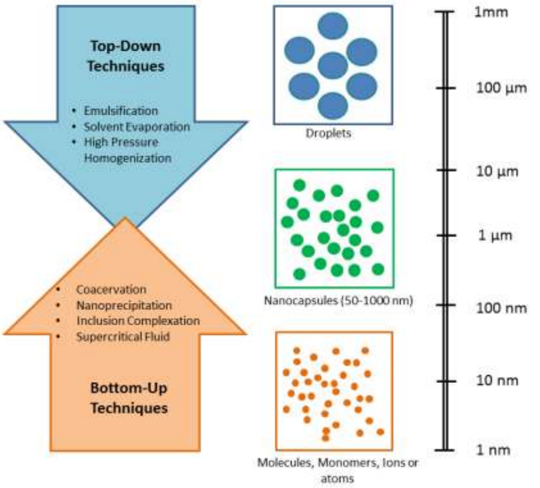

Figure 3. Top-down and bottom-up techniques for the production of nanocapsules.

Emulsification

The emulsification process allows mixing two liquids which are normally immiscible using an interface agent (surfactant). This process permits the incorporation of a lipid into an aqueous media or vice versa by forming droplets (dispersed phase) which remain dispersed into a continuous phase. The droplet size can be determined by the components, the type of emulsion and the production technique, among other parameters. Emulsions with droplet size in the nanometric scale (typically in the range 20 – 200 nm) are often referred to in the literature as miniemulsions, nanoemulsions, ultrafine emulsions, submicron emulsions, etc. The term nanoemulsion is preferred because, in addition to the idea that the nano-scale size range of the droplets is concise, it avoids misinterpretation with the term microemulsion (which are thermodynamically stable systems) (Solans & Solé, 2012).

Nanoemulsion droplet sizes fall typically in the range of 20 – 200 nm and show narrow size distributions. Although most of the publications on either oil-in-water (O/W) or water-in-oil (W/O) nanoemulsions report their formation by dispersion or high-energy emulsification methods, an increased interest is observed in the study of nanoemulsion formation by condensation or low-energy emulsification (Solans *et al.*, 2005). Nanoemulsions, being non-equilibrium systems, cannot be formed spontaneously. Nanoemulsions have been commonly prepared by high-energy methods, using mechanical devices able to produce intense disruptive forces, namely, high-shear stirrers, high pressure homogenizers and ultrasound generators. Nanoemulsion formation by these methods is quite straightforward as the higher the energy input the smaller the droplet size. However, the level of energy required to obtain nanometer-scaled droplets is very high and therefore cost-inefficient, especially considering that only a small amount (around 0.1%) of the energy produced is used for emulsification (Tadros *et al.*, 2004). In contrast, low-energy emulsification methods, making use of the internal chemical energy of the system, are often more energy efficient, as only simple stirring is needed and generally allow the production of smaller droplet size than high-energy methods (Solè *et al.*, 2006). Nevertheless, depending on the system and composition variables, similar droplet sizes can be achieved by both types of methods (Yang *et al.*, 2012). It has been also claimed that high-energy methods allow the preparing of nanoemulsions at higher oil-to-surfactant ratios than low-energy methods (Yang *et al.*, 2012). The use of nanoemulsion technology for delivering food components and nutraceuticals has been comprehensively reviewed by, (Augustin & Hemar, 2009; McClements *et al.*, 2009; Mosquera *et al.*, 2014; Marano & Guadagnini, 2013; Silva *et al.*, 2012).

Coacervation

The coacervation technique involves the phase separation of a single or a mixture of polyelectrolyte from a solution and the subsequent deposition of the newly formed coacervate phase around the active ingredient. Further, a hydrocolloid shell can be cross-linked using an appropriate chemical or enzymatic cross-linker such as glutaraldehyde or transglutaminase, mainly to increase the robustness of the coacervate (Zuidam & Shimoni, 2010). Based on the number of polymer types used, the process can be termed as simple coacervation (only one type of polymer) and complex coacervation (two or more types of polymer). Many factors including the biopolymer type (molar mass, flexibility, and charge), pH, ionic strength, concentration, and the ratio of the biopolymers affect the power of the interaction between the biopolymers and the nature of the complex formed (Tolstoguzov, 2003; De Kruif et al., 2004; Turgeon et al., 2007). Apart from the electrostatic interactions between biopolymers of opposite charges, hydrophobic interactions and hydrogen bonding can also contribute significantly to the complex formation. (Gouin, 2004) stated that coacervation is a distinctive and promising encapsulation technology, because of the very high payloads achievable (up to 99 %) and the possibilities of controlled release based on mechanical stress, temperature, or sustained release. The major problem recognized in this technique lies in commercializing the coacervated food ingredients due to the usage of glutaraldehyde for cross-linking, which must be carefully used according to the country's legislation. Nevertheless, at present, so many suitable enzymes are being developed for cross-linking (Gouin, 2004).

Inclusion complexation

Inclusion complexation generally refers to the encapsulation of a supramolecular association of a ligand (encapsulated ingredient) into a cavity-bearing substrate (shell material) through hydrogen bonding, van der Waals force or an entropy-driven hydrophobic effect. The inclusion complexation technique is mainly used in the encapsulation of volatile organic molecules (essential oils and vitamins); it is useful to mask odors and flavors and preserve aromas. This technique yielded higher encapsulation efficiency with higher stability of the core component. However, only a few particular molecular compounds, like ß-cyclodextrin and ß-lactogloglobulin are suitable for encapsulation through this method (Ezhilarasi *et al.*, 2013).

Nanoprecipitation

The nanoprecipitation method is also called solvent displacement. It is based on the spontaneous emulsification of the organic internal phase containing the dissolved polymer, drug and organic solvent into the aqueous external phase. The nanoprecipitation technique involves the precipitation of a polymer from an organic solution and the diffusion of the organic solvent in the aqueous medium (Galindo-rodriguez *et al.*, 2004). The solvent displacement forms both nanocapsules and nanospheres. Biodegradable polymers are commonly used, especially polycaprolactone (PCL), poly (lactide) (PLA), and poly (lactide-co-glicolide) (PLGA), Eudragit, poly (alkylcyanoacrylate) (PACA) (Pinto Reis *et al.*, 2006; Ezhilarasi *et al.*, 2013).

Emulsification–solvent evaporation

Emulsification–solvent evaporation technique is a modified version of solvent evaporation method. It involves emulsification of the polymer solution into an aqueous phase and evaporation of the polymer solvent inducing polymer precipitation as nanospheres (Pinto Reis *et al.*, 2006). The drug is finely dispersed into the polymer matrix network. The size of the capsules can be controlled by adjusting the stir rate, type and amount of dispersing agent, viscosity of organic and aqueous phases, and temperature (Tice & Gilley, 1985). The most frequently used polymers are PLA, PLGA, ethyl cellulose, cellulose acetate phthalate, PCL, and poly (h-hydroxybutyrate). In order to produce a small particle, often high-speed homogenization or ultrasonication has to be employed (Zambaux *et al.*, 1998).

The nanoencapsulation of different actives like curcumine, coenzyme Q10, quercetin and α-tocopherol using this technique and different wall materials have been reviewed (Ezhilarasi *et al.*, 2013). Besides, this approach showed to be the most efficient for achieving particle sizes below 250 nm (Sowasod *et al.*, n.d.; Prajakta *et al.*, 2009; Mukerjee & Vishwanatha, 2009; Kwon *et al.*, 2002).

Supercritical antisolvent precipitation

Carbon dioxide (CO_2) is an attractive solvent alternative for a variety of chemical and industrial processes, especially because it is plentiful and inexpensive, and has properties that are between those of many liquids and gases. At room temperature and above its vapor pressure, CO_2 exists as a liquid with density comparable to organic solvents, but with excellent wetting properties and a very low viscosity. Above its critical temperature and pressure (31 °C and 73.8 bar), CO_2 is in the supercritical state and has gas-like viscosities and liquid-like densities. Small changes in temperature or pressure cause dramatic changes in the density, viscosity, and dielectric properties of supercritical CO_2, making it an unusually tunable, versatile, and selective solvent (Clark, 2009). Some of the methods under supercritical fluid technology, such as rapid expansion from supercritical solution, gas antisolvent, supercritical antisolvent precipitation, aerosol solvent extraction, and precipitation with a compressed fluid antisolvent have been utilized in recent years (Kikic *et al.*, 1997). Supercritical fluids are used for the encapsulation of thermally sensitive compounds in a process similar to spray drying. In this technique, the bioactive compound and the polymer were solubilized in a supercritical fluid and the solution was expanded through a nozzle. Then, the supercritical fluid was evaporated in the spraying process, and solute particles eventually precipitate (Pinto Reis *et al.*, 2006). This technique has been widely used because of its low critical temperature and minimum use of organic solvent. Lutein and phytosterol nanoparticles were obtained by supercritical fluid, with particle sizes of 219 and 500 nm, respectively (Jin *et al.*, 2009; Türk & Lietzow, 2004).

SOLVENT REMOVAL

As explained in section 2, most of the nanocapsule production techniques are performed in a solvent media. It is well known that the presence of solvents entails a number of disadvantages, such as risk of microbial contamination, increased costs and physico-chemical instability. In addition, for the organic solvents, there is a risk of explosion and toxicity (for operators and consumers). In this context, it might be necessary to eliminate the solvent to make way to a redispersible powdered form. To this purpose, most popular techniques are spray drying and lyophilization. In table 1, freeze drying, spray drying and nanospray drying are shown comparatively.

Table 1. Comparison between laboratory scale equipment commonly used for solvent elimination.

	Freeze Drying	Spray Drying	Nano-Spray Drying
Particle size	Not applicable	2-5 µm	0.3-5 µm
Re-dispersed particle size	No restriction by deagglomeration	No restriction by deagglomeration	< 1 µm
Process Yield	100%	up to 70%	Up to 90%
Process speed	Low	High	Low
Operating temperature	Up to - 50°C	Up to 220°C	Up to 120°C
Viscosity	No restrictions	<300 cP	<10 cP
Sample volume	Max. 1L	30mL-1L	1-200mL
Ease of operation	Simple operation	Trained staff	Trained staff
Operation Cost	+++	+	+
Time of process	+++	+	++
Scalability	+++	+	+++

Spray Drying

Spray drying is a rapid, continuous, cost-effective, reproducible and scalable process for the production of dry powders from a fluid material (Sosnik & Seremeta, 2015). In these devices, the liquid is sprayed through an atomizer into a hot drying gas medium, usually air. The sprayed droplets lose the solvent in the drying chamber leading to a solid particle which is subsequently removed from the air stream and collected.

Main advantages of spray drying are:

- Availability of equipment for the laboratory and the industrial scale;
- Rapid and cost-effective process;
- High reproducibility;
- Ease of scaling up;
- Process flexibility.

One of the main drawbacks of traditional spray drying in the lab scale is the low process yield. In order to overcome this, BÜCHI Labortechnik AG has recently developed the Nano Spray Dryer B-90. It is designed to generate very fine droplets resulting in particle sizes between 300 nm and 5 µm. The main differences, compared with traditional spray drying, are in the droplet generation system and the collector (see figure 4). The atomizer is constituted by a stainless steel mesh with perforations (4.0, 5.5 and 7 µm) coupled to a piezoelectric actuator that produces high frequency vibrations, thereby producing droplets with a very small particle size. On the other hand, the collector works by applying an electrostatic charge to the particles, which produces its adhesion to a cylinder, in which the sample is collected by a rubber spatula (Lee *et al.*, 2011).

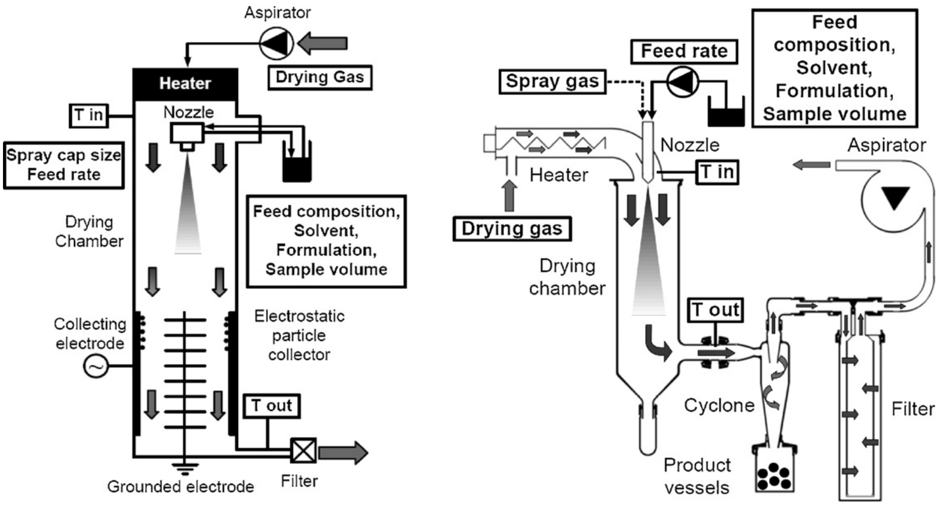

Figure 4. Nano Spray Dryer B-90 and Mini Spray Dryer B-290 from BÜCHI Labortechnik AG (adapted from Bürki, Jeon, Arpagaus, & Betz, 2011).

Freeze Drying

In the freeze drying technique, so called lyophilization, the material is firstly frozen and then, the surrounding pressure is reduced to allow the frozen water in the material to sublimate directly from the solid phase to the gas phase. Nanocapsules present a specific problem on drying because of their fragile structure composed of a thin envelope encapsulating an oily or aqueous core. Nanocapsules cannot withstand the freeze drying stress especially during freezing, the first step of the process, which involves the crystallization of water and the cryo-concentration of dissolved components in the formulation. Nevertheless, (Abdelwahed *et al.*, 2006) demonstrated that the aggregation of cryo-protectants, such as PVP and sucrose prevented nanocapsule destruction.

One of the main challenges in solvent removal is to achieve powders with identical physico-chemical properties of the original material and high product recovery.

In the case of heat-sensitive materials the drying process must to be considered carefully. Although the spray drying process involves the application of temperature, the sample is exposed to the hot air stream for extremely short periods (on the order of milliseconds or seconds) (Sosnik & Seremeta, 2015). Besides, it has been described that the heat transfer mainly occurs between the hot gas stream and the solvent, which takes this energy to evaporate, thereby protecting the material of interest from thermal decomposition (Freitas & Müller, 1998). The great contact surface generated through the atomization, combined with the application of vacuum in the spray drier, favors the solvent evaporation, even at low temperatures (below 50 °C). In the case of extremely heat-sensitive formulations, lyophilization is preferably, since no heat application takes place.

The redispersion of dried nanocapsules must be achieved upon contact with a solvent. To this purpose, soluble carriers such as lactose, maltodextrine, sucrose, maltose, mannitol and others additives are added to the nanocapsule suspension prior to the spray drying processs (Zuo *et al.*, 2013; Freitas & Müller, 1998). When the solvent is eliminated in the drying chamber, the carrier forms soluble links between the nanocapsules, leading to the formation of nanocomposites that are capable of being redispersed upon contact to water (figure 5) (Li *et al.*, 2010). Generally, when a nanocapsule suspension is atomized in a two-fluid nozzle, an abrupt increase in kinetic energy takes place because of the temperature and the share force, at this point the nanocapsules in the suspension may collide with each other if their velocity is high enough. This particle collision can partially damage the surfactant film which coats the interface, producing irreversible particle aggregation. This phenomenon is increased when the particle concentration is higher (Freitas & Müller, 1998). Regarding the redispersion ability of lyophilized materials, the addition of cryoprotectants fulfills the same function as in the spray drying, enabling the original nano-sized particles to be redispersed.

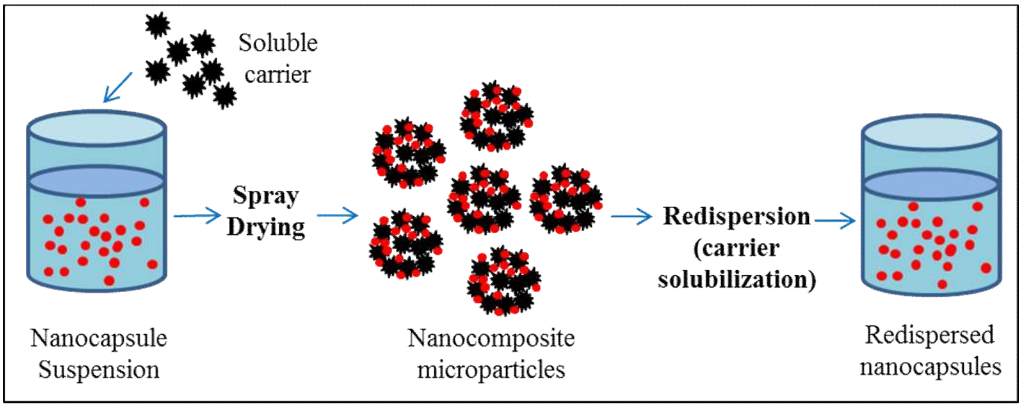

Figure 5. Spray dried nanocapsule suspension and redispersion.

As regards to the process yield, in the freeze drying process the samples are placed into recipients, in which the product is collected, achieving hundred percent in product recovery. On the other hand, for spray drying, the process yield is one of the main challenges, since high adhesion to the drying chamber wall is frequently observed. Besides, small particles (< 2 μm) are not efficiently separated in the cyclone and taken away with the gas stream. Aiming to overcome the main drawbacks of this technology and extend its application to the production of more complex particle configurations, Büchi (Labotechnik AG, Switzerland) introduced the Nano Spray Dryer B-90, which is the fourth and newest generation of laboratory scale spray dryers developed by the company following the previous generations (Mini Spray Dryers B-190, B-191 and B-290) (Lee *et al.*, 2011). In the nano spray drier, the particles are separated from the gas stream by applying an electrostatic charge to the particles which produce their adhesion to the collector, this mechanism of separation is more efficient than the cyclone separator in the B-290 drier. Nevertheless, there has been described that depending on the physico-chemical properties of the wall material, a segregation of particles could take place in the collector (Li *et al.*, 2010).

CARRIER MATERIALS GENERALITIES

Different types of materials can be used as building blocks to create nanostructures as nanoliposomes, nanoemulsions, nanoparticles and nanofibers. Nanomaterials used in food applications include both inorganic and organic substances (Sekhon, 2010). Engineered nanomaterials (ENMs) fall into three main categories: inorganic, surface functionalized materials, and organic engineered nanomaterials (Chaudhry *et al.*, 2008a). Inorganic nanomaterials for applications in food, food additives, food packaging or storage, include transition metals, such as silver and iron; alkaline earth metals, such as calcium and magnesium and non-metals, such as selenium and silicates. Food packaging is the major area of application of metal nanomaterials. Surface functionalized nanomaterials add certain types of functionality to the matrix (e.g.: antimicrobial activity). For food packaging materials, they are used to bind with the polymer matrix in order to offer mechanical strength or a barrier against the movement of gases, volatile components (such as flavors) or moisture. Organic nanomaterials are used in food products for their increased uptake and absorption and improved bioavailability of vitamins, antioxidants in the body.

Nanoencapsulation pack substances in miniature making use of techniques such as nanocomposite, nanoemulsification, and nanoestructuration and provides final product. These substances are functional ingredients rarely utilized directly in their pure form. First, nanoencapsulation serves as a vehicle for carrying the functional ingredient to the desired site of action. Secondly, they protect the functional ingredient from chemical or biological degradation during processing, storage, and utilization. Thirdly, it has to be capable of controlling the release of the functional ingredient. Finally, the delivery system has to be compatible with the other components in the system, as well as being compatible with the physico-chemical and qualitative attributes of the final product (Weiss *et al.*, 2006). The characteristics of the delivery system are the most important factors influencing the efficacy of functional ingredients in many industrial products.

Typically, nanocarrier systems can be carbohydrate, protein or lipid based (Fig. 6). Carbohydrate and protein based nanocapsules, do not have potential of fully scale up, due to the requirement of complicated chemical or heat treatments. On the other hand, lipid based nanocarriers have the possibility of industrial production and bear advantage of more encapsulation efficiency and low toxicity (Fathi *et al.*, 2012; Khare & Vasisht, 2014).

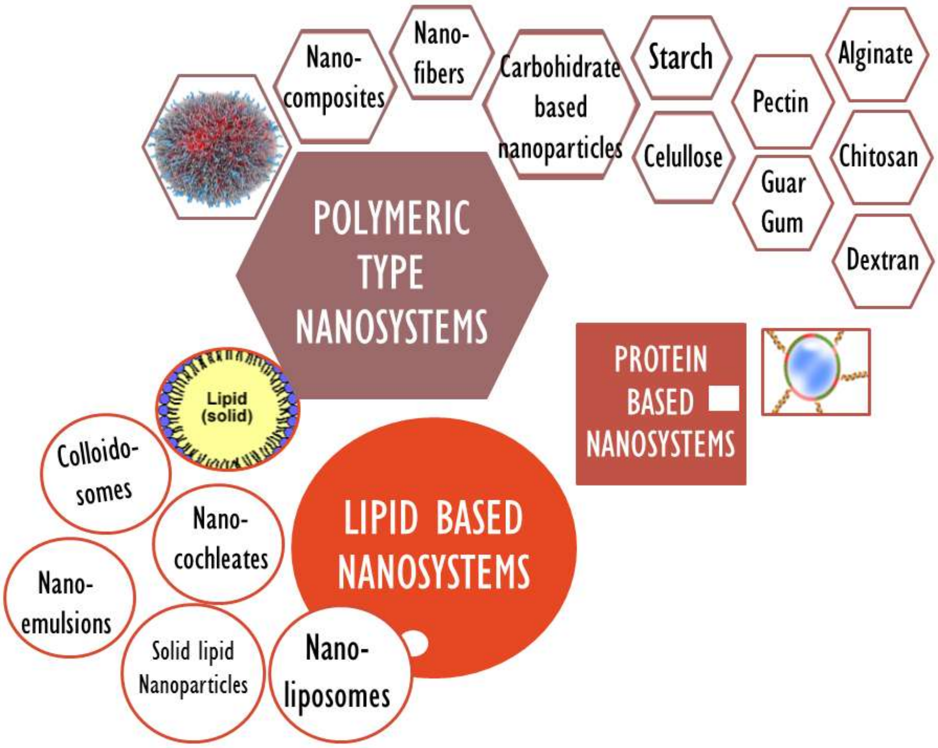

Figure 6. Wall materials used in nanoencapsulation of food ingredients.

Lipids based nanosystems

These systems enhance the performance of antioxidants by improving their solubility and bioavailability, *in vitro* and *in vivo* stability and preventing their unwanted interactions with other food components. The main lipid-based nanoencapsulation systems that can be used for the protection and delivery of foods and nutraceuticals are nanoliposomes, nanocochleates, and archaeosomes (Sekhon, 2010).

Nanoliposomes

Nanoliposomes are useful in areas like encapsulation and controlled release of food materials, as well as they enhanced bioavailability, stability and shelf life of sensitive ingredients. Nanoliposomes are applied as carrier vehicles of nutrients, nutraceuticals, enzymes, food additives, and food antimicrobials (Mozafari *et al.*, 2008).

Compared to other encapsulation technologies, liposomes can generally provide higher chemical stability and protection to sensitive bioactives, such as ascorbic acid and glutathione at high water-activity conditions. Temperature-sensitive liposomes can be produced by the modification of the lipid bilayers with specific polymers. These kinds of carriers are ideal for flavor release by increasing cocking temperature of the ready meals (Kirby, 1993; Fathi *et al.*, 2012; Mozafari et, al., 2008)

Colloidosomes

Colloidosomes are capsules made of particles one tenth the size of a human cell and assemble themselves into a hollow shell. Molecules of any substance can be placed inside this shell (fat blockers, medicine, and vitamins). Soy lecithin is the main structural ingredient in the formation of aqueous nanodispersions that carry high loads of water-insoluble actives.

Nanocochleates

Nanocochleates are nano coiled particles that wrap around micronutrients and have the ability to stabilize and protect an extended range of micronutrients and the potential to increase the nutritional value of processed foods (Thangavel & Thiruvengadam, 2014).

Nanoemulsions

The use of high-pressure valve homogenizers or microfluidizers often causes emulsions with droplet diameters of less than 100 to 500 nm, these emulations are often called “nanoemulsions”. Functional food components can be incorporated within the droplets, the interfacial region, or the continuous phase (Weiss *et al.*, 2006). The process of making a nanoemulsion involves the development of a stable emulsion, which serves as an alternative colloidal drug or biomaterial delivery system. By this technique, delivery of lipophilic bioactive components can be conveniently achieved at their targeted site along with the protection of the nutriceuticals, present as the core material lipids (Sen Gupta & Ghosh, 2014). Caseinates are often used as an effective emulsion stabilizer for fats. (Chung *et al*., 2008).

Nanoemulsions were developed for use in the decontamination of food packaging equipment and in the packaging of food. However, nanoemulsions were discovered to be good candidates for delivery of poorly water-soluble food ingredients, such as fish oil and lipophilic vitamins. Food-grade ingredients (such as proteins, polysaccharides, and phospholipids) and processing operations (such as homogenization and mixing) are widely used in the manufacture of food emulsions (Fathi *et al*., 2012). The advantages of nanoemulsions include toxicological safety and a high content of the lipid phase and the chance of large-scale production using high-pressure homogenization (HPH). However, controlled drug release from nanoemulsions is very unlikely because of the small size and the liquid state of the carrier.

The use of multiple emulsions created delivery systems with novel encapsulation and delivery properties. The most common examples of this are oil-in-water-in-oil (O/W/O) and water-in-oilin- water (W/O/W) emulsions. This technology could be used to separate 2 aqueous phase components that might adversely react with each other if they were present in the same aqueous phase (Garti and Benichou, 2004). Nano-multilayer emulsions consist of oil droplets (the core) surrounded by nanometer thick layers (the shell) comprised of different polyelectrolytes. An ionic emulsifier that rapidly adsorbs to the surface of lipid droplets during homogenization is used to produce a primary emulsion containing small droplets; then an oppositely charged polyelectrolyte is added to the system, which adsorbs to the droplet surfaces and produces a secondary emulsion containing droplets coated with a two-layer interface. This procedure can be repeated to form oil droplets coated by interfaces containing three or more layers (Weiss *et al*., 2006).

Solid Lipid Nanoparticles

Solid lipid nanoparticles (SLN) are formed particles consisting of a matrix made of solid lipid shell, formed by controlled crystallization of food nanoemulsions (Awad *et al*., 2008). The major advantages of solid lipid nanoparticles, compared to nanoemulsions and nanoliposomes include: large-scale production without the use of organic solvents and sterilization, high concentration of functional compounds in the system, long term stability, and the ability to be spray dried into powder form. Two basic production techniques are used for large-scale production of SLN in food processing: (i) Hot homogenization and (ii) Cold homogenization. SLNs can also be prepared easily on laboratory scale by emulsification-evaporation followed by sonification method (Varshosaz *et al*., 2010).

Polymeric type nanoparticles

Research into the production and use of biodegradable polymers for their use in the manufacturing of dispersed systems began70 years ago. Polymeric nanoparticles are generally developed to obtain controlled release and targeted delivery of functional compounds. They are made using polymers and surfactants. Biopolymer nanoparticles are highly bioactive solid particles with diameters of 100 nm or less. These particles may be formed by promoting self-association or aggregation of single biopolymers or by inducing phase separation in mixed biopolymer systems, for example, using aggregative (net attraction) or segregative (net repulsion) interactions. They can include vitamins, antimicrobial agents, beta-carotene as a colorant and many different functional components (Guadarrama-Lezama *et al*., 2012; Pereira *et al*., 2015; Ramsden, 2005). Polymer based nanoparticles are unique compared to other nanoparticle systems due to their better encapsulation, controlled release and less toxic properties (Ghaderi *et al*., 2014).

Many processes have been developed to prepare polymeric nanoparticles including emulsification-solvent evaporation, emulsion polymerization, spray drying and interfacial polycondensation (Kanakubo *et al*., 2010). The emulsification-solvent evaporation method is based on the formation of an emulsion through the addition of a polymer solution to an aqueous phase, followed by the removal of the solvent using evaporation to precipitate polymer. Nanoprecipitation method, produces polymeric based particles and is generally carried out by dissolving the core material in a fully or partly water-miscible solvent and subsequently dropping the solution into an aqueous solution containing surfactant (Ghaderi *et al.*, 2014).

Numerous substances are used to entrap, coat, deliver and controlle the release of bioactives in foods and nutraceuticals. Ethyl cellulose (EC) is a kind of semisynthetic modified cellulose, used for coating and controlled release applications, it is a biodegradable, biocompatible and hydrophobic polymer (Dhana lekshmi *et al.*, 2010). Chitosan (a natural antimicrobial polymer obtained by deacetylating chitin extracted from crustacean shells) and synthetic polymers polylactic acid (PLA), polyglycolic acid (PGA), and polycaprolactic acid are used to encapsulate and deliver compounds. Copolymers created using combinations of the monomers lactide, galactide, and caprolactone have also been examined (Weiss *et al.*, 2006). Depending on the choice of the base biopolymer used to manufacture the nanoparticles, particle surfaces may be hydrophobic or hydrophilic. Thus, the type of solvent in which the particles are dispersed for their application in food systems may lead to problematic particle aggregation. Aggregation of particles renders them poorly dispersible, and this could negate some advantages of these delivery systems. Further studies are needed to predict and determine the interactions and to design polymeric nanocapsules systems.

Nanocomposites

They are fine nanoparticulates (100 nm or less) incorporated into plastics in order to improve the properties over those of conventional counterparts. Polymer nanocomposites are thermoplastic polymers that have nano-scale inclusions (nanoclays, carbon nanoparticles, nano-scale metals and oxides, and polymeric resins), 2% – 8% by weight. The most widely studied type of polymer-clay nanocomposites, a class of hybrid materials composed of organic polymer matrices and organophilic clay fillers (Kim *et al.*, 2003), is montmorillonite (MMT). Recently, the preparation of a nanoclay containing carbohydrate film has been developed. Moreover, the introduction of dispersed clay layers into biopolymer matrix structure has improve the overall mechanical strength of films, making the use of these films industrially practicable. The best example of this is chitosan. Its hydrophilic character and consequently, its poor mechanical properties in the presence of water and humidity limit its application. In contrast, chitosan films containing exfoliated hydroxyapatite layers maintain functionality in humid environments, providing good mechanical and barrier properties, while having comparable antimicrobial efficacies (Alonso *et al.*, 2010; Weiss *et al.*, 2006). The insertion of active nanoparticles into polymer matrices could bring two fold advantage: to improve the performance of food packaging materials and to impart it an additional functionality (antimicrobial, antioxidant, and scavenger), thus promoting the prolongation of the shelf life of the packaged product. Natural biopolymer-based nanocomposite packaging materials with biofunctional properties have a huge potential for application in the active food packaging industry. Polymer-clay nanocomposite has emerged as a novel food packaging material due its benefits, such as enhanced mechanical, thermal, and barrier properties (Ray, 2006).

Nanofibers

An emerging technology is the production of nanofiber. These fibers have diameters of less than 100 nm, produced by the electrospinning process. Electrospinning is capable of producing thin, solid polymer strands from solution by applying a strong electric field to a spinneret with a small capillary orifice. Fibers used in food and agriculture are not typically composed of biopolymers; they are made primarily from synthetic polymers. As progress in the production from food biopolymers is made, the use of biopolymeric nanofibers in the food industry will increase (Weiss *et al.*, 2006).

Carbohydrate based delivering systems

Polysaccharides, due to their massive molecular structure and ability to entrap bioactives are suitable as building blocks of delivery systems. Thus, they are widely used as safe and inexpensive ingredients (Fathi *et al.*, 2014).

Starch

Starch, which is the most abundant storage polysaccharide in plants, is a biodegradable, biocompatible, and digestible polymer, that has been used to encapsulate insulin, flax seed, unsaturated fatty acids and flavors (Li *et al.*, 2010; Chung *et al.*, 2008; Fathi *et al.*, 2014). Natural starch is hydrophilic, which limits its application for encapsulating hydrophobic food bioactives. However, hydrophobic starch derivatives have therefore been developed: dialdehyde starch, propyl starch, octenyl succinic anhydride modified starches, PEGylated starch, etc. Apart from the low cost of starch, it is relatively pure and does not need intensive purification procedures. The main limitation of starch application are in its sensitivity to acid attack and amylase hydrolysis (Scheller & O'Sullivan, 2011; Fathi *et al.*, 2014).

Cellulose

It is the most abundant polysaccharide on earth, but it is not suitable as a building block of delivery systems because of its low-water solubility and large dimensions. However, is has been physically, chemically, and biochemically modified to be used as an encapsulating agent (Ozeki *et al.*, 2011; Jin *et al.*, 2009; Alonso *et al.*, 2010). Cellulose esters are modified celluloses that are divided into two categories: non-enteric and enteric esters. Non-enteric cellulose esters are insoluble in water across a wide range of pH values. As a consequence they are not suitable for encapsulation. On the other hand, enteric cellulose and cellulose esters (acetate phthalate (CAP) or hydroxypropylmethyl cellulose phthalate (HPMCP)) are insoluble in acidic solutions, but soluble in mildly acidic to slightly alkaline solutions, so they are widely used as encapsulating agents (Bagheri *et al.*, 2014; Alonso *et al.*, 2010; Ozeki *et al.*, 2011; Fathi *et al.*, 2014; Jin *et al.*, 2009).

Pectin

Pectin is a linear anionic polysaccharide. It is resistant to enzymatic digestion in the mouth and stomach, but is degradable by the microbiome in the colon, which makes it suitable for delivery of acid sensitive food bioactives. It is usually classified according to the degree of esterification: low methoxyl (LM) pectin and high methoxyl (HM) pectin. LM can form gels in the presence of divalent calcium ions, whereas HM can form gels under acidic conditions in high sugar contents. A disadvantage of calcium pectinate carriers is their relatively porous structure, which causes low entrapment efficiency and fast release of incorporated bioactives, especially for hydrophilic, low molecular weight compounds (Polavarapu *et al.*, 2011; Esfanjani *et al.*, 2015; Fathi *et al.*, 2014).

Guar gum

Guar gum is a water soluble polysaccharide derived from the seeds of *Cyamopsis tetragonolobus*. This biopolymer has been used as thickening, emulsification, and retrogradation retardant agent in food products. It is soluble in cold water and forms a gel-like structure in hot water. Native guar gums often form highly viscous solutions, which limits its application for encapsulating, its modification beeing necessary. It has been depolymerized to obtain a low molar mass, water-soluble fiber by different methods of hydrolysis (Fathi *et al.*, 2014).

Chitosan

Chitosan, a natural linear, cationic, biocompatible, and biodegradable polymer, is obtained by alkaline deacetylation of chitin. It also has antimicrobial and antioxidant activity (Hsieh *et al.*, 2006; Avila-Sosa *et al.*, 2012; Alonso *et al.*, 2010). Chitosan exhibits pH-sensitivity as it dissolves easily at acidic pH values ($pH < 6.5$), but is insoluble at higher pH ranges. This polymer was also physical or chemical modified to extend or improve its functional properties (Fathi *et al.*, 2014).

Alginate

Alginate is a linear polysaccharide extracted from brown sea algae. It has been used for the encapsulation of lipid nanoparticles, lipase and different essential oils (Rojas-Graü *et al.*, 2007; Belščak-Cvitanović *et al.*, 2011; Yeh *et al.*, 2011). Due to its hydrophilic properties, this biopolymer has potential for entrapment of hydrophilic food bioactives. However, its two major limitations are encapsulant leaching during preparation (low encapsulation efficiency) and rapid dissolution in the intestinal pH or in presence of sodium ions (Fathi *et al.*, 2014).

Dextran

Dextran is a bacterial polysaccharide of glucan, composed of chains of varying length of glucose. It is a linear polysaccharide containing hydroxyl groups, used for the covalent attachment of various organic functional groups, especially hydrophobic compounds. Changing the degree of substitution, modified dextrans become water soluble or insoluble. This biopolymer might be used for self-assembled nanocarrier production to entrap active materials with different hydrophobicities. There are few reports of nanoencapsulation of food bioactives using modified dextran polymers (Fathi *et al.*, 2014).

Cyclodextrins

Cyclodextrins (CDs) are well-known truncated cone shape oligosaccharides. They possess a lipophilic central cavity and a hydrophilic outside surface. They are able to form inclusion complexes with hydrophobic food bioactives entrapped in the inner cavity. CDs are useful for entrapment of poorly soluble, temperature-sensitive, or chemically labile food bioactives. Moreover, they have been used to encapsulate antimicrobials, antioxidants, fish oil, essential oils, flavors, ethylene and other bioactive ingredients (Fathi *et al.*, 2014).

Non-traditional sources of polysaccharides have also been identified and isolated from different seeds (Sen Gupta & Ghosh, 2014; Fathi *et al.*, 2014). Also the combination of two or more carbohydrates were reported to improve their functional properties (Gonnissen *et al.*, 2007; Fathi *et al.*, 2014; Alonso *et al.*, 2010).

Proteins

The benefits of protein nanoparticles include non-toxicity, stability for long duration, non-antigenicity and biodegradability (Hilty *et al.*, 2009).

APPLICATIONS IN FOOD SCIENCE

Food science is a multi-technological industry involving a variety of materials, high biosafety requirements, and well-regulated technological processes. Four major areas may benefit from nanotechnology: development of new functional materials, micro-scale and nano-scale processing, product development and methods and instrumentation design for improved food safety and biosecurity (Weiss *et al.*, 2006).

The main areas of application of nanocapusles include food products that contain nano-sized or nanoencapsulated ingredients, food packaging additives and food additives (Sekhon, 2010).

Example applications include food additives (benzoic acid, citric acid, and ascorbic acid), dietary supplements and functional food ingredients (vitamins A and E, lipoic acid, soybean isoflavones, ß-carotene, lutein, omega-3 fatty acids, and coenzyme Q10) (Mohammadi *et al.*, 2015; Ezhilarasi *et al.*, 2013). Great developments have been aimed at altering the texture of food components, encapsulating food components or additives, developing new tastes and sensations, controlling the release of flavors, and/or increasing the bioavailability of nutritional components (Chaudhry *et al.*, 2008b). The novel application of nanostructured (nanotextured) food ingredients and delivery systems are being developed with the claims that they offer improved taste, texture and consistency. Low-fat nanostructured mayonnaise, claims to be as ‘‘creamy’’ as its full fat alternatives and, hence, offer a healthier option to the consumer. A number of nanomicelle based carriers for nutraceuticals and nutritional supplements have been developed: nanocochleates (50 nm in size), based on a phosphatidylserine carrier derived from soya bean, generally regarded as safe (GRAS). They are obtained by the addition of calcium ions to small phosphatidylserine vesicles. The nanocochleate system is claimed to protect micronutrients and antioxidants from degradation during manufacture and storage. Another application are self-assembled nanotubes, developed from hydrolysed milk protein lactalbumin, which can offer a new naturally derived carrier for nanoencapsulation of nutrients, supplements and pharmaceuticals (Graveland-Bikker & de Kruif, 2006). Nutraceuticals and nutritional supplements containing nanoingredients and additives (e.g. vitamins, antimicrobials, antioxidants etc.) are currently available (Han *et al.*, 2015; Mohammadi *et al.*, 2015; Mosquera *et al.*, 2014). Nanoceuticals, Nutrition-be-nanotech, are commercial names for supplements. Nano-sized powders are used for increasing absorption of nutrients, nanocochleates are considered an effective tool for nutrient delivery to cells, without affecting the color and the taste of food products. Vitamin sprays disperse nanodroplets are used for better absorption of nutrients. The supplementary aspect mainly involves encapsulation techniques where probiotics and other products are targeted into the human system with the help of iron and zinc nanostructured capsules (Chaudhry *et al.*, 2008b).

For food packaging applications, the developments have led to new materials with improved mechanical, barrier and antimicrobial properties (Chaudhry *et al.*, 2008b). Nanotechnology derived food packaging materials are the largest category of current nanotechnology applications for the food sector (Duncan, 2011). These applications include incorporating nanomaterials to improve packaging properties (flexibility, gas barrier properties, temperature/moisture stability); incorporating nanoparticles with antimicrobial or oxygen scavenging properties; 'Intelligent' food packaging with nanosensors can monitor and report the condition of the food; biodegradable polymer–nanomaterial composites. Nanocomposites are incorporated in the polymer matrix of the substances due to their large surface area which favors the filler matrix interactions and its performance. Also the nanoreinforcement acts as a small barrier for gases by complicating the path of the material; known as polymer nanocomposites (Azeredo, 2009). Nanoclays are composite materials having complex metallic cores and provide a barrier against the permeation of gases (Chellaram *et al.*, 2014; Ray, 2006).

Antimicrobial packaging generally includes natural nanoparticles that control the microbial growth (Makwana *et al.*, 2014). Silver nanoparticles are used in all forms including biotexiles, electrical appliances, refrigerators, kitchenwares (Azeredo, 2009). The antibacterial activity of zinc oxides increases with the decrease in particle size, it can be stimulated by visible light. Titanium dioxide as a coating in packing material is combined with silver to improve the disinfection process. Antimicrobial packaging would be highly healthy and consumer friendly products (Chellaram *et al.*, 2014).

Biodegradable plastics are a different application of nanotechnology regarding packing. They have a lack of mechanical strength and are permeable to water and gases. These disadvantages are prevailed over by nanotechnology incorporated packaging materials having properties like biodegradable, renewable resources having high mechanical strength (Chellaram *et al.*, 2014).

In smart packaging, sensors are used to detect physical quality of substances. It is dominated by oxygen scavengers, moisture absorbers and barrier packing product. Packaging containing nanosensors give information of enzymes produced in the breakdown of food molecules, making them unsafe for human consumption. The packages could also be used to let air and other enzymes out, but not in, thus increasing shelf life, as well as the reduction of synthetic preservatives (Sanguansri & Augustin, 2006). Another important potential application of nanoparticles in food packaging is the degradation of ripening gas, such as ethylene (Zandi *et al.*, 2012).

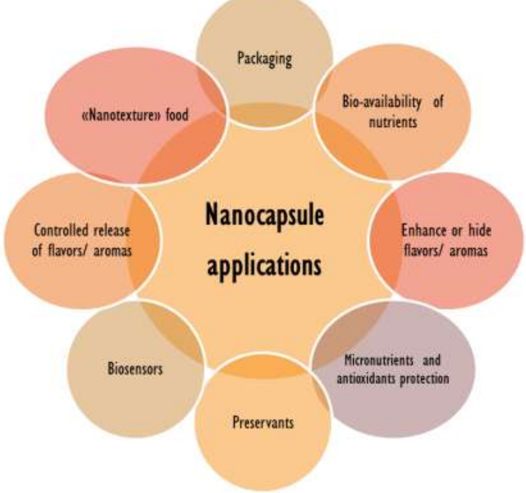

Figure 7. Applications of nanoencapsulation technology in the food industry.

The food environment is continuously nanosensed for oxygen content, temperature and pathogens. Gold nanoparticles are incorporated in enzymes for microbe detection and nanofibrils of perylene-based fluorophores indicates fish and meat spoilage, by detecting gaseous amines. Others include zinc oxide and titanium oxide nanocomposites for the detection of volatile organic compounds. Nanocapsules delivery systems play an important role in the food processing sector and the functional properties are maintained by encapsulating simple solutions, colloids, emulsions, biopolymers and others into foods (Abbas *et al*., 2009).

CHARACTERIZATION

The inclusion of nanoparticles (naturally occurring nanoparticles or engineered nanoparticles) in food or in production methods is widely studied for its implications in both, potential toxicity and functionality. Therefore, it is crucial to understand the behavior of nanoparticles in food materials, consumer products and environmental matrices, as well as their toxicity to humans and the environment. To accomplish this, access to robust analytical methodologies is essential for detecting and characterizing engineered or naturally occurring nanoparticles in a wide range of matrix types.

While there are numerous techniques for the characterization of nanosystems, the methods described below are the most widely used routines of both developing and control of nano-scale substances used in food.

Analysis of Particle Size and Morphology

To analyze the size of nano-scale particles, dynamic light scattering (DLS) and electron microscopy are commonly used. With respect to electron microscopy, two most frequently methods are used: scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Electron microscopy has better resolution than optical microscopy. Atomic force microscopy (AFM) can be used for the morphological analysis of the surface of the particles.

Dynamic Light Scattering (DLS)

Dynamic light scattering (DLS), a technique often referred to as photon correlation spectroscopy (PCS), is the most versatile and useful set of techniques for measuring in situ the sizes, size distributions and (in some cases) the shapes of the nanoparticles in liquids (Berne and Pecora, 2000). The basic principle of this method is to observe the motion of the particles and measuring their Brownian motion. The particle velocity is inversely proportional to particle size and is called translational diffusion coefficient (Hoo *et al*., 2008). The diffusion coefficients of nanoparticles are first determined and the average diameters of the particles are then calculated from these coefficients by using the Stokes–Einstein relationship (Kato *et al*., 2012). The DLS method is fast, sensitive, accurate and provides a good statistical representation of the sample. It is able to measure particle size between ~ 1x10^{-3} to 6 µm. Moreover, the properties of the solution are not deteriorated by the beam. However, performs indirect measurements, particles must be in suspension (solutions or gels) and undergoing Brownian motion.

Electron microscopy

Transmission Electron Microscopy (TEM) and Scanning Electron Microscopy (SEM) are widely considered the gold standard for nanoparticle characterization. However, choosing which to employ is a complex process, as both techniques provide similar, but distinct analysis.

Scanning Electron Microscopy (SEM)

In this technique, an electron beam from a source (e.g., tungsten) strikes the surface of the sample for its visualization. The electrons suffer from the influence of an electromagnetic field (generated by lenses), which forces the electron beam to strike the surface of the sample. After this, electrons are diffracted in different directions and generate a number of signals that can be imaged on the screen (Zhou *et al*., 2006). The particles must be able to withstand vacuum;\ the electron beam can damage the polymer. The mean size obtained by SEM is comparable with the results obtained by dynamic light scattering (Pal *et al*., 2011). SEM is, to a certain extent, a limited tool to characterize nanoparticles. The main problem with the application of SEM to nanoparticle characterization analysis is that sometimes it is not possible to clearly differentiate the nanoparticles from the substrate. Problems become even more exacerbated when the nanoparticles under study have the tendency to adhere strongly to each other, forming agglomerates. In contrast to TEM, SEM cannot resolve the internal structure of these domains (Formatex Research Center, 2012).

Transmission electron microscopy (TEM)

Transmission electron microscopy is a microscopy technique whereby a beam of electrons is transmitted through an ultra-thin specimen and interacts as passes through the sample. An image is formed from the electrons transmitted through the specimen, magnified and focused by an objective lens and appears on an imaging screen (Ponce *et al*., 2012). The contrast in a TEM image is not like the contrast in a light microscope image. In TEM, the crystalline sample interacts with the electron beam, mostly by diffraction rather than by absorption (Joshi *et al*., 2008). The vacuum environment inside the microscope chamber dictates that the samples usually need to be prepared in such a way that they are in a dry or solid state (Luo *et al*., 2013). TEM has already proved to be a suitable technique to image and characterize various kinds of NPs. For example, TEM has been applied to investigate milk protein-based nanotubes under different conditions, the shape of serum albumin NPs and the fabrication of enzyme-incorporated peptide nanotubes. Furthermore, TEM has been used to control the size distribution and morphology of cyclodextrin nanospheres. TEM also provides valuable information on (nano) liposomal delivery systems, since it yields a view of morphology and can resolve particles of varying sizes (Luykx *et al*., 2008).

Atomic force microscope (AFM)

The atomic force microscope is ideal for quantitatively measuring the nanometer scale surface roughness and for visualizing the surface nanotexture on many types of material surfaces, including polymer nanocomposites and nanofinished or nanocoated materials (Joshi *et al*., 2008). Advantages of the AFM for such applications are derived from the fact that the AFM is a nondestructive technique and it has a very high three dimensional spatial resolution. The high resolution (~0.1 nm) afforded by AFM has been utilized to directly view single atoms or molecules that have dimensions of a few nanometers. AFM relies on the raster scanning of a nanometer-sized sharp probe over a sample that has been immobilized onto a carefully selected surface, such as mica or glass, which is mounted onto a piezoelectric scanner. The tip is attached to a flexible cantilever (Luykx *et al*., 2008). Changes in the tip specimen interaction are often monitored using an optical lever detection system, in which a laser is reflected off of the cantilever and onto a position sensitive photodiode. During scanning, a particular operating parameter is maintained at a constant level and images are generated through a feedback loop between the optical detection system and the piezoelectric scanners. AFM was developed to overcome the basic drawback of scanning microscopies, that it can only image conducting or semiconducting surfaces. AFM has the advantage of imaging almost any type of surface, including polymers, ceramics, composites, glass, and biological samples. Since AFM scans have the ability to identify large bimodal size distributions, regardless of particle shape, AFM analysis of an unknown particle mixture serves as an excellent screening technique prior to DLS analysis (Hoo *et al*., 2008).

Zeta potential measurement

Zeta potential is a key factor used in the preparation or destruction of colloidal dispersions and in manufacturing processes and it is also employed across a broad spectrum of industrial and academic sectors to monitor and tune the behavior of colloidal systems (Hae-Soo Kwak, 2014). Zeta potential is the measure of overall charge a particle acquires in a specific medium and gives an indication of the potential stability of a colloidal system. Electrostatic repulsion interaction is used to measure and control the stability of the solution. It explains the reasons for the occurrence of dispersion, aggregation, or flocculation and can be used to improve the conditions of the colloidal solution (Anandharamakrishnan, 2014). Zeta otential is commonly measured by laser Doppler electrophoresis, which evaluates electrophoretic mobility of suspended NPs in the medium (Cho *et al*., 2013).

Analytical Ultracentrifugation (AU)

AU is an extremely versatile and powerful tool for the characterization of biological macromolecules and the interactions between them. The AU instrument spins a sample under vacuum at a controlled speed and temperature, while, at set times, the concentration distribution is recorded. Monitoring the sedimentation of macromolecules in a centrifugal field allows their hydrodynamic and thermodynamic characterization in solution, without interaction with any matrix or surface (Luykx *et al*., 2008).

CONCLUSIONS

As reviewed in this work, nanotechnology has the potential to improve food quality either in taste, packaging and storage, as well as making them healthier and nutritious. Nanoencapsulation specifically, permits a wide variety of applications ranging from increase/hide of flavors to the creation, of biosensors for food expiration. Many researchers around the world have paid attention to this field and have done really promising advances. Besides, many strategies to obtain nanocapsules have been developed to different applications, complexity and scalability, with the physico-chemical nature of the bioactive compound being one the most conditioning features on the manufacture method. Although all these lines of work are at an elementary stage, nanoencapsulation is well established in the beverage segment of the food industry especially with emulsions. The research in nanotechnology applied to different fields, such as pharmaceuticals, food, paint, minerals, etc. allowed the development of a variety of techniques for the characterization of nanoparticles. A great relevance factor in food production is the cost. At least by now, the application of nanotechnology implies a high degree of investment, which is reflected in the small number of products in the food market involving nanotechnology. Besides, the production and quality control of nanoparticles at large scale can be a great challenge.

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Conflicts of Interest

The authors declare no conflict of interest.