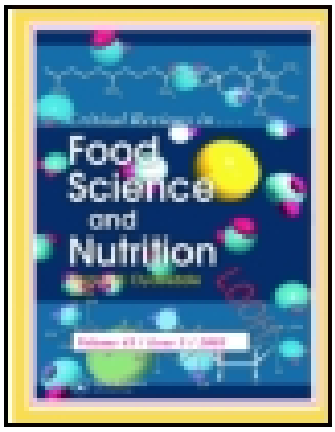

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Suitability of Different Food Grade Materials for the Encapsulation of Some Functional Foods Well Reported for Their Advantages and Susceptibility

Touseef Ahmed Wani[a], Adil Gani Shah[a], Sajad Mohd Wani[a], Idrees Ahmed Wani Ph.D.[a], Farooq Ahmad Masoodi[a], Nazia Nissar Msc Food technology[a] & Mudasir Ahmad Shagoo[a]
[a] Department of Food Science and Technology, University of Kashmir, Hazratbal, Srinagar, Jammu and Kashmir 190006, India, Srinagar, India, , , , , ,
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Dr Touseef Ahmed Wani (Corresponding Author)
Email: wanitouseef24@gmail.com

Dr Adil Gani Shah
Email: adil.gani@gmail.com

Dr Sajad Mohd Wani
Email: wanisajad82@gmail.com

Dr Idrees Ahmed Wani Ph.D.
Email: idwani07@gmail.com

Farooq Ahmad Masoodi
Email: masoodi_fa@yahoo.com

Miss Nazia Nissar Msc Food technology
Email: babanazia@gmail.com

Mudasir Ahmad Shagoo
Email: mudasirahmad63@yahoo.in

Department of Food Science and Technology University of Kashmir, Hazratbal, Srinagar, Jammu and Kashmir 190006, India, Srinagar, India

Abstract

Functional foods find a very important place in the modern era, where different types of cancer, diabetes, cardiovascular diseases, etc. are on a high. Irrespective of the abundance of bioactive components in different fruits and vegetables, their low solubility in aqueous solution, vulnerability to destruction in different environmental and gastrointestinal conditions and a low intestinal absorption becomes a concern. Because it is quite difficult to commercialize non food materials for the food encapsulation purposes due to their safety concerns in the human body, scientists in the recent times have come up with the idea of encapsulating the different bioactive components in different food grade materials that are able to safeguard these bioactive components against the different environmental and gastrointestinal conditions and ensure their safe and targeted delivery at their absorption sites. Different food grade encapsulation materials including various oligosaccharides, polysaccharides (starch, cyclodextrins, alginates, chitosan, gum arabic, carboxymethyl cellulose) and proteins and their suitability for encapsulating various bioactive components like flavonoids (catechins, rutin, curcumin, hesperetin and vanillin), nonflavonoids (resveratrol), carotenoids (β-carotene, lycopene and lutein) and fatty acids (fish oil, flaxseed oil and olive oil) of high medical and nutritional value are reviewed here.

Keywords encapsulation, capsule designing materials, emulsions, pickering emulsions, functional foods, nutraceuticals, antioxidants, controlled release, target delivery.

INTRODUCTION

A variety of functional foods and dietary supplements have been introduced to the market over the past, offering excellent prospects for improving public health. However, a concern for researchers is that bioactive compounds may not be fully absorbed into the body because, they are degraded for example by the harsh acidic condition, enzymatic reactions, insufficient residence time and low permeability in the gastrointestinal tract. Hence, the delivery and release of bioactive cores from ingestion to digestion have been recognized as the most important criteria in improving their absorption (Subirade and Chen, 2008). The development of delivery systems for biologically active compounds in food systems is an important issue in modern food technology. Encapsulation has previously been reported as a technology to protect sensitive substances against the influences of adverse environments (Champagne and Fustier, 2007). Encapsulation techniques and encapsulated materials play a significant role in pharmaceutical and food processing industries. Encapsulation techniques involve a substance (guest or core) being entrapped into another material or system (host or carrier). Encapsulation imparts some degree of stabilization to the active compound since the wall material acts as a physical barrier for oxygen or other molecules, preventing deleterious reactions. Besides, the encapsulated compound can be released in a controlled way in complex biological systems or in product applications (Augustin et al., 2001; Desai and Park, 2005; Paramera et al., 2011). Encapsulation enables conversion of gasses and liquids into powder forms that are easier to handle and apply hence, improving retention, quality preservation and convenience while dealing with active and

volatile compounds (Ho et al., 2011b). The spatial configuration and the size of the binding molecule significantly effect the degree of encapsulation, the interactions with water and the structure of the inclusion complex (dos Santos et al., 2012).

Since the stability and release properties of microcapsules are highly dependent on wall material's composition, various kinds of carriers have been used, including sugars, cyclodextrins, maltodextrins, modified starches, gums, proteins and nanoparticles, micelles or liposomes (Gibbs et al., 1999). The health benefits associated with lipids such as carotenoids, phytosterols, omega-3 fatty acids and natural antioxidants have been studied for many decades. However, most of these bioactive substances not only are least water soluble but also possess low solubility saturation in oil at room temperature. For example, the solubility of β-carotene in oil is reported to be only about 0.2 g/l. The low solubility of the functional lipids impairs their bioavailability and limits their use in food formulations (Ax et al., 2001; Yin et al., 2009). Like any other industry, several challenges continue to frustrate the use of encapsulation technologies in food processing such as, the maintenance of optimum physical stability of encapsulated ingredients during processing, packaging and storage. Ingredient manufacturers need to address issues encountered during reduction in capsule sizes and also gain control regarding targeted release behaviors. It is therefore not surprising that a large percentage of research projects are focused on shrinking capsule sizes, enhancing stability and retaining adequate bioavailability of encapsulated ingredients (Champagne and Fustier, 2007; de Vos et al., 2010).

The technology of encapsulation is a modern one relative to other sciences and technologies. Encapsulation finds its application in so many fields of life but its applications are being explored more in the field of food technology and pharmaceutical science for the particular

reasons of evading conditions harsh for the encapsulated materials, improving their organoleptic character and ensuring their targeted delivery. For the aim of using the technology of encapsulation in the food and pharmaceutical fields, food grade encapsulating materials find direct application in the aforesaid because, it is very difficult to commercialize non food materials for the encapsulation purposes for their safety concerns in the human body. For the same reasons, we have focused in this article on reviewing different food materials that have been used as encapsulating materials in the recent past and the fact that in the modern era, where the food technologists focus on the stability of functional foods and their applications in the field of human health, the encapsulation of various functional foods that have been reported to be very sensitive to different environmental and gastrointestinal conditions are also reviewed here.

FOOD GRADE MATERIALS FOR ENCAPSULATION

Emulsion systems

Liquid-oil-liquid ($W_1/O/W_2$) double emulsions consist of small water droplets contained within larger oil droplets, which by themselves are also dispersed as droplets within a watery continuous phase. The $W_1/O/W_2$ double emulsions particularly the nanoemulsions fabricated from food grade ingredients are being increasingly utilized in the food industry to encapsulate lipophilic functional components, such as biologically active lipids (e.g., omega-3 fatty acids, conjugated linoleic acid), oil soluble flavors, vitamins, preservatives, and nutraceuticals, there by allowing the supplementation of products with sensitive micronutrients, masking unpleasant

flavors, achieving the controlled delivery of various substances and producing low fat foods by incorporating dispersed water into fat droplets due to the dispersal of one phase inside the droplets of another (Choi et al., 2009; McClements and Rao, 2011; Su et al., 2006; Sagalowicz and Leser, 2010). However, the thermodynamic instability of the droplets of the emulsions and the uncontrolled release of markers entrapped within the inner phase have somehow restricted their application in food systems (Su et al., 2008; Surh, 2009). The encapsulation properties of $W_1/O/W_2$ double emulsions are often characterized in terms of encapsulation efficiency (the amount of the aqueous phase marker which remains entrapped in the inner aqueous phase (W_1) on manufacture of the $W_1/O/W_2$ double emulsion) and encapsulation stability (the amount of the aqueous phase marker which remains entrapped in the inner aqueous phase (W_1) on storage or on exposure of the $W_1/O/W_2$ double emulsion to environmental stresses) (O' Regan et al., 2009).

In order to produce a long term stable multiple emulsion, the stability of the water-in-oil (W/O) emulsion from which it is prepared should be ensured (Surh et al., 2007). Two procedures for stabilization of oil droplets by protein-polysaccharide complexes being the mixed emulsion preparation, with both biopolymers present together during emulsification (co-adsorption) and the layer-by-layer preparation (sequential adsorption), because of its potential for encapsulation of nutrients and protection of emulsions against severe environmental stresses, have attracted considerable attention recently (Patino and Pilosof, 2011). However, the major problem in exploiting this sequential adsorption approach is the tendency for the emulsions to become extensively flocculated during preparation. Two different mechanisms may be involved here: bridging flocculation (when the polysaccharide content is so low that droplet collisions occur faster than the rate of polysaccharide saturation on the protein coated droplet surfaces) and

depletion flocculation (when the concentration of unadsorbed polysaccharide exceeds a certain critical value) but, the problem of bridging flocculation is especially troublesome and hence, it is much more convenient to make emulsions with protein and polysaccharide present together before homogenization (Dickinson, 2008). The criteria for effectiveness in protecting newly formed droplets against flocculation and coalescence are contrasted with the requirements to maintain long term stability against aggregation, creaming and Ostwald ripening. Interfacial complexation between protein and polysaccharide may occur through covalent bonding or electrostatic bonding. For the case of electrostatic protein-polysaccharide complexes, the interfacial nanostructure and the stabilizing properties of the adsorbed layer are dependent amongst other things on the sequence of adsorption of the biopolymers to the emulsion droplet surface (Dickinson, 2009). Increasing the fat content in the semi-crystalline oil phase of $W_1/O/W_2$ results in a decreased release of encapsulated hydrophilic compounds from polysaccharide gels with embedded multiple emulsions (Weiss et al., 2005). $W_1/O/W_2$ double emulsions containing gelatin and sodium chloride in the inner aqueous phase are developed for controlled release applications (Sapei et al., 2012).

Particle stabilized emulsions also known as Pickering emulsions show special features such as being extremely stable with respect to coalescence. Starch granules have proved to be a suitable stabilizer for food grade Pickering emulsions. Starch double $W_1/O/W_2$ Pickering emulsions show high encapsulation efficiency and encapsulation stability after one month storage at room temperature. The initial encapsulation efficiency being more than 98.5% immediately after emulsification production and the encapsulation stability remains over 90% after 21 days (Matos et al., 2013). A novel one-pot method for the preparation of starch gel

microspheres by thermal gelation of starch solution-in-oil emulsions with no use of chemical cross linkers has been developed. The micro-droplets of the dispersed aqueous phase in the emulsion-gelation method allow the templating of the starch gels in the form of microspheres. The starch aerogel particles show high loading capacities (16 wt %) of a model chemical (ketoprofen) in the amorphous form (Garcia-Gonzalez et al., 2012). Starch hydrophobically modified with octenyl succinic anhydride (OSA) introduces negatively charged groups and shows good emulsifying activity by adsorbing at the oil-water interface, oil retention capability and capability to modify viscosity of continuous phase due to the hydrophobic OSA starch side chains (Murua-Pagola et al., 2009). The encapsulation potential of waxy corn starch, regular corn starch, waxy barley starch, regular barley starch and their succinylated and OSA starches are effective in encapsulating and retaining a model volatile flavor mixture containing components typical of roasted chicken flavor and have proven to be better than β-cyclodextrin, which is used commonly for encapsulation. Also, succinylated corn and barley starches of regular varieties show the most promising results for flavor encapsulation (Jeon et al., 2003). Changes in the rheological properties of oil-in-water emulsions like increase in apparent viscosity with a pronounced pseudoplastic behavior of emulsions and significant delay of creaming at high oil concentrations in emulsions occur with an increase in OSA starch concentration (Dokic et al., 2012). OSA starch is assisted by maltose to stabilize the oil-in-water emulsion system by intensifying the elastic structure and increasing the viscosity of the emulsion. OSA starch combined with 1.5% (w/w) of maltose proves to be an attractive stabilizer in the emulsion application. Moreover, incorporation of some other types of small molecular sugars such as glucose, fructose, sucrose or lactose and the like may also be useful for designing OSA starch

emulsions with improved properties (Li et al., 2013). The addition of 4-α-glucanotransferase (4αGTase)-treated starch into the internal aqueous phase improves the encapsulation efficiency, with 20% 4αGTase-treated starch being considered to be the most effective for improving the encapsulation efficiency. The $W_1/O/W_2$ emulsions containing 4αGTase-treated starch also show better stability against heat and shear stresses (Mun et al., 2011; Mun et al., 2013). These results suggest that starch modified by using different techniques, especially the OSA starch can be used to improve the various physicochemical properties of emulsion systems, which can be used as a potential delivery carrier for bioactive food components.

Oligosaccharides and Polysaccharides

Starch

Starch (mainly its linear glucose homo-polymer fraction named amylose) complexes can molecularly include guest molecules within or in between hollow helices in a form termed V-amylose of nanometric dimensions (Lalush et al., 2005; Lesmes et al., 2009). Corn starch has been tested for the potential formation of V-type inclusion complexes in a continuous process that has implications on the supplementation and controlled delivery of bioactive fatty acids, e.g., conjugated linoleic acid and other nutraceutical foods and formulations based on V-type starch micro/nanocapsules. The waxy corn starch not being suitable for such purposes, mainly due to the lack of control over fatty acid release (Lesmes et al., 2008). The addition of starch microgranules to calcium-alginate beads is found to improve the sphericity, flowability, density,

visual quality and rigidity of the beads, which are desirable qualities for processing, handling and consumer usage. These characteristics result from the ability of the starch microgranules to reinforce the hydrogel network and fill the interstitial voids (Chan et al., 2011). Incorporation of the starch filler to alginate matrix increases the entrapment capacity of yerba mate (*Ilex paraguariensis*) polyphenols; modulates the antioxidants release rate and diminishes the contribution of matrix erosion to the whole release mechanism. Hydrogels reinforced with corn starch granules improve the classic calcium alginate system leading to a promising strategy to protect and deliver yerba mate antioxidants into food products (Cordoba et al., 2013). Taro starch spherical aggregates produced from spray drying present physicochemical and functional characteristics, having potential for encapsulation of substances in the food and pharmaceutical industry (Gonzalez-Soto et al., 2011).

Hydrolyzed hydroxypropyl corn starch and hydroxypropyl amaranth starch show excellent encapsulating efficiency for encapsulation of lemon oil but are not suitable for orange oil (Kshirsagar and Singhal, 2008). The resistant starch content of OSA starch increases with increasing degrees of substitution and can reach upto 98.6% when the degree of substitution is 1.21, the swelling ratios of the OSA starch particles after incubation being higher than those of the native starch. From in vitro release assays, the OSA starch based matrix tablets are able to deliver bioactive components to the colon, when the degree of substitution is suitable (Wang et al., 2011). New hydroxyethyl starch-based polymer derivatives are synthesized that are well suited for the production of hydrogels and hydrogel microspheres for the controlled release and delivery systems of biomacromolecules. Using hydroxyethyl starch functionalized with polyethylene glycol (PEG) methacrylate or methacrylate, polymers with good water solubility

and crosslinking capabilities are obtained. Very high encapsulation efficiencies are achieved by changing the solution ratio between polymer and PEG solution in the microsphere production process (Wohl-Bruhn et al., 2012). PEG is conjugated with starch acetate to obtain an amphiphilic polymeric derivative. Micellar nanoparticles are formed on self association of PEGylated starch acetate in the presence of aqueous insulin solution, which are highly bioadhesive and can be utilized as a carrier system for controlled delivery of insulin or other proteins for various therapeutic applications (Minimol et al., 2013). Starch spherules can be formed even in the absence of bonding agents, nevertheless, the presence of gelatin leads to differences in the formed structures more so on the structures' internal porosity (Beirao-da-Costa et al., 2011). Gelatin and upto 50% hydroxypropylated high amylose corn starch blends have been developed as a hard capsule material. The linear microstructure of the high amylose starch and the flexible and more hydrophilic hydroxylpropylene group grafted onto the starch improves the compatibility between the gelatin and starch, even though they are immiscible. The addition of PEG both as a plasticizer and a compatibilizer improves the compatibility between the gelatin and starch as it dissolves well into both (Zhang et al., 2013).

Cyclodextrins

The production and structure description of Cyclodextrins (CDs) have been discovered a long ago (Singh et al., 2002). The CDs are cyclic oligomers, the cyclic products formed through α(1-4) linkage of glycosidic oxygen bridges among units of glucopyranose, which constitute the dextrins (Astray et al., 2009). The most common CDs are α-, β- and γ-CD, comprising six, seven

and eight glucose units respectively (Cravotto et al., 2006). Complexation between the guest and the cyclodextrin molecule takes place once hydrophobic groups of the guest molecules interact with the inner cavity surface of the CD. The binding forces are usually van der Waals, hydrophobic and dipole-dipole interactions. As a versatile substance, CD has been increasingly employed in food technology, pharmacy, biotechnology, polymeric nanoparticles and other applications (Dodziuk, 2006; Hashimoto, 1996; Yoshii, 2004). CDs have been used as encapsulating agents for various purposes such as stabilization of aroma, docosahexaenoic acid (DHA), vitamins (Bhandari et al., 1999; Goubet et al., 2001; Hashimoto, 2006), organoleplic modification (Szejtli and Szente, 2005) and cholesterol removal (Smith et al., 1995). Complex formation with dextrin of high amylose corn starch is a tool to disperse hydrophobic compounds in water as nanoparticles with improved stabilities against oxidation and enzymatic digestion (Kim et al., 2013). Encapsulated ethylene in the form of inclusion complexes with CD, which is in powder form, might be used in fruit ripening and other aspect of plant growth regulation (Ho et al., 2011a). Hence molecular encapsulation of various apolar compounds with CDs is becoming a widely applied technique to produce food, pharmaceutical and agricultural materials.

Alginates

Alginates are generally referred to as a family of polyanionic copolymers (consist of two basic building blocks, α-L-guluronic acid and β-D-mannuronic acid residues, linearly linked together by 1-4 linkages) derived from marine kelp, mainly the brown sea algae. The monomers do not occur randomly but rather in a block like fashion, where the α-L-guluronic acid residues

are responsible for the specific ion binding and hence also the gelling properties of alginates. Alginates are useful as a matrix for cell immobilization as well as entrapment of bioactive compounds and drugs. The material encapsulated within the inert alginate environment could be delivered at a desired rate in a controlled release system (Draget and Taylor, 2011; Goh et al., 2007).

Alginate beads are usually produced by the extrusion of alginate droplets into millimolar concentrations of calcium or barium ions. In general, the negatively charged alginate droplets are coated with a polycation with the aim of stabilizing and controlling the molecular weight cut-off of the microcapsule membrane (Orive et al., 2006). Gelation of alginate by external Ba^{2+} (or other divalent cations) produces non-homogeneous cross-linking of the polymeric mannuronic and guluronic acid chains however, homogeneous cross-linking of alginate microcapsules can be achieved by injecting $BaCl_2$ crystals into alginate droplets before they come into contact with external $BaCl_2$ (Zimmermann et al., 2003). Ca-alginate beads are used to produce lipid nanoparticles by two different methods, i.e. the electrostatic droplet generation technique and the spraying method using the two-fluid spray nozzle of a spray dryer that may have the application of being the carriers for lipophilic compounds in pharmaceutical and food systems (Strasdat and Bunjes, 2013). Ca-alginate beads (Liu et al., 2002) and alginate-chitosan microcapsules are prepared with external or internal calcium sources, so called external gelation microcapsule or internal gelation microcapsule respectively. Because the core of microcapsules is Ca-alginate hydrogel, when it encounters electrolytic solutions such as sodium chloride and sodium citrate, the ionotropy will occur between Ca^{2+} and Na^{+}, resulting in its conversion to a liquid with the trend of volume expansion which is called liquefaction. When drug loaded alginate-chitosan

microcapsules are administered, volume swelling usually occurs under the environment in vivo and the rupture of microcapsules even takes place on some conditions, which results in the burst release of the entrapped drugs (Liu et al., 2004). The combination of alginate and pectin polymers results in capsules with high encapsulation efficiency (Madziva et al., 2006). Hence alginate capsules can be used for the targeted delivery of different drugs and nutraceuticals in the human body.

Chitosan

Chitosan (α(1-4)-2-amino-2-deoxy β-D-glucan) obtained from partial N-deacetylation of chitin due to the protonation of amino groups ($-NH_2$) on the C-2 position of the D-glucosamine repeated units, is a linear polysaccharide present in crustaceous shells; soluble at acidic pH and insoluble at neutral pH however, forms such as chitosan chlorhydrate and glutamate are soluble at neutral pH also; biodegradable since it undergoes enzymatic degradation in vivo; biocompatible and non-toxic. Its hydrophilicity and positive charge enable chitosan interaction with negatively charged polymers, macromolecules and with certain polyanions, upon contact in the aqueous environment. These interactive forces and the resulting sol-gel transition stages have been exploited for microencapsulation purposes and chitosan based controlled and targeted delivery systems have been developed and examined (Marguerite, 2006; Pillai et al., 2009). The ingestion of chitosan preparation containing 1% chitosan and 6% pectin results in reduced body weight, food and water intake in rats but not essentially changing their serum lipids. Accordingly, the investigated chitosan emulsion could be introduced as a low calorie, relatively

stable and a safe functional food preparation for enhancing satiety when ingested as a meal replacement diet (Qinna et al., 2013).

The incorporation of proteins or polysaccharides into edible biopolymer particles may also be useful for controlling the rate or extent of their digestibility in the human digestive system (Chen et al., 2006; Mouecoucou et al., 2004; Parada and Aguilera, 2007). Chitosan and β-lactoglobulin double wall coating is designed by layer-by-layer deposition technique as a shell structure to achieve prolonged release of core material in the gastrointestinal tract for potential food applications (Lee et al., 2012). Formation of complex between oxidized xyloglucan and chitosan which is attributed to the covalent linkage between aldehyde and amino group has fibrous network structure in which oxidized xyloglucan is observed as spherical and nanosized. The complex made from renewable resources is transparent, colourless, thermostable, biocompatible with ordered structure, cost effective and is in great demand globally (Simi et al., 2010).

Gum arabic

Gum arabic is an exudate of the Acacia tree; is a natural composite polysaccharide; contains three main components, two of relatively low molecular weight, namely arabinogalactan and glycoprotein and one of high molecular weight, namely arabinogalactan protein (the greater the amount and molecular mass of the arabinogalactan protein component in the gum, the better the interfacial properties) and is a multipurpose ingredient in food systems presenting good properties for different functionality features (emulsification, encapsulation,

stabilization, adhesion) (Castellani et al., 2010). The backbone is composed of 1,3-linked galactopyransyl (Galp) residues and is substituted at O-2, O-6 or O-4 position, with residues of →2,3,6-β-D-Galp1→, →3,4-Galp1→, →3,4,6-Galp1→ (Nie et al., 2013). Gum arabic-sucrose-gelatin mixture is an efficient encapsulation matrix for limonene encapsulation in freeze drying (Kaushik and Roos, 2007). Gum arabic has better encapsulation efficiency for orange and lemon oil than both Hydrolyzed hydroxypropyl corn and amaranth starch (Kshirsagar and Singhal, 2008). Pullulan when combined with gum arabic, maltodextrin and its blends in the absence of diluents and non-polymeric stabilizer stabilizes the emulsion of turmeric oleoresin (Kshirsagar et al., 2009).

With the increased knowledge of formation and structure of protein-polysaccharide complexes, their functional properties are becoming more lucid. Owing to excellent viscoelastic properties, coacervates can be applied as a shell material in microencapsulation or nanoencapsulation (Lv et al., 2013b). β-lactoglobulin and acacia gum interact electrostatically at pH 4.2 and undergo complex coacervation the stabilization of which increases with the total biopolymer concentration (Schmitt et al., 2001). Soybean protein isolate (SPI) is quite compatible with gum arabic for complex coacervation. The highest coacervate yield is achieved with a soybean protein isolate to gum arabic ratio of 1:1, the core material load for the highest microencapsulation efficiency and microencapsulation yield being 10%, but the addition of sucrose improves the microencapsulation efficiency and microencapsulation yield quite significantly (Jun-xia et al., 2011). Using sunflower oil to prepare the primary emulsion, gum arabic along with gelatin is used as wall material. The microcapsules so formed are not very hygroscopic or soluble in water and show reduced equilibrium moisture content and release rates

(Rocha-Selmi et al., 2013). Complex formation between sodium caseinate and gum arabic occurs above a critical temperature driven through hydrophobic attraction, largely reversible when the mixture is cooled (Ye et al., 2012). Gum arabic and gelatin are employed for the formation of heat resistant flavor nanocapsules based on complex coacervation, driven by electrostatic interactions between gelatin and gum arabic. The soluble complexes are formed at a pH 4.80 with the gelatin to gum arabic mixing ratio of 1:1 (Lv et al., 2013a). A complex surface layer of sodium caseinate and gum arabic can be formed by increasing the temperature, through either the adsorption of complexes of sodium caseinate and gum arabic formed in the solution or direct complexation on the surface of the droplets, which is a new approach to the formation of a complex surface layer on emulsion droplets (Ye et al., 2011).

Carboxymethyl cellulose

Carboxymethyl cellulose (CMC) particles with high encapsulation efficiency are synthesized in a single step with reverse micelle microemulsion polymerization using divinyl sulfone as the crosslinking agent (Butun et al., 2011). A novel stimuli-responsive polyelectrolyte multi-layer hollow microcapsule system has been designed by the sequential layer-by-layer electrostatic self-assembly technique from the sacrificial templates $CaCO_3$ with CMC as the polycation and polyallylamine hydrochloride as the polyanion; opening at pH $\leq$ 5; closing at pH $\geq$ 7 and shows initial burst release in the first 1 h followed by a sustained release up to 7 h (Tripathy and Raichur, 2013). Beads of CMC/kappa-carrageenan formed with enhanced stability due to crosslinking of genipin, show various swelling and release characteristics in simulated

gastrointestinal tract conditions that may be used as a suitable carrier for nutraceuticals (Muhamad et al., 2011). CMC and chitosan are used to prepare biocompatible polymer-magnetite hybrid nanoparticles, chemically crosslinked by genipin with high dispersion stability and sensitivity to a magnetic field. These nanoparticles being fabricated from naturally derived materials can be one of the important tools in biomedical fields such as drug delivery and hyperthermia (Kaihara et al., 2011). Carboxymethyl cellulose sodium is used as a template to prepare zirconium hydroxide nanoparticles but, with a decreased thermal stability due to the poor thermal stability of CMC components (Liu et al., 2011). However, the study on the heat survival of model probiotics reveal that aluminum carboxymethyl cellulose-rice bran composite microcapsules show a promising potential for the protection of probiotics in functional foods that require heat treatment (Chitprasert et al., 2012). Fe^{3+}-crosslinked alginate-CMC carrier beads are developed by dropping an alginate-carboxymethyl cellulose solution into a ferric chloride solution containing a protein therapeutic. All procedures used for preparing the beads and loading the proteins are performed in aqueous media, which is beneficial for preserving the bioactivity and stability of fragile proteins or drugs. The bead system will be useful for bypassing the acidity of gastric fluids without wasting loaded protein or retarding protein release in the intestine (Kim et al., 2012). These biocompatible polymeric particles derived from carboxymethyl cellulose could be very useful as a site-specific oral delivery system of bioactive substances and may be used in the controlled and targetable drug release systems for potential biomedical applications.

Proteins

Whey protein based microcapsules containing a model apolar core, anhydrous milk fat are prepared using a process consisting of double emulsification and subsequent heat gelation, suggesting that the microencapsulation process might be used to prepare whey protein based microcapsules for controlled release applications in food systems (Lee and Rosenberg, 2000). Denatured whey protein nanoparticles with controlled size and properties, covalently cross-linked by disulphide bonds are developed through pH-cycling (Giroux et al., 2010). Complexes prepared from globular proteins (β-lactoglobulin) and anionic polysaccharides {high methoxyl pectin (HMP) and low methoxyl pectin (LMP)} show greater pH stability for β-lactoglobulin-HMP complexes than for β-lactoglobulin-LMP complexes (Jones et al., 2010). β-lactoglobulin and LMP show synergistic effects of on oxidative stability of encapsulated lipophilic ingredients both in liquid as well as in a spray-dried state (Serfert et al., 2013). Food grade ovalbumin fibrils and HMP microcapsules obtained by using layer-by-layer deposition technique can be used for food or pharmaceutical purposes. The release of active ingredients can be controlled by controlling the number of layers of the shell (Humblet-Hua et al., 2011). Stable dispersions of protein aggregates can be formed by heating aqueous solutions of β-lactoglobulin or whey protein isolate (WPI). Because of its excellent gel forming properties whey protein is suggested as a suitable food grade alternative for hydrogels, gel beads and submicron particles (Nicolai et al., 2011). WPI and LMP form soluble or insoluble complexes for water soluble ingredient encapsulation depending on polymer ratios, mode of acidification and final pH (Bedie et al.,

2008). A hybrid method to prepare microcapsules involves combining a layer-by-layer adsorption of WPI and HMP and deposition of silica colloidal particles for reinforcement (Rossier-Miranda et al., 2012). Camel β-casein micelles are reported to be excellent nano vehicles in the functional food formulations (Esmaili et al., 2011). Soybean protein isolates are used to encapsulate casein hydrolysate using spray drying process opening a new path for specific applications and the development of innovative delivery systems and functional food products (Ortiz et al., 2009). The layer-by-layer electrostatic deposition of soybean lecithin liposomes results in building up of nanosized, spherical and stable liposomes that can be used for the sustained release of bioactive compounds (Madrigal-Carballo et al., 2010). Egg yolk lipoprotein interacts with some polymers (Xanthan gum, sodium carboximethylcellulose, Pectin and k-Carrageenan) forming soluble and insoluble complexes as a function of pH and/or temperature (Souza et al., 2013).

Protein-polysaccharide biopolymer particles formed from a globular protein (β-lactoglobulin) and an anionic polysaccharide (beet pectin) are stable to aggregation over a range of pH values, which increases as the amount of pectin is increased. Neutral cosolvents can be used to modulate the properties of biopolymer nanoparticles prepared by thermal treatment of protein-polysaccharide electrostatic complexes (glycerol with a little impact on the pH-induced aggregation and sorbitol decreases the pH where insoluble protein-polysaccharide complexes are formed while greatly increasing their thermal aggregation temperature). The biopolymer particles prepared may be useful for encapsulation and delivery of bioactive food components, or as substitutes for lipid droplets (Jones et al., 2009; Chanasattru et al., 2009). The properties of stable and reinforced protein-polysaccharides complex coacervations firstly formed by

electrostatic interaction between WPI and beet pectin and then by laccase cross-linking through the oxidative coupling of ferulic acid present in beet pectin show that laccase catalyzed cross linking of ferulic acid present in beet pectin leads to the biofabrication of stable WPI/beet pectin complex coacervations with new characteristics. The reinforced complex coacervations forms fine networking structures which may provide convenient means for food grade delivery system for encapsulation of bioactive ingredients (Chen et al., 2012).

Zein

Zein, the prolamin of corn, is capable of self assembly into microspheres to form core shell structures, potentially useful in encapsulation and delivery systems (Wang et al., 2013). Zein and zein/carboxymethyl chitosan nanoparticles are also used to encapsulate bioactive components (Luo et al., 2013). Electrospinning technique has shown promising results on zein ultra-fine fibres as an efficient and effective method for the preparation of sub-micron structured encapsulated functional ingredients that may find use in food industry (Neo et al., 2013). Spray drying of zein as a carrier polymer, which is a cost effective technique, is used to encapsulate lysozyme and nisin for sustained release delivery systems (Jin et al., 2009; Xiao and Zhong, 2011). A chitosan/zein nano delivery system has been successfully developed to encapsulate hydrophilic nutrients with high bioactivities and the release profile of hydrophilic/ hydrophobic nutrients or drugs from chitosan nanoparticles can be greatly improved after the nanoparticles are coated by zein protein (Luo et al., 2010; Luo et al., 2011). The technology of encapsulating dodecane in the zein matrix can be of interest in the food industry in order to develop new smart

packaging materials with the ability to maintain temperature control e.g., to preserve the cold chain (Perez-Masia et al., 2013).

Table 1.

ENCAPSULATION OF NUTRACEUTICALS

Flavonoids

Catechins

Catechins are an important class of dietary flavonoids with promising use as therapeutic agents due to their potent antioxidant activity and diverse biological properties. The main catechin species include catechin, epicatechin, epicatechin gallate, epigallocatechin and epigallocatechin gallate (EGCG). However, catechins are highly unstable in alkaline solutions such as those present in some biological fluids and experimental protocols and are sensitive to oxidation, which limits their enrichment in the diet as a preventive medicine. Encapsulation of (+)-catechin and (-)-epigallocatechin gallate in chitosan-tripolyphosphate nanoparticles stabilizes these catechins in an alkaline environment leading the way for the development of nanoparticle formulations intended for the protection and delivery of catechins via the gastrointestinal tract (Dube et al., 2010). Thermally modified β-lactoglobulin forms coassembled nanovehicles that confer considerable protection to epigallocatechin-3-gallate against oxidative degradation,

enabling its controlled delivery (Shpigelman et al., 2010). The nanoencapsulation significantly improves the taste and the mouth feel of the enriched product by suppressing the bitterness and astringency of EGCG. Also the very limited release of EGCG from the nanoparticles during simulated gastric digestion suggests that this system would be useful as an enteric carrier for polyphenols and other bioactive compounds too (Shpigelman et al., 2012). Using a partially denatured protein for improving the binding and protection of polyphenolic nutraceuticals may broaden the possibilities of harnessing proteins particularly milk proteins as nanodelivery vehicles. The small particle size obtained enables the use of such a system in clear solutions (e.g., clear beverages), with the aim of promoting and facilitating diet enrichment of wide populations with EGCG and similar polyphenolic nutraceuticals, as a means of preventive medicine. These results further emphasize the feasibility of industrial application of this nanodelivery system, especially due to the fact that all components used here are natural food grade ingredients and can be purchased in bulk quantities.

Ellagic acid has been investigated in a wide array of pharmacological activities like prevention and treatment of cancer, diabetic complications and atherosclerosis. However, ellagic acid shows poor solubility, permeability and stability at physiological pH, limiting its potential for therapeutic applications. However, ellagic acid can be encapsulated in soybean lecithin liposomes to stabilize and deliver it properly (Madrigal-Carballo et al., 2010). Gallic acid is a hydroxybenzoic acid and is the main component of tea. It has several properties that are beneficial for health, such as anti-inflammatory, antifungal and anticarcinogenic properties (Daneshfar et al., 2008) Gallic acid has been successfully incorporated into zein ultra-fine fibres at different loading amounts using an encapsulating technology called electrospinning for

functional food ingredient delivery (Neo et al., 2013). Encapsulation of gallic acid in acetyled starch improves gallic acid-polymer interaction as measured by the encapsulation efficiency while as, opposite effect is observed for acetylated inulin as compared to native starch and inulin respectively. However, gallic acid release is fast from all the systems evaluated which suggest that the microparticles would be best suited for dry mixes or instant foods to maintain the nutritional value of gallic acid (Robert et al., 2012).

Rutin

Rutin (quercetin-3-rhamnosylglucoside) is a natural flavone derivative found in abundance in buckwheat and is one of the primary flavonoids in a number of plants including asparagus, citrus fruits and berries (Ikeda, 2002; Kim et al., 2005). Like many flavonoids, rutin has been found to have a strong antioxidant activity comparable to many common antioxidants such as ascorbic acid and butylated hydroxytoluene (Yang et al., 2008). It has numerous biological activities which are potentially beneficial to human health such as cardioprotective (Ihme et al., 1996; Izzo et al., 1994), anti-inflammatory (Guardia et al., 2001; La Casa et al., 2000; Selloum, 2003), asthma reducing (Jung et al., 2007), cholesterol lowering (Park et al., 2002; Ziaee et al., 2009), protective effect against hepatotoxicity (Janbaz et al., 2002), anticancer (Deschner, 1992; Webster et al., 1996) and neuronal protective (Khan et al., 2009; Koda et al., 2008; Pu et al., 2007) properties. Therefore, rutin has emerged as a major bioactive ingredient with potential applications in many functional food, nutraceutical and pharmaceutical products. However, a major problem related to this phytochemical is its poor water or oil solubility which

severely restricts its applications (Luo et al., 2011; Luo et al., 2012). Thus, improving the solubility of rutin would greatly enhance the application potential of this flavonoid.

Chitosan-tripolyphosphate submicron particles are formed as carriers of entrapped rutin with good entrapment efficiencies. The particles are sufficient in size to facilitate absorption across the intestinal wall. The particles retain the sensitive core material (rutin) through simulated stomach fluids and release a small portion of its contents (~20% release) in simulated intestinal conditions (Konecsni et al., 2012). Rutin forms 1:1 stoichiometric inclusion complexes with (2-hydroxypropyl)-α-cyclodextrin (HP-α-CD), β-cyclodextrin (β-CD), (2-hydroxypropyl)-β-cyclodextrin (HP-β-CD) and (2-hydroxypropyl)-γ-cyclodextrin (HP-γ-CD), the complexes formed with HP-β-CD and HP-γ-CD having the greatest stability constants followed by β-CD and HP-α-CD. Formation of such inclusion complexes confer moderate degrees of protection to rutin from degradation by heat and ultra violet (UV) radiations during storage and significantly enhance its antioxidant capacity (Nguyen et al., 2013). Rutin is encapsulated within multiple emulsions {(polyethylene-30 dipolyhydroxystearate), (polyglycerol-3 polyricinoleate), (polyoxyethylene (20) stearyl ether) and Synperonic} with a high degree of encapsulation efficiency (>80%) and protection (Akhtar et al., 2013). Quercetin loaded biopolymeric colloidal particles prepared by co-precipitating quercetin with zein in aqueous medium using sodium caseinate as an electrosteric stabilizer result in enhanced chemical stability of quercetin in the alkaline pH and against photodegradation under UV light irradiation (Patel et al., 2012). Hence, these carrier designs could be used for the delivery of concentrated extracts of phenolic compounds in food and natural health products.

Curcumin

Curcumin [1,7-bis(4-hydroxy-3-methoxyphenyl)-1,6-heptadiene-3,5-dione] is a polyphenol found in the rhizomes of turmeric plant, *Curcuma longa*. *Curcuma longa* extracts contain three different diarylheptanoids: curcumin, demethoxycurcumin, and bisdemethoxycurcumin (Jayaprakasha et al., 2002). Curcumin is responsible for most of the pharmacological actions of turmeric. Natural curcumin, isolated from *Curcuma longa* contains curcumin I (diferuloylmethane, 94%), curcumin II (demethoxycurcumin, 6%), and curcumin III (bisdemethoxycurcumin, 0.3%). A number of studies have highlighted antioxidant (Jayaprakasha et al., 2006; Sandur et al., 2007), anti-inflammatory (Aggarwal et al., 2006; Chen et al., 2008), anticancer (Hatcher et al., 2008; Johnson and Mukhtar, 2007), nephroprotective (Cekmen et al., 2009), hypolipidemic (Manjunatha and Srinivasan, 2007), hepatoprotective (Naik et al., 2004) and immunomodulatory (Gao et al., 2004) properties of curcumin. However, certain problems limit the use of curcumin in foods: its low water solubility (Wang et al., 2009) which limits its dispersion in food matrices; its low bioavailability, which negatively affects its biological efficacy (Shaikh et al., 2009) and its rapid degradation under neutral or alkaline pH conditions or when exposed to light (Tonnesen, 2002).

Curcumin shows increased solubility by about 1670 folds and greatly enhanced in vitro anticancer activity upon encapsulation in hydrophobically modified starch, a food grade biopolymer as compared to free curcumin, which may be due to the hydrophobic interaction and hydrogen bonding between curcumin and the hydrophobically modified starch, as suggested by results from infrared and fluorescence spectroscopy (Yu and Huang, 2010). Multilayer β-

cyclodextrin and pluronic polymer (F127) coated magnetic nanoparticles encapsulating the anticancer drug, curcumin, offer good stability, enhanced cellular uptake, sustained release characteristics, improved anticancer therapeutic efficacy and enhanced molecular effects in cancer cells toward apoptosis (Yallapu et al., 2011). Compact curcumin nanoparticles obtained from 1% zein solution show high encapsulation efficiency and present good dispersion in an aqueous food matrix: semi-skimmed milk. The curcumin content remains unaltered and the size or morphology of the nanoparticles does not undergo significant changes after three months of storage at 23 ºC and 43% relative humidity in the dark (Gomez-Estaca et al., 2012). Encapsulation of curcumin in oil-in-water nanoemulsions using different lipids: long, medium, and short chain triacylglycerols (LCT, MCT and SCT respectively) reveal that the bioaccessibility of curcumin decreases in the order of MCT › LCT ›› SCT and is slightly higher in conventional emulsions than in nanoemulsions but nanoemulsions show much better physical stability (Ahmed et al., 2012). All these provide novel food grade encapsulation formulations to increase the stability, solubility and bioaccessibility of curcumin.

Hesperetin

Hesperetin (5,7,3'-trihydroxy-4'-methoxyflavanone) is a flavonone and is abundantly found in citrus fruits (Tomas-Barberan and Clifford, 2000). It is considered to be a powerful antioxidant and has been shown to inhibit chemically induced mammary tumourigenesis (So et al., 1996), colon carcinogenesis (Miyagi et al., 2000), heart attack (Erlund, 2004) and blood pressure (Horcajada and Coxam, 2004). In spite of these valuable benefits, its poor solubility in

water (20 ppm or less) and bitter taste impose considerable obstacles to its use for food fortification.

The inclusion complexes of hesperetin with (2-hydroxypropyl)-β-cyclodextrin are obtained by coevaporation from aqueous suspensions of the host and guest molecules, resulting in a significantly better solubility of the complexes in the aqueous medium with respect to the free flavanone. The in vivo protection efficacy in all cases is higher for the complexes with respect to the free ones (Tommasini et al., 2005). Lipid nanocarriers (solid lipid nanoparticles and nanostructure lipid carriers) for hesperetin fortification in food systems having small size, high encapsulation efficiency and potential for large scale production, make nanostructure lipid carriers (NLC) very interesting to the food sectors (Fathi et al., 2013). Using the layer-by-layer coating technique employing carbohydrate biopolymers (chitosan, alginate and low methoxypectin), hesperetin loaded nanostructure lipid carriers are formed with high encapsulation efficiency and stability. Hesperetin encapsulation also improves the sensory properties (bitter taste, yellowish colour and low homogeneity) of the fortified milk (Fathi and Varshosaz, 2013). Taking these findings into consideration, carbohydrate layer-by-layer coated nanostructure lipid carriers represent a promising vehicle for the delivery of food bioactives and the production of functional foods.

Vanillin

Vanillin is the major flavor component of natural vanilla, which is one of the most popular flavoring materials worldwide. The source of vanilla is the bean or pod of the tropical

Vanilla orchid (principally *Vanilla planifolia* Andrews, syn. *V. fragrans*) (Walton et al., 2003). Vanillin is a tracer component in many dairy products such as butter, ice cream and pastry products. It is used as a food preservative due to its antioxidant properties in food industry. Moreover, vanillin is used for other purposes such as a constituent in cosmetics and drug preparations (Davidson and Naidu, 2000; Karathanos et al., 2007).

Vanillin encapsulated in gum arabic and modified corn and waxy amaranth starches (oxidized) results in higher encapsulated vanillin than the surface vanillin for both the two types of the above mentioned oxidized starches than for gum arabic (Chattopadhyaya et al., 1998). Encapsulation of vanillin in β-cyclodextrin molecules prepared by freeze drying method makes the active compound more soluble in water than the free molecules and is protected from oxidation (Karathanos et al., 2007). The cross linking of xanthan with lignins in the presence of epichlorohydrin leads to hydrogel film formation which possesses a very high degree of swelling and a high swelling rate in aqueous medium, causing a slower vanillin release in vitro (Raschip et al., 2011). Vanillin encapsulated in carnauba wax microcapsules release vanillin relatively easily, suggesting that the Carnauba wax can be suitably used as a carrier for vanillin in its various applications especially in the food industry (Stojakovic et al., 2012). Therefore, the complex can be used as an additive in foods for flavor with the advantage of higher antioxidant activity. Functional polyvinyl alcohol electrospun nanofibres containing vanillin facilitated by cyclodextrin inclusion complexation, provide prolonged shelf life and high temperature stability to the volatile natured vanillin (Kayaci and Uyar, 2012).

Nonflavonoid

Resveratrol

Resveratrol (trans-resveratrol; trans-3,5,4'-trihydroxystilbene), is a naturally occurring polyphenolic phytoalexin, synthesized by a wide variety of plant species such as grapes, berries, peanuts, pistachios and a variety of food sources, as a defense response to situations of stress such as microbial infection, application of chemicals, UV irradiation, change in temperature, mechanical damage, exposure to ozone or heavy metal ions. Resveratrol has been shown to provide health promoting activities such as lowering the incidence of coronary heat disease, inflammatory disease and platelet aggregation, cancer chemopreventive activity especially colon cancer and alleviates oxidative stress. However, its application is limited by light instability and poor aqueous solubility (Signorelli and Ghidoni, 2005; Vella et al., 2008; Rahman, 2008; Leifert and Abeywardena, 2008; Rimando and Suh, 2008; Kang et al., 2009; Zhang et al., 2013).

Hydroxypropyl-β-cyclodextrins are the most effective agents for complexing resveratrol as compared to native α-, β- and γ-cyclodextrins and modified cyclodextrins (hydroxypropyl-β-cyclodextrins, maltosyl-β-cyclodextrins, methyl-β-cyclodextrins, carboxymethyl-β-cyclodextrins and acetyl-β-cyclodextrins). Encapsulation of resveratrol within cyclodextrins can be a useful tool in improving its water solubility, stability and bioavailability as an ingredient in foods. The delay in the resveratrol oxidation is caused by its entrapment in the internal cavity of cyclodextrins, which act as substrate reservoir in a dosage controlled manner (Lucas-Abellan et

al., 2008; Lucas-Abellan et al., 2007; Mantegna et al., 2012). Chitosan microspheres containing resveratrol are prepared using vanillin as a natural and nontoxic cross linker, possessing better stability than the free resveratrol and controlled release that can provide a more effective and continuous supply of resveratrol within the body (Peng et al., 2010). Resveratrol nanodispersions with high light stability, high water dissolution rate and better antioxidant activity in vitro are prepared in a combination of antisolvent precipitation in the presence of nontoxic polymer (Hydroxypropylmethyl cellulose, Polyvinyl pyrrolidone, Polyethylene glycol and Poloxamer188) by spray drying (Zhang et al., 2013). This study can be helpful to promote the application of resveratrol and provide an effective route for enhancing stability and water solubility of photosensitive lipophilic foods or nutraceuticals.

Carotenoids

Carotenoids are a class of natural pigments found mainly in fruits and vegetables, the most abundant being β-carotene, lycopene, lutein and zeaxanthin, which when consumed in sufficient levels are claimed to have biological activities that may reduce the risk of certain chronic diseases, such as cancers, cardiovascular disease, age-related macular degeneration and cataracts (von Lintig, 2010). Among the carotenoids, β-carotene has the highest pro-vitamin A activity, and is therefore a strong candidate for incorporation into functional foods. However, the absorption of β-carotene from many natural and processed foods is often inefficient and highly variable. This has been attributed to a number of causes: entrapment within food matrices, low water-solubility, high melting point and poor chemical stability (Boon et al., 2010; Yonekura and

Nagao, 2007). Its stability towards oxidation depends on its dispersion form and can be increased through encapsulation. The encapsulation of β-carotene in polylactic acid particles gives rise to a more stable supramolecular organisation which offers better protection against oxidation, thus resulting in less prooxidizing oxidation compounds upon degradation. β-carotene nanocapsulation leads to slower release rate, greater stability and a prolonged antioxidant activity against strong free radicals in vitro (Cao-Hoang et al., 2011; Gupta and Ghosh, 2012).

β-carotene

Nanostructures of casein micelles protect β-carotene from degradation during the most common industrial stabilization processes such as heating, sterilization, pasteurization, high hydrostatic pressure and baking. The subsequent release of the entrapped nanoencapsulated structure occurs during the usual digestion process of a protein such as casein, thus ensuring the release of the compound after intake. This opens new possibilities for introducing thermolabile ingredients in bakery products (Saiz-Abajo et al., 2013). β-carotene has successfully been incorporated into food grade oil-in-water nanoemulsions containing a non-ionic surfactant (Tween 20) as emulsifier and long chain triglycerides or medium chain triglycerides or orange oil as carrier oils (Qian et al., 2012). A high β-carotene bioaccessibility can be achieved either by using low-fat long-chain triglyceride or high-fat medium-chain triglyceride nanoemulsions. The bioaccessibility in mixed oil nanoemulsions appears to be highly dependent on oil composition (Salvia-Trujillo et al., 2012). β-carotene possesses the highest stability against lipid oxidation in the sodium caseinate-stabilized nanodispersions as compared to Tween 20, decaglycerol

monolaurate and sucrose fatty acid esters. It is thought that both the physical protection and antioxidative peptides of sodium caseinate contribute to the inhibitory effects on the oxidation of β-carotene in the nanodispersions (Yin et al., 2009). Formulations of β-carotene by precipitation from a pressurized ethyl acetate-in-water emulsion using OSA starch refined from waxy maize as carrier material with a high encapsulation efficiency of β-carotene, high antioxidant activity are obtained. The concentration of modified starch and the organic solvent/water flow ratio being the most influential process parameters on the product properties (de Paz, 2012).

Complex formation with starch dextrin can be used a tool to disperse hydrophobic compounds (β-carotene) in water as nanoparticles with improved stabilities against oxidation and enzymatic digestion. Using separate systems of organic and aqueous phases with ultrasonication, β-carotene complexes with high amylose corn starch dextrin into nanoscale particles that can be dispersed in aqueous media. The aqueous β-carotene dispersion remains homogeneous over 3 weeks in ambient storage with improved stability against oxidation (Kim et al., 2013). Acid modified tapioca starch provides good retention of β-carotene during drying process. The low surface carotene contents with higher cold water solubility than its native starch indicate better microencapsulation efficiency (Loksuwan, 2007). High pressure treated β-lactoglobulin promotes the formation of nano- and micro-particles able to entrap bioactive substances such as β-carotene and protect them during relatively long term storage and possibly also during gastroduodenal digestion (Mensi et al., 2013). Films of gelatin, zein, soy protein, whey protein concentrate and corn and potato starch have been observed to greatly photostabilize β-carotene without greatly affecting the mechanical properties of the materials, when incorporated as a glycerol solution (Lopez-Rubio and Lagaron, 2011). All techniques these have important

implications for the design of effective delivery systems for encapsulation of β-carotene and other lipophilic bioactive components.

Lycopene

Lycopene (ψ,ψ-carotene) is the most abundant carotenoid in tomatoes and is also the red pigment of rosehips, watermelon, papaya, pink grapefruit and guava. The eleven conjugated and two non-conjugated double bonds in lycopene make it highly reactive towards oxygen and free radicals and this antioxidant activity probably contributes to its efficacy as a chemopreventive agent. The reactivity of lycopene also explains why it isomerizes rapidly in blood and tissues from the biosynthetic all-*trans* form to a mixture of cis-isomers. Prospective and retrospective epidemiological studies indicate an inverse relationship between lycopene intake and prostate cancer risk that have been supported by in vitro and in vivo experiments, showing that oral lycopene is bioavailable; accumulates in prostate tissue and is localized to the nucleus of prostate epithelial cells. In addition, lycopene can induce apoptosis in cancer cells and inhibit their proliferation by producing cell cycle arrest (van Breemen and Pajkovic, 2008). However, because of the presence of conjugated double bonds in the molecular structure, lycopene is susceptible to oxidants, light and heat, which can be easily deteriorated when exposed to such factors (Lee and Chen, 2002).

Water soluble complexes of the dietary carotenoid, ψ,ψ-carotene (lycopene) with cyclomaltohexaose (α-cyclodextrin) and cyclomaltoheptaose (β-cyclodextrin) have long been prepared (Mele et al., 2002). Lycopene is encapsulated in gum arabic and maltodextrin by

lyophilization with a half life of 13 days and 10 days for samples stored in the dark and under ultraviolet light at room temperature, respectively (Matioli and Rodriguez-Amaya, 2003). Lycopene microcapsules are prepared by a spray drying technique using a wall system consisting of gelatin and sucrose (Shu et al., 2006). All-*trans*-lycopene from tomato complex with β-cyclodextrin and the encapsulated lycopene remain stable at least for half a year (Blanch et al., 2007). Lycopene extract from tomato pulp waste which is highly susceptible to oxidation and isomerization reactions can have a possible application in the manufacture of functional food formulations by microencapsulation, producing an emulsion system with porcine skin type-A gelatin and poly(γ-glutamic acid) as carriers. The release of lycopene from the microcapsules occurs rapidly at pH 5.5 and 7.0 while no lycopene is released at pH 2.0 and 3.5, which means that this system could be useful as an enteric carrier for lycopene over a range of physiological pH values (Chiu et al., 2007). Submicrometer particles of lycopene with high stability and solubility in aqueous media are produced by extraction of the organic solvent from the droplets of an oil-in-water emulsion with supercritical CO_2 (Santos et al., 2012). Lycopene is microencapsulated in modified starch using the spray drying technique, offering lycopene greater protection as compared to its free form with release of pigment and color from the microcapsules in a homogenous manner (Rocha et al., 2012). Encapsulation of lycopene in corn zein by spray drying is a rapid and simple method. Zein powder can protect lycopene from degradation during storage and being released in the stomach (Xue et al., 2013).

Lutein

Lutein is a non-provitamin A carotenoid, most widely distributed in fruits and vegetables (Granado et al., 2003). It is a strong antioxidant, which protects the retinal epithelial cells from reactive oxygen species, reduces the risk of coronary heart disease and protects the skin from UV induced damage. A vast amount of research indicates that supplementation of lutein decreases the risk of age related macular degeneration, heart disease, lung cancer and skin cancer (Stahl and Sies, 2002; Calvo et al., 2005). However, its application in food industry is limited by the instability towards oxygen, light and temperature due to the eight conjugated double bond structure. The encapsulation of lutein in gelatin/gum arabic system besides providing a high encapsulation efficiency effectively enhances the product stability against light, humidity, temperature and oxygen (Qv et al., 2011). Nanoencapsulated lutein prepared using a low molecular weight chitosan, is reextractable in its native state and shows an increased level of lutein absorption in vitro and in vivo. Hence, low molecular weight chitosan nanoencapsulated lutein can be suggested as a better nanofood dietary compound for health benefits (Arunkumar et al., 2013). Lipid nanocarriers with improved characteristics as effective delivery systems for lutein are developed from fish oil enriched with omega-3 fatty acids, with a high encapsulation efficiency of 88.5%, high oxygen free radical scavenging activity of 98% and a sustained release of lutein as compared to conventional nanoemulsions in vitro (Lacatusu et al., 2013). Taking lutein properties into consideration, the technology of encapsulation is adoptable for its multiple advantages.

Fatty acids and structural lipids

The addition of polyunsaturated fatty acids (PUFAs), familiar to the public as omega-3 and omega-6 fatty acids, to food products and the increased consumption of these fats in the daily diet is one area within the functional foods market that has experienced dramatic increase in the recent years. The well documented health benefits of PUFA include the potential mechanisms for the cardioprotection, including anti-arrhythmic, anti-inflammatory, hypotriglyceridemic effects, lowering blood pressure and improved endothelial function, besides improved performance of the immune system, protective effects on various cancers in human cell lines, possible roles in foetal and early childhood development and improved cognition (Balk et al., 2006; Abeywardena and Head, 2001; McLennan and Abeywardena, 2005; Weitz et al., 2010; Shahidi and Miraliakbari, 2004; Miraliakbari, 2005; Wendel and Heller, 2009). PUFAs cannot be synthesized by the human body and therefore, should be provided with the diet. However, enrichment of food products with PUFAs is a challenging technological task due to the fact that PUFAs include two or three methylene interrupted double bonds, which render them susceptible to heat, light and oxidation, resulting in the development of off flavours and off odours. Therefore, they have a tendency to degrade and auto-oxidize at high rates during production, storage and passage in the digestive system, with the result, the daily uptake is on an average lower than the recommended amount (Barrow et al., 2007; Lalush et al., 2005; McClements et al., 2007; Semo et al., 2007).

Microencapsulation is a well recognized approach to protect PUFAs against oxidation caused by environmental factors such as oxygen, light and humidity as well as chemical factors such as cupric ions that are catalysts of oxidation reactions (Thautwein, 2001) and increases their

bioavailability in vivo simultaneously (Augustin et al., 2011). Many processes have been developed to incorporate the oil body in particulate structures. Oil can be converted into emulsions that can be used in products such as beverages directly or prepared into the powdered form by further coating oil droplets with other materials. Preparation of powdered products can be achieved by processes such as supercritical antisolvent, spray freeze drying, spray drying, fluidized bed drying, and freeze drying. The powdered products can be incorporated in various products, dry or wet. Dairy proteins, gelatin, maltodextrins, starch, gum acacia, alginate, etc. are the various food grade biomaterials that have been used to coat oil droplets (Heinzelmann et al., 2000; Hogan et al., 2003).

Fish oil

Shark liver oil is a good source of nutritional factors such as lipid soluble vitamins and essential fatty acids. Of great interest is its composition rich in omega-3 polyunsaturated fatty acids. Shark liver oil can be efficiently encapsulated in calcium alginate beads coated with chitosan in order to mask its unpleasant taste. The capsules are degraded by lipase and pancreatine. The shark liver oil loaded chitosan/calcium alginate capsules are initially resistant to the acid environment of the stomach but, after 4 h at the intestinal pH (7.4), the capsule wall weakens and can be easily deteriorated and disintegrated by the mechanical and peristaltic movements of the gastrointestinal tract (Peniche et al., 2004). Linseed pectin shows poor performance as an encapsulation matrix for shark liver oil but, in combination with alginate coated by chitosan through formation of a polyelectrolyte complex membrane, offers a new strategy to mask the strong flavor and odor of shark liver oil towards its utilization as a diet and

health supplement (Diaz-Rojas et al., 2004). Baikal grayling, *Thymallus baikalensis* (*Salmonidae* family) has higher muscle levels of EPA and DHA, the main PUFAs of fish oil, than some marine *Salmonidae* fish. Encapsulation of Baikal fish oil in methacrylic acid copolymer results in a high encapsulation efficiency and pH sensitivity of the nano and microparticles obtained. These formulations are promising systems for improving the site specific delivery and bioavailability of bioactive oils, fatty acids and dissolved liposoluble active ingredients (Averina and Allemann, 2013). Stable tuna oil-in-water emulsions containing droplets stabilized by lecithin-chitosan membranes can be produced using an electrostatic deposition method, which involves adding a positively charged biopolymer to an emulsion containing negatively charged droplets. The emulsions remain stable to droplet flocculation and coalescence in the presence of quite high levels of corn syrup solids, which is commonly used in the microencapsulation of oils. The multilayered emulsions have better stability to thermal processing, freeze thaw cycling and drying than primary emulsions (Klinkesorn et al., 2005). Chitosan incorporated with maltodextrin and whey protein isolate is used to encapsulate tuna oil, using ultrasonic atomization, producing the encapsulated powder containing high eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) content, low moisture content, acceptable color and encapsulation efficiency (Klaypradit and Huang, 2008).

Microencapsulation of fish oil by spray drying in a matrix of sugar beet pectin and glucose syrup generally reflects a good microencapsulation efficiency and good oxidative stability. However, the proportion of nonencapsulated fat being higher in samples with 50% oil compared to samples with 20% oil and may limit the maximum oil load of the microcapsules (Drusch, 2007). Increased lipolysis of microencapsulated fish oil powder in the presence of

amylase and/or trypsin attributed to the digestion of the microcapsule made up of sodium caseinate and pre-processed resistant starch, which facilitates the displacement of the interface of oil droplets by bile salts provides further understanding about digestion mechanisms of emulsified oil systems and the important role of interfacial design to control lipolysis in vitro (Chung et al., 2011). β-cyclodextrin shows a higher encapsulation efficiency of fish oil and retards the fish oil release in liquid or in powder form as compared to polycaprolactone, which retards the release of fish oil in liquid or powder form more efficiently and better protects fish oil because of its water insolubility (Choi et al., 2010). By using a casein based Maillard reaction product (MRP), (caseinate–glucose-dried glucose syrup) and its corresponding non-MRP-based encapsulating material, a fish oil/water emulsions is prepared and spray dried to obtain the free flowing fish oil microcapsules. The amount of oil released after subjecting to the sequential in vitro protocols being <2% and 36% respectively for caseinate and whey protein based MRP microcapsules. This is an important factor to consider the digestibility of an interface and is one factor that will influence the bioavailability of the lipid (Kosaraju et al., 2009). Surface accumulation of proteins at the air-water interface leads to a modified surface composition, which is beneficial for certain applications. In case of lipophilic ingredients, interfacial rheological characteristics need to be taken into consideration to maintain the emulsion structure throughout the drying process and to minimize non encapsulated oil. Lipid oxidation during storage of fish oil microencapsulated in spray-dried carrier matrices based on sodium caseinate and casein hydrolyzate increases with the protein content in the formulation. Excess protein leads to an increase in free volume elements and is suspected to negatively affect oxygen diffusion (Drusch et al., 2012). Emulsions of fish oil stabilised by Tween 20 oxidise faster than either

microspheres of high methoxy pectin and sodium caseinate or emulsions stabilized by casein, while microspheres and the casein stabilized emulsions show similar oxidation rates (Matalanis et al., 2012). Electrostatic nanocomplexes consisting of β-lactoglobulin and pectin, which entrap omega-3 polyunsaturated fatty acid, DHA molecules, show a very good colloidal stability, resulting in transparent dispersions, potentially useful for enrichment of acid non-fat drinks, particularly clear ones and confer protection to DHA against its oxidation (Zimet and Livney, 2009).

Flaxseed oil

Flaxseed oil is a rich source of essential fatty acids e.g., α-linolenic acid, which induce a variety of health benefits upon consumption such as reducing the risk of coronary heart diseases (Li et al., 2003) and the prevention of breast and prostate cancers (Bougnoux and Chajes, 2003). However, in spite of these health benefits, the use of flaxseed oil in aqueous food systems is restricted due to its high polyunsaturated fatty acid content which is hydrophobic in nature and susceptible to oxidation, producing off flavours and off odours (Łukaszewicz et al., 2004; Bozan and Temelli, 2008).

Flaxseed oil is encapsulated in a matrix composed of maltodextrin, lecithin and xanthan gum, using the freeze drying technique. The microencapsulation process besides having high encapsulation efficiency protects the flaxseed oil well from oxidation (Grattard et al., 2002). Flaxseed oil microcapsules produced using zein as a coating material by spray drying and freeze drying processes exhibit very poor handling properties. However, microcapsules prepared by spray drying method show higher microencapsulation efficiency than those prepared by freeze

drying method (Quispe-Condori et al., 2011). Flaxseed oil is microencapsulated by spray drying using gum arabic as the wall material, in which higher solid content and lower oil concentration lead to higher encapsulation efficiency and lower lipid oxidation (Tonon et al., 2011). Starch mixed with flaxseed oil and held in supercritical carbon dioxide at 15 or 30 MPa and 40, 60 or 80 ºC under static or dynamic conditions, results in particles with encapsulation efficiency of 6.6% achieved at 30 MPa and 80 ºC (Comin et al., 2012a). β-glucan aerogels are impregnated with flaxseed oil using supercritical carbon dioxide as a mass transfer medium. The highest level of impregnation i.e. 65.39% is achieved when predried gels are impregnated, employing a dynamic process at 40 ºC and 15 MPa (Comin et al., 2012b), indicating the potential of supercritical carbon dioxide technology for food grade polymer impregnation, targeting nutraceutical delivery.

Microencapsulation of flaxseed oil by spray drying using maltodextrin in combination with different wall materials reveals that maltodextrin in combination with modified starch shows the highest encapsulation efficiency while as, maltodextrin in combination with whey protein concentrate shows the highest protection of the active material against lipid oxidation (Carneiro et al., 2013). Flaxseed oil microencapsulated by employing a wall material matrix of either chickpea isolate or lentil protein isolate and maltodextrin followed by freeze drying, exhibits a protective effect against oxidation over a 25 day storage period at room temperature. The microcapsules prepared present low surface flaxseed oil content, a high flaxseed oil encapsulation efficiency and high release properties under simulated gastrointestinal conditions (Karaca et al., 2013). These findings suggest that the developed food grade microencapsulation

systems could lead to increased utilization of flaxseed oil and legume proteins in food and bioproduct formulations and applications.

Olive oil

Olive oil from olive fruit (*Olea europaea* L.; Oleaceae) is of dietetic and therauptic importance. The benefits of increased intake of olive oil include its rapid digestibility together with the beneficial health effects that are related to the prevention of cardiovascular diseases, cancer (especially breast cancer), neuro-degenerative diseases anti-ulcer, anti-aging, stress and plasma cholesterol lowering properties, therapy potentials for type 1 and 2 diabetes as well as skin care (Servili et al., 2004; Menéndez et al., 2009; Visioli et al., 2002; Owen et al., 2000; Ozyilkan et al., 2005; Shah et al., 2004; Strychar et al., 2003). Olive oil contains triglycerides composed mainly of oleic acid (MUFA) and a small amount of saturated fatty acid resulting in its poor storage stability (O'Brien, 2004). Oxidation results in the loss of nutrients and flavour, conversion of unsaturated to saturated fatty acid and development of deleterious products such as reactive oxygen species. Protection from lipid oxidation is a critical factor in oil quality. However, fortification of the oil with antioxidants and encapsulation has been adopted as approaches to address this issue (Anwar et al., 2000; Heinzelmann and Franke, 1999).

Olive oil to which caffeic acid is added, encapsulated in sodium alginate shells provides a greater protection against oxidation (but not hydrolytic rancidity) than the encapsulation process not involving caffeic acid addition. The addition of caffeic acid to olive oil not only provides additional protection to the olive oil, but also improves the nutritional values of the final oil products in terms of the elevated total extractable phenolic content and desirable unsaturated

fatty acids (Sun-Waterhouse et al., 2011). An instantaneous food emulsion is formulated containing olive oil and lemon juice using combinations of polymers such as alginate, gum arabic, maltodextrin and carboxymethyl cellulose by freeze drying, aiming at the development of a new microencapsulated product. The characterization of the samples reveal the suitability of gum arabic in combination with maltodextrin as a better mixture for microencapsulating emulsion with 50% v/v of olive oil-lemon juice by freeze drying (Silva et al., 2013). The association of the emulsifying properties of gelatin and the high resistance of alginate as a delivery system for the production of mixed alginate and gelatin gelled emulsions of olive oil are produced using high pressure homogenization. The alginate-gelatin mixed emulsions show enhanced oxidation and pH stability as compared to systems produced with only one biopolymer. Such improved stability of mixed gelled systems is associated to the emulsifying properties of gelatin with the high pH resistance of alginate as a delivery system (Sato et al., 2012). Encapsulation of olive oil in maltodextrin, carboxymethylcellulose and lecithin show a great deal of encapsulation yields. Irrespective of the presence of BHT (2,6-Di-tert-butyl-4-methylpenhol), the presence of protein constituents in the microcapsule wall material is believed to extend the shelf life of the microencapsulated olive oil more effectively than carbohydrates (Calvo et al., 2012). The emulsifying property of chitosan is enough to stabilize olive oil droplets in a homogeneous, thin and translucent film based on chitosan and olive oil emulsion, offering it a good deal of emulsion stability (Pereda et al., 2012). Olive oil has a good potential to be incorporated into gelatin through microfluidic emulsification to make edible films or coating for some food applications (Ma et al., 2012).

Table 2.

CONCLUSION

Encapsulation of bioactive compounds aimed for human consumption using the food grade materials, is a way for their safe guard against the harsh environmental and gastrointestinal conditions, ensuring their targeted delivery at the absorption sites. Oils rich in MUFA and PUFA that are beneficial for health and used as protective medicine, have issues of off flavor and off odour production and susceptibility to oxidation, which can be encapsulated in biomaterials like starch, dextrins, β-glucan, gum arabic, alginate, carboxymethyl cellulose, chitosan, xanthan, pectin, zein and whey protein isolates; starch being the predominant one; ensuring their oxidative stability, high pH resistance, controlled delivery, masking their off flavor, off odour and improving their bioavailability. Polyphenols with issues of being susuptible to oxidation, high temperature and low aqueous solubility, can be encapsulated in starch, cyclodextrins, lipids, alginate, chitosan, zein and whey protein isolates; β-cyclodextrin and zein being the predominant materials, resulting in improved aqueous solubility, stability against pH, heat and UV radiations, improved sensory properties, controlled release and enhanced anti-cancer activity and bioaccessibility. Carotenoids with issues of being susuptible to oxidation and high temperature and having low aqueous solubility, can be encapsulated predominantly in starch, β-cyclodextrin, lipids, gum arabic and gelatin, enabling their stabilization against light, humidity, temperature and oxygen while improving their cold water solubility, controlled delivery, high anti-radical activity and high bioaccessibility.

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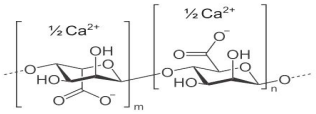
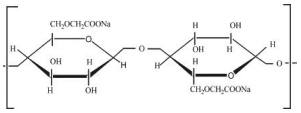
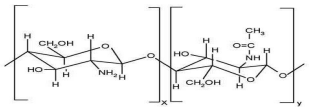
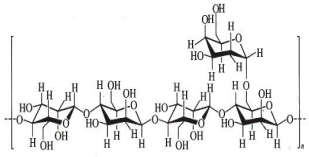
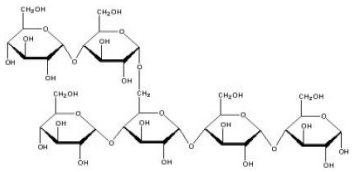
Table 1: Different food grade materials used for the encapsulation of nutraceuticals.

Starch Encapsulating Material	Structure	Source	Type of the material used	Material used as or in tandem	References
Alginate		Brown sea algae	Ca-alginate & Ba-alginate.	Alginate beads Pectin Chitosan	Strasdat and Bunjes, 2013 Orive et al., 2006 Zimmermann et al., 2003 Liu et al., 2002 Madziva et al., 2006 Liu et al., 2004
Carboxymethyl cellulose		Wood pulp	Na-carboxymethyl cellulose	Poly allylamine hydrochloride Alginate k-carrageenan Chitosan Divinyl sulfone	Tripathy and Raichur, 2013 Kim et al., 2012 Muhamad et al., 2011 Kaihara et al., 2011 Butun et al., 2011
Chitosan		Crustaceous shells	Chitosan-tripolyphosphate	Xyloglucan β-lactoglobulin	Marguerite, 2006 Pillai et al., 2009 Simi et al., 2010 Dube et al., 2010 Lee et al., 2012 Konecsni et al., 2012
Gum arabic		Acacia tree	Arabinogalactan, glycoprotein & arabinogalactan protein.	Gelatin Na-caseinate SPI Starch Sucrose-gelatin β-lactoglobulin	Rocha-Selmi et al., 2013 Lv et al., 2013a Ye et al., 2012 Ye et al., 2011 Jun-xia et al., 2011 Kshirsagar and Singhal, 2008 Kaushik and Roos, 2007 Schmitt et al., 2001
Polysaccharides Oligosaccharides		Cereals	Starch Cyclodextrins	Pickering emulsion Maltose Calcium-alginate	Matos et al., 2013 Mun et al., 2013 Garcia-Gonzalez et al., 2012 Li et al., 2013

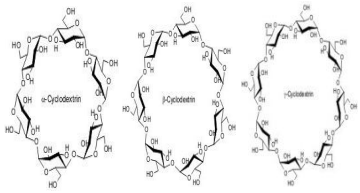
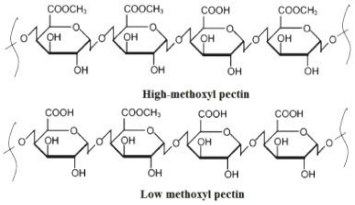
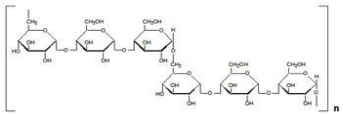
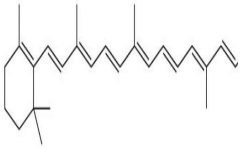
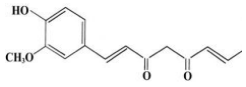
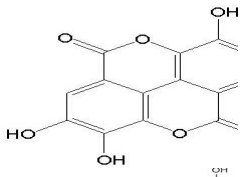
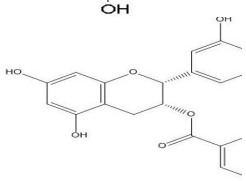
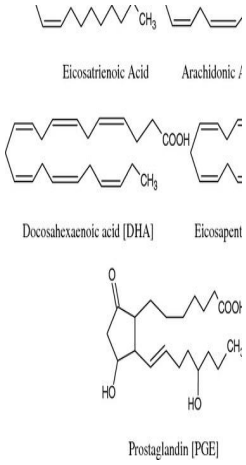
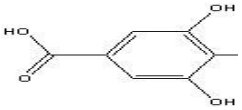
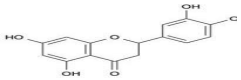
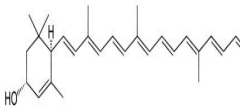
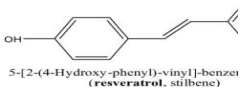
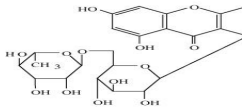
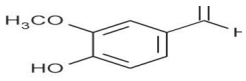
				PEG Gelatin	Cordoba et al., 2013 Chan et al., 2011 Minimol et al., 2013 Wohl-Bruhn et al., 2012 Zhang et al., 2013 Beirao-da-Costa et al., 2011 Kim et al., 2013 Ho et al., 2011a Hashimoto, 2006 Szejtli and Szente, 2005
pectin		Fruits & vegetables	High & low methoxyl pectin.	β-lactoglobulin Ovalbumin β-casein SPI	Serfert et al., 2013 Rossier-Miranda et al., 2012 Chen et al., 2012 Nicolai et al., 2011 Jones et al., 2009 Bedie et al., 2008 Humblet-Hua et al., 2011 Esmaili et al., 2011 Ortiz et al., 2009
Pullulan		*Aureobasidium pullulans*	Pullulan	Gum arabic & maltodextrin	Kshirsagar et al., 2009
Proteins		Maize Egg, meat, poultry & soybean	Zein β-lactoglobulin, ovalbumin, caseins & lipoproteins.	Carboxymethyl chitosan Chitosan HMP & LMP, xanthan gum, sodium carboxymethyl cellulose, pectin & k-carrageenan.	Wang et al., 2013 Neo et al., 2013 Perez-Masia et al., 2013 Xiao and Zhong, 2011 Jin et al., 2009 Luo et al., 2013 Luo et al., 2010 Luo et al., 2011 Chen et al., 2012 Lee and Rosenberg, 2000 Giroux et al., 2010 Souza et al., 2013 Jones et al., 2009 Chanasattru et al., 2009

Table 2: Impact of encapsulation on different nutraceuticals using various materials.

Encapsulated Species	Structure	Encapsulating Material(s)	Impact on the Encapsulated Species	References
β-carotene		Lipids, casein, starch dextrin, polylactic acid β-lactoglobulin, gelatin, zein & soy protein,	Controlled delivery, greater stability, prolonged antioxidant activity, high bioaccessibility, heat stabilization & cold water solubility.	Saiz-Abajo et al., 2013 Kim et al., 2013 Mensi et al., 2013 Gupta and Ghosh, 2012 Salvia-Trujillo et al., 2012 de Paz, 2012 Cao-Hoang et al., 2011 Lagaron, 2011 Loksuwan, 2007
Curcumin		Hydrophobically modified starch, β-cyclodextrin, zein & lipids.	Enhanced anti-cancer activity, aqueous dispersion & bioaccessibility.	Gomez-Estaca et al., 2012 Ahmed et al., 2012 Yallapu et al., 2011 Yu and Huang, 2010
Ellagic acid		Soybean lecithin liposomes	pH stability & controlled release.	Madrigal-Carballo et al., 2010
Epigallocatechin-3-gallate		β-lactoglobulin	Oxidative stability, controlled enteric delivery, improved taste & mouth feel.	Shpigelman et al., 2012 Shpigelman et al., 2010

Fish, olive & flaxseed oils		Linseed pectin, alginate, chitosan, resistant starch, maltodextrin, whey proteins & methacrylic acid.	Controlled delivery, improved bioavailability & flavour & odour masking.	Averina and Allemann, 2013 Drusch et al., 2012 Chung et al., 2011 Choi et al., 2010 Kosaraju et al., 2009 Klaypradit and Huang, 2008
		Alginate, arabic gum, maltodextrin, chitosan, gelatin & carboxymethyl cellulose.	Oxidative protection & high pH resistance.	Silva et al., 2013 Calvo et al., 2012 Pereda et al., 2012 Ma et al., 2012 Sato et al., 2012 Sun-Waterhouse et al., 2011
		Maltodextrin, starch zein, lecithin, β-Glucan, gum arabic, xanthan gum, chickpea & lentil protein isolate.	Oxidative stability & controlled release.	Karaca et al., 2013 Carneiro et al., 2013 Comin et al., 2012a Comin et al., 2012b Tonon et al., 2011 Quispe-Condo et al., 2011 Grattard et al., 2002
Gallic acid		Zein fibres, native & acetyled starch & inulin.	Controlled release & suitable for dry mixes or instant foods.	Neo et al., 2013 Robert et al., 2012
Hesperetin		Lipids, β-cyclodextrin, chitosan, alginate & low methoxypectin.	Stability, better solubility & improved sensory properties.	Fathi et al., 2013 Fathi and Varshosaz, 2013 Tommasini et al., 2005
Lutein		Gelatin, gum arabic, chitosan & ω-3 fatty acids.	Stability against light, humidity, temperature & oxygen, bioaccessibility & high anti-radical activity.	Arunkumar et al., 2013 Lacatusu et al., 2013 Qv et al., 2011

Lycopene		Cyclodextrins, gum arabic, sucrose, starch, zein & gelatin.	Controlled enteric delivery & oxidative stability.	Xue et al., 2013 Rocha et al., 2012 Chiu et al., 2007 Blanch et al., 2007 Shu et al., 2006 Matioli and Rodriguez-Amaya, 2003 Mele et al., 2002
Resveratrol		β-cyclodextrin derivatives & Chitosan.	Improved water solubility, stability, bioavailability & controlled release.	Zhang et al., 2013 Mantegna et al., 2012 Peng et al., 2010 Lucas-Abellan et al., 2008 Lucas-Abellan et al., 2007
Rutin		Chitosan-tripolyphosphate, β-cyclodextrins & multiple emulsions.	Controlled enteric delivery & protection against heat & UV radiations.	Nguyen et al., 2013 Akhtar et al., 2013 Konecsni et al., 2012
Vanillin		Xanthan, β-cyclodextrin, polyvinyl alcohol & starch.	Improved aqueous solubility, prolonged shelf life, high temperature stability & slower vanillin release.	Kayaci and Uyar, 2012 Raschip et al., 2011 Karathanos et al., 2007 Chattopadhyaya et al., 1998