Encapsulation of New Active Ingredients*

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Abstract

The organic construct consumed as food comes packaged in units that carry the active components and protect the entrapped active materials until delivered to targeted human organs. The packaging and delivery role is mimicked in the microencapsulation tools used to deliver active ingredients in processed foods. Microencapsulation efficiency is balanced against the need to access the entrapped nutrients in bioavailable forms. Encapsulated ingredients boosted with bioactive nutrients are intended for improved health and well-being and to prevent future health problems. Presently, active ingredients are delivered using new techniques, such as hydrogels, nanoemulsions, and nanoparticles. In the future, nutraceuticals and functional foods may be tailored to individual metabolic needs and tied to each person's genetic makeup. Bioactive ingredients provide health-enhancing nutrients and are protected through encapsulation processes that shield the active ingredients from deleterious environments.

INTRODUCTION

This review focuses on the benefits of bioactive ingredients and the encapsulation processes used to protect these beneficial nutrients. Functional foods boosted with bioactive nutrients are consumed for enhanced health and mitigating disease conditions. Functional foods may address deficiency or excess of certain nutrients in response to the demand of health-conscious consumers (Richardson 2009, Jacobs & Tapsell 2007). For example, poor diet and limited consumption of bioactive nutrients have been implicated in the initiation or progression of cardiovascular disease (CVD) and cancer. Farmers and food manufacturers have responded to the increased demand for healthy foods by creating new nutrient-enriched produce and products, using innovative technology (Lindsay 2000). Food processing techniques, such as encapsulation, are used to preserve and deliver active nutrients through deleterious environments, until assimilated in the proper human organs where their functions are needed (Galland 2005).

Protected delivery or some form of encapsulation is an important means of delivering bioactive ingredients. For example encapsulation can increase nutrient bioavailability, increase flavor retention, mask strong flavors, and stabilize food ingredients (Versic 1988). Encapsulation could also be used to immobilize cells or enzymes within food matrices for timed release (Chan & Zhang 2002).

Functional foods may be optimized for improved health and quality of life on an individual level using the emerging tools of nutrigenomics and metabolomics. Nutrigenomics is the interaction of diet and disease based on individual genetic makeup (Getz et al. 2010), and metabolomics is the use of particular active compounds for health-enhancing properties (Wishart 2008, Hall 2007). Ultimately, personalized foods may lower disease risks and speed up recovery after illness (Wishart 2008). Metabolomics explores individualized pathways linking personal genomics with nutrition, healthy eating patterns and lifestyles, and increased consumption of small active components, such as polyphenols, organic acids, and minerals, to enhance health (Hasler 2002, Getz et al. 2010).

BIOACTIVE COMPONENTS

Bioactives are compounds in the structural matrix of foods that provide enhanced health and well-being effects. Active components linked to benefits by physiology or forms include omega-3 fatty acids, minerals, vitamins, proteins, peptides, probiotics, fiber, and prebiotics. Food structure and nutrients interact to provide biological activity and enhance health by maintaining human biological processes (Saura-Calixto 2011). The consumption of whole foods rather than isolated active components is preferable for optimal health function. For example, it has been shown that phytochemicals locked into the fiber matrix are more bioactive because consumption of whole grains lowered the risk of chronic disease more than the refined grain (Jacobs & Steffen 2003). Scientific evidence shows that natural antioxidants, including polyphenols, from fruits and vegetables are effective against cancer and CVD (Arts & Hollman 2005).

Some risks, such as overconsumption of bioactive nutrients, may exist, as focus on active nutrients may place more emphasis on enriching selected bioactive nutrients in foods. Some studies have suggested that focusing on a class of foods, such as dairy (Hartmann & Meisel 2007), and maintaining food patterns, such as consuming high quality proteins from different sources (Dzuib & Darewicz 2007, Hu et al. 2000), may reduce chronic disease risk over time (Lockheart et al. 2007). Some examples are studies on food patterns that show relevant health outcomes of whole grains on CVD and type 2 diabetes (Ros & Mataix 2006, Murtaugh et al. 2003), nuts and olives on cardiovascular risk factors (Estruch et al. 2006), fish oils on coronary heart disease and stroke

(He et al. 2004a,b), and olive oils and nuts on overall well-being (de Lorgeril et al. 1999), stroke, and heart disease (Schulze and Hoffmann 2006).

ACTIVE INGREDIENTS

Some functional bioactive nutrient subgroups include phytosterols, polyphenols, carotenoids, dietary lipids, probiotics, prebiotics, synbiotics, and botanicals such as teas, herbs, and spices (see **Table 1**). Functional foods are not consumed for therapeutic effects or as drugs. They are used mostly to reduce the risk of developing disease. Health claims describe relations between a food, food component, or dietary supplement and reduction of disease risk or health-related conditions (Hasler 2008). For example, the U.S. Food and Drug Administration (FDA) allows several claims that cover bioactive nutrients in functional foods, such as increased active nutrient content, improving overall health, and new structure-based functions. In the United States, structure-based function claims that demand that dietary supplements positively affect functions in the body were authorized under the Dietary Supplement Health and Education Act of 1994 (FDA 2010).

The main purpose of functional foods or the active components is reducing the risk of a number of the leading causes of death, such as cancer, diabetes, CVD, and hypertension. In the past, fortification of nutrient-deficient foods with micronutrients (minerals and vitamins) was used to overcome mineral deficiency and health problems in various places in the developing world, but now foods are intentionally boosted with micronutrients in the Western affluent world to create a new generation of super-functional foods (Akhtar et al. 2011). In the future, functional foods will have the potential to provide health benefits beyond that of basic nutrition and may be better than consuming micronutrient-enriched supplements as pills (Griffiths 2010). For example, boosting the active components in dietary proteins, such as whey, soy, and wheat gluten, has shown to decrease postprandial appetite; in particular, dairy whey proteins have an added thermogenic benefit of increasing satiety through a cascade of hormonal changes leading to the release of cholecystokinin (Bowen et al. 2006).

Minerals and trace elements of inorganic ions may function as bioactives; for example, salts can be bound with proteins, peptides, carbohydrates, fats, and small molecules, and thus become functional foods. The mineral binders caseins, whey proteins, and lactoferrins bind specific elements like calcium, magnesium, zinc, iron, sodium, and potassium, enriching their functions (Vegarud et al. 2000). Through specific and nonspecific binding sites, milk proteins can carry or entrap various minerals and thus enhance the bioavailability of the minerals (Parada & Aguilera 2007). For example, iron-binding peptides may mitigate the problems of anemia by boosting bioavailability of irons (Chaud et al. 2002).

Vitamins differ greatly in their structures, and their rate of degradation depends on processing conditions, but minimizing temperature and shear rates protects most vitamins during processing (Anal & Singh 2007). The primary functional benefit of these nutrients is to defend against the risk of developing diseases, such as atherosclerosis and cancers. Other benefits are reducing oxidative damage to human tissues, providing antiinflammatory, antiarthritis, and anti-Alzheimer's properties. Functional bioactive components may also help in weight loss (Gruenwald 2009).

Phytochemicals are biologically active secondary metabolites derived from the color and flavor components of fruits and vegetables (Kalt 2001). Phytosterols occur in small amounts in vegetable oils and can lower raised plasma cholesterol levels in humans by inhibiting the absorption of dietary and endogenously produced cholesterol in the small intestine. Phytosterols are structurally similar to cholesterol and so compete with cholesterol for binding sites in the gastrointestinal (GI) tract, thereby lowering plasma cholesterol (Kaput et al. 2007).

Table 1 Food and active components and associated benefits

Compound or component	Food source	Associated use/benefits	Associated study	Literature
Phytosterols Sitosterol, campesterol, stigmasterol	Nuts, seeds, whole grains, legumes	Blocking low-density lipoprotein (LDL), cholesterol	Phytosterols lowered cholesterol at dosages ranging from 3 to 53 g per day Doses of 1.5 to 3 g per day blocked low-density lipoprotein (LDL), reducing cholesterol absorption in the intestine from 8% to 15% Phytochemicals mitigate chronic and degenerative diseases, heart disease, diabetes, Parkinson's disease, and Alzheimer's	Kritchevsky & Chen 2005, Kaput et al. 2007, Gruenwald 2009
Polyphenols Tannins, phenylpropanoids (lignins & flavonoids) hydroxytyrosol, caffeic acid, oleuropein, ferulic acid, phytic acid, catechins, epigallocatechin, epicatechin gallate, gallocatechin gallate, (EGCG)	Legumes, fruits, and vegetables; red wine, chocolate, green tea, olive oil and fruit oil; bee pollen, cereal grains and seeds; green coffee extract	Antioxidant activity, metal chelators, anticancer, anti-arthritis, protects from Alzheimer's, weight loss properties	Green tea polyphenols showed 12% reduction in breast cancer risk among 3,454 women with breast cancer Flavonoids lower cardiovascular disease risk and mortality from incidence of myocardial infarction. Anthocyanins may help to prevent hypertension	Chen et al. 2006, Manarch et al. 2004, Peterson & Dwyer 1998, Mandel et al. 2005
Carotenoids α-Carotene, β-carotene, lycopene	Carrots, tomatoes, spinach, maize, citrus, potatoes, pumpkins, yellow and red peppers, carrots, apricots, cantaloupe, collard greens, kale	Antioxidant (singlet oxygen quenchers), antioxidants, trapping free radicals	Carotenoids increased breast cancer-free survival with plasma carotenoid concentration from 1.7 to 10.0 μmol L^{-1}	Hennekens et al. 1996, Rao & Rao 2007, Rock et al. 2009
Dietary lipids Omega-3 α-linolenic acid (ALA), eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA), conjugated linoleic acid (CLA)	Flaxseed, vegetable oils, nuts, oily fish, cow's milk, meat	Improves joint health, cardiovascular health, brain development, visual acuity, depression, cancer. Mitigates type 2 diabetes, skin disorders, asthma, irritable bowel syndrome, weight loss	Omega-3 polyunsaturated fatty acid mediated the regulation of common signaling pathways. CLA blocked three stages of cancer and slowed the growth of breast tumors; meta-analysis of a CLA study showed weight loss and weight gain prevention benefits, and slowed fat regain following a weight loss diet	Ma et al. 2004 Gillet et al. 2011 Kim & Mendis 2006 Bhat & Bhat 2011 Bocca et al. 2010

Prebiotics Lactobacilli, fructo-oligosaccharides Resistant starch	Inulin Processed starch	Digestion of lactose, reducing constipation and helping to relieve irritable bowel syndrome	Dosage of 20 g per day of resistant starch increased levels of butyrate Fructo-oligosaccharides preferentially promote the growth of bifidobacteria in the large intestine	Quigley 2010 Wang 2009 Bielecka et al. 2002 Tuohy et al. 2003
Probiotics *Lactobacillus*, bifidobacteria, yeasts	Yogurt, kefir, cultured products	Improved digestion, immune function; reduction of allergy, suppression of allergy and cancer	Alleviating symptoms of malabsorption, enhancing natural resistance to infections of the intestinal tract, suppression of cancer, reduction in serum cholesterol, improved digestion, and stimulation of immune functions	Wang 2009, Bielecka et al. 2002, Bruzzese et al. 2006
Synbiotics Prebiotics and probiotics	Inulin, bifidobacteria	Improved digestion, immune function	Yogurt containing *Lactobacillus acidophilus* and 2.5% fructooligosaccharides reduced serum cholesterol levels and decreased low-density lipoprotein	Tuohy et al. 2003, Sanders & Marco 2010, Douglas & Sanders 2008
Botanicals Teas, bitter melon, bitter orange (*Citrus aurantium*), cinnamon (*Cinnamomum verum*), circumin, elderberry extract, hibiscus extract, fruit peel extract, ginkgo (*Ginkgo biloba*), kumquat (*Fortunella margarita*)	Teas, bitter melon, bitter orange, cinnamon, circumin, elderberry, hibiscus, *Ginkgo biloba*, kumquat	Neuroprotective, antioxidants, anticoagulant, boost immune function, cytokines	Procyanidins reduced plasma cholesterol, chronic pancreatitis, vomiting, and pain, in dosages ranging from 160 mg to 1 g per day Glycosides extracts of bitter melon and cinnamon for type 2 diabetes Ginger provides antimicrobial, antiinflammatory, or antiplatelet biologically active constituents; cinnamon oil (cinnamaldehyde), phenols and terpenes, with antifungal, antidiarrheal, vasoactive, and analgesic effects Cinnamon increases the sensitivity of insulin cells and may prevent type 2 diabetes	Gruenwald 2009, Kritchevsky & Chen 2005, Shrubsole et al. 2009, Blevins et al. 2007

Carotenoids are phytochemicals that play important roles in maintaining health and preventing human diseases. Carotenoid bioactive substances in the pigmented parts of fruits and vegetables are known to mitigate oxidative stress and to prevent chronic conditions, such as CVD and cancer (Rao & Rao 2007). Carotenoids provide antioxidant effects and mitigate damages to cells by modulating immune functions, cell growth, and gene expression. The major carotenoid pigments include β-carotene (yellow to orange), α-carotene (light yellow), lycopene (red), lutein (yellow), zeaxanthin (yellow), and β-cryptoxanthan (orange) (Lindshield & Erdman 2010); epidemiological evidence links higher intake of carotenoids with reduced cancer and CVD (Rock 1997).

Polyphenols are plant-derived functional compounds associated with many health benefits, mainly through antioxidant activity. For example, green tea is used in functional beverages for antioxidant, antibacterial, antiviral, and prebiotic activity. Taylor et al. (2005) showed that tea catechins provide antimicrobial properties, inhibiting a wide range of gram-positive and gram-negative bacteria species. A large group of phenolic plant bioactives, flavonoids, numbering more than 6,000, is suggested to function as protection against CVD; examples of flavonoids with known bioactivity include quercetin, hesperetin, and naringenin (Erlund 2004). Dietary lipids play a role as bioactives in health and wellness, particularly the omega-3 family of essential fatty acids, α-linolenic acid (ALA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) (Rioux 2011). EPA and DHA are found naturally in oily fish and are associated with promoting human health by preventing atherosclerosis, reducing blood pressure, and improving other health conditions, such as diabetes (Kim & Mendis 2006), sudden cardiac death from coronary heart disease, and metastatic breast cancer (see **Table 1**). In general, lipids play key functional roles as signaling molecules controlling cellular development and preventing diseases (Ma et al. 2004). Bioactive milk components such as conjugated linoleic acid (CLA), sphingomyelin, and butyric acids are bioactive lipids providing anticancer, immune modulation, atherosclerosis prevention, and cholesterol absorption and inhibitory effects (Bocca et al. 2010).

Prebiotics are nondigestible, but fermentable, foods that stimulate the growth and activity of beneficial bacteria already residing in the colon of the host (Quigley 2010). Prebiotics interact mainly with the colon microflora but are known to modulate immune function in other systems, such as the oral cavity, the urogenital tract, the small intestine, and mucosa (Wang 2009). Prebiotics can be fermented selectively to allow for specific changes in the composition or site-specific activity in the gut microflora; for example, inulin, a functional oligosaccharide, is fermented by specific colonic bacteria, such as bifidobacteria and lactobacilli, with the benefits of increasing microbial population. Prebiotics can also produce short-chain fatty acids (Wang 2009). The prebiotic effects of increasing the number of bifidobacteria stimulate the immune system, produces B vitamins, inhibits pathogenic growth, reduces blood cholesterol levels, and helps to restore the normal flora.

Probiotic bacteria are living microorganisms that, when administered in adequate amounts, confer beneficial physiological effects in the host. Examples of probiotics are lactobacilli, bifidobacteria, and nonpathogenic yeasts (Quigley 2010). Probiotic microbiota include *Lactobacillus* spp. (*L. acidophilus*, *L. casei*, *L. johnsonii*, *L. plantarum*), bifidobacterium spp. (*B. bifidum*, *B. animalis*, *B. breve*), and yeasts (*Saccharomyces boulardii*) (Alvarez-Olmos & Oberhelman 2001). Probiotics can help alleviate symptoms of lactose-intolerance, treat viral and antibiotic-associated diarrhea, and lowers the risk of allergy in infancy (Touhy et al. 2003). Probiotics may be effective in conditions of GI-tract microbiota imbalance (Bruzzese et al. 2006).

Synbiotics are products composed of both prebiotics (nondigestible beneficial ingredients) and probiotics (live microorganisms) that synergistically confer health benefits on the host when consumed in sufficient amounts (Sanders & Marco 2010). Synbiotics may work to enhance the survival and activity of known probiotics as well as stimulate indigenous bacteria; for example, a symbiotic mix of inulin and bifidobacteria increased overall numbers of bifidobacteria in healthy volunteers (Bruzzese et al. 2006). Food processing can change the nature of starch materials, making them partially resistant to enzymatic digestion; resistant starches may occur naturally in the form of nonfructan prebiotics, producing high levels of butyrate in the large intestine when consumed (Ouwehand et al. 2005). Butyrates are energy sources for epithelial cells and may be protective against colon cancer (Douglas & Sanders 2008, Rastall et al. 2000).

Botanicals are plant sources of bioactive components, such as teas, herbs, and spices, that are added to food to enhance flavor and taste. Other plant bioactives may help to inhibit spoilage, and some have medicinal uses, making them functional foods. (Kritchevsky & Chen 2005). For example, thyme (*Lamiaceae* spp.) oils possess antimicrobial properties; ginger root (*Zingiber officinale*), cinnamon bark (*Cinnamomum* spp.), and licorice root (*Glycyrrhiza glabra*) are all common ingredients used for treating digestive disorders (Rastall & Maitin 2002).

There is growing demand for foods with specific functions for increasing the health and well-being of the consumer, not only in terms of boosting nutrients, but removing specific counter-beneficial components, such as excess salt (IOM 2010). Also, removing potential detrimental components, such as toxins or allergens, may qualify foods as functional or bioactive (IOM 2010). Among the health issues that consumers would like functional foods to mitigate are heart disease, vision problems, lack of energy, obesity, joint disease, high cholesterol and blood pressure, memory concentration problems, diabetes, osteoporosis, frequent cold and flu, blood sugar imbalance, acid reflux, and intestinal regularity (Getz et al. 2010). Also, a healthy diet may include or exclude components that reduce overall metabolic function. For example, a typical American consumes almost 150% of the recommended daily value for sodium as reported by the Institute of Medicine; hence, there is considerable effort in the new U.S. Department of Agriculture dietary guidelines to reduce salt intake to reduce deleterious effects (van Kleef et al. 2005).

BIOACTIVE FOODS

Awareness of foods that can maintain overall health and wellness, improve heart, bone, and digestive health, and contribute to a healthy body weight is increasing. The top recognizable functional foods are fruits and vegetables, seafood (fish or fish oil), dairy foods (milk, yogurt, and other fermented products), lean meats and poultry, herbs and spices, fiber, tea, nuts, whole grains and cereals (oats), native seeds (quinoa and flax), beans (lentils and peas), purified water, and vitamin and mineral supplements (IFIC 2009). The demand for functional foods is expected to continue increasing among consumers as the knowledge of benefits of functional ingredients and their positive impact on human health and physiological functions increases (Day et al. 2009).

Nutraceutical foods provide medical or health benefits, including the prevention and treatment of diseases (Mandel et al. 2005). Nutraceuticals deliver a more concentrated form of bioactive nutrients in foods for the purpose of enhancing health in dosages in excess of normal amounts in foods (Espin et al. 2007). For example, one nutraceutical, anthocyanin, found abundantly in berries, showed protection in the realms of vision, cognitive functions, obesity, ulcers, CVD, and cancer. Epidemiological studies show a link between dietary habits and food choices and health; however, these studies tend to be narrowly focused on single nutrients (Espin et al. 2007). Nutraceuticals tend to have a positive effect on overall health and may help to prevent certain diseases (Lachance & Das 2007, DeFelice 1995).

Functional foods contain increased levels of polyphenols, phytosterols, and carotenoids. Studies with pharmafoods have shown clear benefits for polyphenols, flavonoids, flavones/flavanones, catechins, and anthocyanins; epidemiological studies have shown a relationship between consumption of these compounds and reduction of CVD risk (Rock et al. 2009). As a group, the major focus of research on pharmafoods has emphasized the antioxidant activity of polyphenols, particularly their ability to prevent oxidation of low-density lipoprotein (LDL) cholesterol (Rock et al. 2009).

PROTECTION OF ACTIVE INGREDIENTS

The most important deleterious substances to bioactive nutrients are oxygen and water. To achieve effective protection from oxygen and water, physical structures are formed from biological complexes; for example, food-grade materials are formed into nanoemulsions (Leclercq et al. 2009). Spray drying is the most commonly used method of encapsulation and preservation for food products. Selection of appropriate coating materials, preparation of emulsions with core and coating materials, and the drying processes influence the shape and type of capsule formed; the efficiency and rate of retention of core compounds are also affected (Graves & Weiss 1992). An understanding of the physical properties of food-grade materials used in encapsulation is needed, along with their interactions with substances like lipids, proteins, carbohydrates, and their mixtures or complexes (Zuidam & Shimoni 2010).

Processed foods, such as baked goods, extruded snacks, and breakfast cereals, are made into multicomponent structures through cooking processes that create matrices assembled from natural components, such as proteins, fats, and carbohydrates (Aguilera 2006). Processed food structures mimic nature by preserving active ingredients through encapsulation within starch or protein matrices. Encapsulation of biologically active components in functional structures serves the primary role of delivering health-sustaining nutrients at boosted levels to enhance bodily functions, maintain health, and alleviate disease conditions (van Kleef et al. 2005).

Nutraceuticals can be delivered through emulsion-based particles entrapped in hydrogels (Chen et al. 2006). A food may be considered nutraceutical if there is demonstrable beneficial effect on one or more target functions relevant to health, well-being, or reduction of disease (ADA 2009). For example, a food can be made nutraceutical by increasing the concentration of active components, and the benefits can be proven by clinical nutrition research data showing more positive health outcomes (Roberfroid 2000).

Encapsulation of probiotics for live delivery of microbial food supplements is more challenging. In general, encapsulated bacteria exhibit low survivability in the harsh conditions of the GI tract and need to be protected to preserve their activity. Several food matrices and encapsulation techniques offer varying degrees of success (Krasaekoopt et al. 2003). For optimum protection of probiotics, milk proteins, hydrocolloids, or liposomes are used; they are effective transport and protection media for functional nutrients (Livney 2010). Dairy products are the natural and obvious carriers of probiotics because yogurt, fermented milks, and cheeses contain probiotics (Doleyres & Lacroix 2005). Research has shown that the interaction of the components and the food matrix may be needed to provide complete physiological benefit of active components to the living organisms (Jacobs & Steffen 2003), e.g., delivering viable live cells in alginate beads (Champagne & Fustier 2007).

COATING AND PROTECTION METHODS

Many types of capsules and reservoir types are attainable (Zuidam & Shimoni 2010). The various means used to create encapsulated particles include spray drying and spray chilling, fluidized bed drying, hot melt, coacervation, coencapsulation, extrusion, rotating disks, hydrogel, and nanoparticles (Krasaekoopt et al. 2004, Drusch & Berg 2008). Microencapsulation techniques include spray drying, spray chilling, extrusion, coacervation, liposomes, cocrystallization, and freeze drying (Gouin 2004). The wall and core material properties, as well as the emulsion characteristics

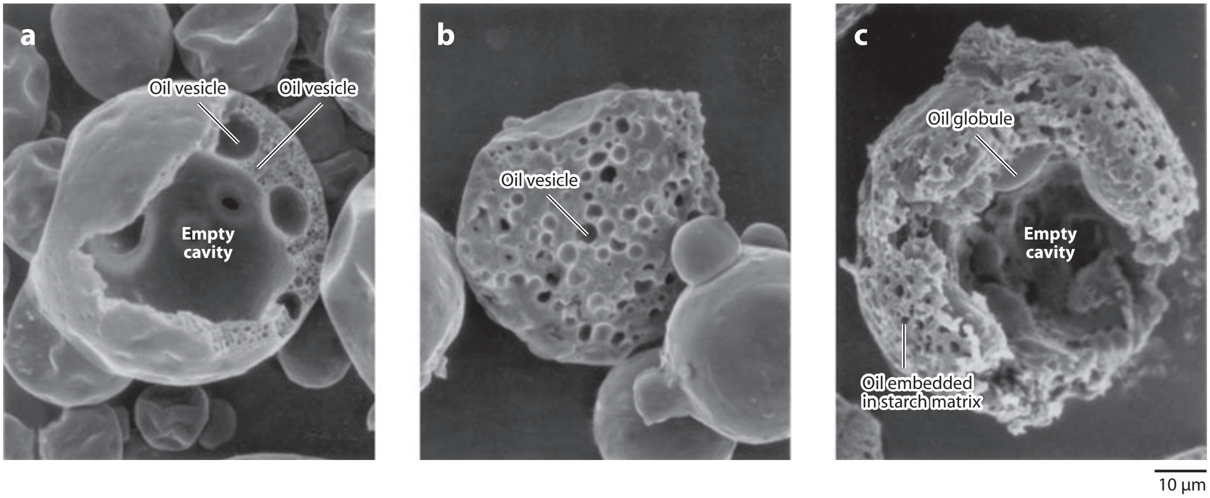


Figure 1

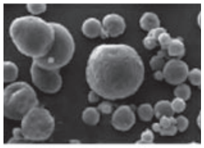
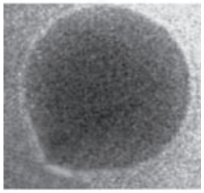
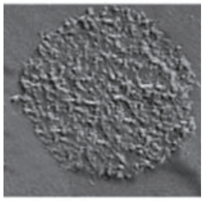
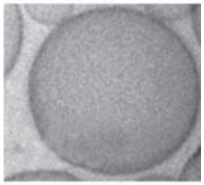
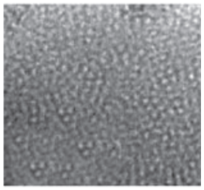
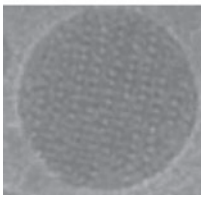
Encapsulation scheme from an emulsion of starch or sugar and butter oil, spray dried emulsion of butter oil and (*a*) starch, (*b*) sugar, and (*c*) wheat flour. Single-coated microcapsules depicting a matrix and voids (*a*) smooth surface particle with butter oil vesicles embedded in the wall matrix. (*b*) Typical sugar encapsulated particle containing multi-microcapsules with butter oil vesicles and without an internal void. (*c*) Rough wheat flour matrix with empty cavity and large butter oil globules. Adapted from Onwulata et al. 1998.

and drying parameters, are the primary factors that determine the effectiveness of encapsulation (de Vos et al. 2010).

Spray drying, in either hot or cold media, is a relatively inexpensive drying process for encapsulating active flavors and aromas in food products. It is also a widely used technique because of its relative simplicity (Ubbink and Kruger 2006). The process involves creating a matrix layer with the encapsulating material and forcing core materials into the matrix through a spinning atomizer, resulting in multicomponent spheres (**Figure 1**). The fine droplets are encapsulated within the core materials in the drying medium, as the hot or cold medium evaporates the dried powder containing the encapsulated within the core material (Graves & Weiss 1992). Spray chilling is applied principally to retard volatilization during thermal processing of sensitive solid food additives, including vitamins, minerals, and flavors. For systems in which a more positive barrier or shell is required, other encapsulation techniques may be used (Fuchs et al. 2006).

Fluidized bed drying is similar to spray drying (Graves & Weiss 1992); a coating of liquid material is sprayed onto a core material in high-pressure aerosol (Takei et al. 2002). The difference between spray drying and fluidized bed coating is that the core material is already in powdered form. A good core material for fluid bed coating is smooth and spherical to minimize the amount of fluid needed to coat it and to reduce the likelihood of uneven coating along the jagged edges, which limits coating efficiency and functionality (Ivanova et al. 2005, Dewettnick & Huyghebaert 1999). An example of powder manufactured from a fluidized bed drying is depicted in **Figure 2**.

Coacervation is a relatively simple technique balancing the electrostatic interaction between the two components of the encapsulation emulsion to create water- and heat-resistant microcapsules (Dong et al. 2011). Coacervation is an aqueous-phase separation process. A typical complex coacervation process begins with the suspension, or emulsification, of core material in either gelatin or gum arabic solution. When a solution of the core material is mixed with an oppositely charged encapsulating material, a complex is formed, resulting in phase segregation and associative complexation; the size and other characteristics of the capsules formed can be altered by changing pH,

Delivery system	Characteristics and limitations	Structure
Powder particles • Glass encapsulation • Core-shell capsules • Matrix capsules	**Size: 10 μm–1 mm** • Good encapsulation for solid food products **Drawback:** • Hardly adapted for delivery in liquids	 10 μm
Oil/water emulsions • Ordinary emulsions • Multilayered emulsions • Double emulsions • Nanoemulsions • Solid lipid nanoparticles (SLNs)	**Size: 100 nm–10 μm** • Hosts lipophilic molecules • Better chemical protection of sensitive oil achieved when multilayered emulsions or SLNs used • Controlled release with SLNs **Drawbacks:** • Physical stability sometimes an issue • Polymorphism stability and encapsulation for SLNs difficult to control	 100 nm
Molecular complexes • Cyclodextrins • Amylose • Proteins • Protein aggregates	**Size: 10 nm–600 nm** • Solubilization of small lipophilic molecules • Protection of sensitive molecules • Removal of cholesterol **Drawback:** • Loading capacity may be limited	 100 nm
Liposomes, vesicles	**Size: 20 nm–100 μm** • Solubilization of hydrophilic and lipophilic molecules • Sustained release of nutrients **Drawbacks:** • High costs (ingredients and processing) • Poor loading efficiency and capacity	 100 nm
Oil/water microemulsions	**Size: 5 nm–100 nm** • Solubilization of lipophilic molecules • Solubilization of crystalizing molecules • Increase in bioavailability • Transparent appearance (water) **Drawbacks:** • Large amount of surfactant needed • Often off-taste • Used surfactants often not well accepted	 100 nm
Dispersed reverse surfactant systems • Cubosomes, hexosomes • Dispersed reverse microemulsions • Micellosomes	**Size: 100 nm–1 μm** • Solubilize amphiphilic and lipophilic molecules • Controlled release • Solubilization of crystalizing molecules **Drawback:** • Large amount of surfactants may be needed	 100 nm

temperature, the bioactive component properties, or the type of encapsulating agent (Singh et al. 2007, Schmitt et al. 2001). Coacervation works by aqueous-phase separation of immiscible solutions, such as oil and water or protein and ionic polysaccharides (de Kruif et al. 2004). Examples of microcapsule deliver systems are depicted in **Figure 2**.

Co-matrix encapsulation or inclusion complexation is one form of encapsulation in which cyclic polymers, such as β-cyclodextrins, are used to encapsulate or entrap other molecules. β-cyclodextrins are approved for food use (Astray et al. 2009). For example, α-, β-, γ-cyclodextrins have been shown to encapsulate and stabilize lycopene (Blanch et al. 2007). The cyclodextrin molecules have doughnut-shaped hollow centers that entrap or form complexes with other molecules, such as flavors, colors, and vitamins; the molecules form inclusion complexes in the presence of water with compounds that fit dimensionally within its cavity (Zeller et al. 1999).

Hot melt processes are special encapsulation methods used to apply coating to solid matrices to form multicoated particles (Henrist et al. 2001). Melt extrusion is used for particle-to-particle comatrix inclusion at high temperature and high shear forces (Breitenbach 2002). For example, extrusion-based encapsulation was used to produce stable, bioavailable iron premixes and iodized salt encapsulated in ferrous fumarate. The extrusion process is a physical entrapment method using mostly sugars and starch. The process involves the preparation of a low-moisture (5% to 10%) melt (100°C to 130°C), and then the agglomerated starch structures entrap the flavor to be encapsulated within its cavities (Yuliani et al. 2006).

Spray drying has limited potential in nutraceutical delivery because of moisture and oxygen limitations (Parada & Aguilera 2007). The technology needed to create stabilized, physically linked, or chemically bonded protective capsules for wider use in the functional food delivery is cost prohibitive for the large scale volumes needed for food production (McClements et al. 2009). Therefore, new encapsulation techniques will be needed to address the delivery of bioactive nutrients in large volumes.

DELIVERY OF ACTIVE NUTRIENTS

Encapsulation is the art of coating sensitive materials (core) with other more inert or less functionally active materials; for example, coating oxygen sensitive polyunsaturated fats with starch to provide an oxygen barrier (Graves & Weiss 1992).

Encapsulation is the most effective and least expensive packaging for active ingredients intended for targeted delivery and controlled release of nutrients (Weinbreck et al. 2004, Ubbink & Schoonman 2003). The challenge of delivering sensitive active ingredients is relatively new to the food industry (Shah 2000, Siegrist et al. 2008). Therefore, developing products with active ingredients is more challenging because of the necessity to simultaneously keep food products safe, maintain natural appearance, and maintain viability in storage conditions, and in most cases, subsequent reprocessing or cooking before consumption (Burgain et al. 2011, Shah & Ravula 2000). The delivery of bioactive nutrients through the GI tract depends on the carriers, type of preparation, and methods of protection (Kailasapathy 2006, Lesmes & McClements 2009). With probiotics, high oxygen concentrations generate increases in toxicity in the capsules, decreasing bacterial survival (Shah & Ravula 2000, Kailasapathy 2002).

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Figure 2

Schematic description of the microencapsulation of food ingredients along with some examples of core and wall materials, wall material properties, aims, and different techniques of the microencapsulation process. Adapted with permission from Sagolowicz & Leser 2010 (Copyright Clearance Center confirmation number: 10396869).

Lesmes & McClements (2009) described some common approaches for fabricating particulate delivery systems depending on the nature of the starting ingredients and the desired functional performance required in the gut system. Such systems include milling and grinding to break down large particles into smaller units, creating emulsions for mixing the bioactive ingredients and coating materials, and drying, using methods such as spray drying, spray coating, extrusion, mixing, and homogenization (Ubbink & Kruger 2006). Other methods assemble molecules or colloidal particles into specific structures, through molecular inclusion of complexes; these complexes may be formed using carbohydrates and proteins, microemulsion surfactants, hydrogels from polysaccharides and proteins, and lipid crystals (Lesmes et al. 2008).

Delivery of lipid-based health-benefiting components, such as omega-3 polyunsaturated fatty acids (PUFAs), while preserving taste is an important challenge because of taste issues (Gillet et al. 2011). Encapsulation is needed for the prevention of off-taste or strong flavor above certain concentrations of functional active ingredient; for example, green tea extract has a naturally bitter taste, but in higher concentrations the bitterness is more intense. Therefore, green tea is sometimes encapsulated to mask the off-flavor that may develop with oxygen reacting with fatty acids. Encapsulation can be used to mask off or bitter flavors (Sagalowicz & Leser 2010).

Emulsion-based delivery systems consisting of mixed materials, such as starch, gums, or proteins, may be linked together using shear forces and emulsifiers to create hydrogels that enhance incorporation of bioactive nutrients into liquid foods and beverages (Palzer 2009). Hydrogels have several advantages over conventional emulsions, including protection against oxidation and targeted release inside the human body (McClements & Li 2010). Protein hydrogels can act as carriers for controlled release of bioactive molecules in flavor compounds, and for minerals delivery; for example, microstructure gels were used to determine release profiles for iron (Kandile & Nasr 2011). When whey proteins are used to create hydrogels, the main whey protein component β-lactoglobulin acts as the gelling agent (Gunasekaran et al. 2007). Protein-based hydrogels are particularly suitable for incorporating lipophilic constituents into aqueous foods and beverages and for controlling digestion and release of lipids (McClements & Li 2010).

Newly developed colloidal nanoemulsion particles are positioned for use as delivery systems for micronutrients in nutraceuticals containing bioactive ingredients. These new active foods deliver micronutrients specifically for improved health (Lesmes & McClements 2009). Bioactive foods may include omega-3 PUFA, probiotics, whole grain– and fiber-enriched foods, phytosterols, functionalized water, calorie-burning foods, superfruits, beauty foods, and energy drinks (IFIC 2009).

NANOPARTICLES TECHNOLOGIES

Newer technologies, such as nanoemulsions and nanoparticles, may aid in the delivery of functional bioactives. Nanoemulsions and submicron emulsions are liquid-in-liquid dispersions with small droplets; typically in the range of 20–200 nm (Solans et al. 2005). Nanoemulsions result from high kinetic energy conditions induced by shearing, which results in emulsified small droplets stable against sedimentation or creaming (Gonnet et al. 2010). Stability of nanoemulsions may be enhanced by adding emulsifiers using high-shear homogenization; high-shear homogenization makes it possible for manufacturers to lower levels of surfactants in products. Nanoemulsions are used in cosmetics and personal-care formulations and in some agrochemical industries (Qian & McClements 2010, Guitierrez et al. 2003).

Nanoparticle matrix systems are dense colloidal polymeric nanoemulsions typically less than one micron in size, characterized by high stability and even dispersion of particles (Anton et al. 2008). Nanoparticles, because of their small size, are better suited for targeted delivery of nutrients in small quantities to specific sites (Wang et al. 2011). Modern nanoparticles are usually less than five microns in size and can increase core loading within a matrix up to 97%. Nanoparticle emulsions and hydrogels can be made from egg white, soybean, and whey proteins. For example, mucosal delivery systems were created from peptides derived from proteins and plasmids (Janes et al. 2001).

Nanoparticle-sized colloidal dispersions are used in a broad range of products, including foods, cosmetics, paints, and drugs. Nano-sized emulsions are kinetically stabilized monolayers of uniformly poly-dispersed spherical particles with large surface areas (Dickson 2010). Some nano-disperse nanoparticle systems have been explored for oral drug delivery with different degrees of success. Future application of nanoparticle technology in the areas of micronutrient and nutraceutical delivery will depend largely on the type of active molecule/ions and whether the product format is sprays or gels. Chen et al. (2010) showed that colloidal particles and nanoemulsions could be used as delivery systems for micronutrients and nutraceuticals.

PRESERVATION OF ACTIVE INGREDIENTS IN THE DIGESTIVE SYSTEM

Bioaccessibility and bioavailability are descriptive tools to measure the efficiency of retrieving and absorbing nutrients (Scheepens et al. 2010). Bioaccessibility defines the amount of an ingested nutrient available for absorption in the gut after digestion (Palafox-Carlos et al. 2011, Hedren et al. 2002). Bioaccessibility also measures the effectiveness of removing nutrients from matrices. Bioavailability measures the blood plasma levels of particular nutrients and accounts for individual variability and physiological states (Faulks and Southon 2005). In most cases, bioaccessibility and bioavailability depend on the physical food matrix, which affects the digestion processes that may limit availability of functional nutrients and active components delivered at specific digestion sites (Velikov & Pelan 2008, Gregory et al. 2005).

Encapsulated foods containing active nutrients draw heavily on the extensive knowledge developed by the pharmaceutical and medical industries for drug delivery systems (McClements et al. 2009). Structural matrices provide protection and controlled release of bioactive core material (Corcoran et al. 2004). Active ingredients introduced in a variety of structures include flavors (Inglett et al. 1988), vitamins and minerals (Ubbink and Mezzenga 2006, Lukaski 2004), and probiotic microorganisms (Iyer & Kailasapathy 2005, Zuidam & Shimoni 2010). Active food ingredients require special handling because of their sensitivity to a variety of physical and chemical factors that may cause loss in biological functionality, chemical degradation, or improper release (Ubbink & Kruger 2006). Advances in the design and fabrication of structured delivery systems or the encapsulation of functional food components may result in a wide variety of delivery systems (Barrow et al. 2009).

To survive the hurdles of food handling, oral processing, transport through the acidic digestive tract, and assimilation, nutrients must be protected for safe delivery (de Vos et al. 2010). The hurdles presented by oral processing may limit nutrient availability and negate the benefits of microencapsulation and the function of active nutrients and nutraceuticals. Digestive conditions, such as insufficient gastric time, low permeability, or insolubility within the gut, and unstable conditions such as changing pH, presence of enzymes, and other nutrients, may affect digestibility and availability of nutrients. The precise delivery and release of bioactive food components must use the principle of targeted release controlled by enzymatic activity of the microbiota at specific sites (Chen et al. 2010).

The use of chitosan to increase colon mucosa is an example of successful delivery of microencapsulated microspheres through the digestive tract. This delivery of bioactives was illustrated by the work of Lorenzo-Lamosa et al. (1998), where the chitosan core showed special release features at the specific pH of 8.4; the release rates were controlled by changing the core/coat proportions for timed release. A wide variety of different types of delivery systems are available for functional bioactives, but each type has its specific advantages and disadvantages. Some of the variables include encapsulation and protection efficiency, differences in compatibility with functional agents, cost, regulatory status, ease of use, biodegradability, and biocompatibility (McClements et al. 2009).

REGULATION OF ACTIVE INGREDIENTS

The regulation of claims associated with different foods and active ingredients is managed by several government jurisdictions. For example, in the United States the FDA determines appropriate claims guided by several food laws, such as the 1994 Dietary Supplement Health and Education Act. Similar laws guide other countries and subcontinents; for example, the European Food Safety Authority (EFSA) evaluates proposed health claims for foods or active ingredients (Ruckman 2008). Recently, the EFSA has allowed health claims relating to the consumption of walnuts for improved blood vessels, antioxidant properties of olive oil for reducing LDL cholesterol, and caffeine for increased alertness and physical endurance.

CONCLUSIONS

Food in all its forms provides benefits to consumers. Identifying and quantifying the optimal positive activity levels and linking them to particular health benefits is the focus of research on active foods. New active components developed are tagged to benefits; for example, bioactives such as peptides, plant extracts such as flavonoids, and marine extracts such as chitosan are providing antiinflammation, antioxidant, antimutagenic, and anticancer benefits. Simple structured delivery systems for the active ingredients can be fabricated using relatively uncomplicated processing operations, such as emulsions, colloids, suspensions, gels, and solid matrices. Site-activated delivery of functional foods will be possible with techniques, such as microencapsulation, microemulsions, colloidal particulation, and nano-structuring. Natural triggers may be used to release bioactive components at health-optimizing doses. Delivering functional bioactive nutrients will enhance the health benefits provided through foods; however, the challenge will be delivering the functions at appropriate sites in cost-effective forms.

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The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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LITERATURE CITED

ADA. 2009. Position of the American Dietetic Association (ADA): functional foods. *J. Am. Diet. Assoc.* 109:735–46

Aguilera JM. 2006. Food product engineering: building the right structures. *J. Sci. Food Agric.* 86:1147–55

Akhtar S, Anjum FM, Anjum MA. 2011. Micronutrient fortification of wheat flour: recent development and strategies. *Food Res. Int.* 44:652–59

Alvarez-Olmos MI, Oberhelman RA. 2001. Probiotic agents and infectious diseases: a modern perspective on a traditional therapy. *Clin. Infect. Dis.* 32:1567–75

Anal AK, Singh H. 2007. Recent advances in microencapsulation of probiotics for industrial applications and targeted delivery. *Trends Food Sci. Technol.* 18(5):240–51

Anton N, Benoit JP, Saulnier P. 2008. Design and production of nanoparticles formulated from nano-emulsion templates: a review. *J. Control Release* 128:185–99

Arts ICW, Hollman PCH. 2005. Polyphenols and disease risk in epidemiologic studies. *Am. J. Clin. Nutr.* 81(Suppl.):317–25

Astray G, Gonzalez-Barreiro C, Mejuto JC, Rial-Otero R, Simal-Gandara J. 2009. A review on the use of cyclodextrins in foods. *Food Hydrocoll.* 23:1631–40

Barrow CJ, Nolan C, Holub B. 2009. Bioequivalence of encapsulated and microencapsulated fish-oil supplementation. *J. Funct. Food.* 1:38–43

Bhat ZF, Bhat H. 2011. Milk and dairy products as functional foods: a review. *Int. J. Dairy Sci.* 6(1):1–12

Bielecka M, Biedrzycka E, Majkowska A. 2002. Selection of probiotics and prebiotics for synbiotics and confirmation of their in vivo effectiveness. *Food Res. Int.* 35:125–31

Blanch GP, Ruiz del Castillo ML, del Mar Caja M, Perez-Mendez M, Sanchez-Cortes S. 2007. Stabilization of all-*trans*-lycopene from tomato by encapsulation using cyclodextrins. *Food Chem.* 105:1335–41

Blevins SM, Lejva MJ, Brown J, Wright J, Scofield RH, Aston CE. 2007. Effect of cinnamon on glucose and lipid levels in non-insulin-dependent type 2 diabetes. *Diabetes Care* 30(9):2236–37

Bocca C, Bozzo F, Cannito S, Colombatto S, Miglietta A. 2010. CLA reduces breast cancer cell growth and invasion through ERα and PI3K/AKt pathways. *Chem. Biol. Interact.* 183:187–93

Bowen J, Noakes M, Clifton PM. 2006. Appetite regulatory hormone responses to various dietary proteins differ by body mass index status despite similar reductions in ad libitum energy intake. *J. Clin. Endocrinol. Metab.* 91:2919–19

Breitenbach J. 2002. Melt extrusion: from process to drug delivery technology. *Eur. J. Pharm. Biopharm.* 54:107–17

Bruzzese E, Volpicelli M, Squaglia M, Tartaglione A, Guarino A. 2006. Impact of prebiotics on human health. *Dig. Liver Dis.* 38(Suppl. 2):S283–87

Burgain J, Gaiani C, Linder M, Scher J. 2011. Encapsulation of probiotic living cells: from laboratory scale to industrial applications. *J. Food Eng.* 104:467–83

Champagne C, Fustier P. 2007. Microencapsulation for the improved delivery of bioactive compounds into foods. *Curr. Opin. Biotechnol.* 18:184–90

Chan ES, Zhang Z. 2002. Encapsulation of probiotic bacteria *Lactobacillus acidophilus* by direct compression. *Trans. IChemE.* 80(Part C):78–82

Chaud MV, Izumi C, Nahaal Z, Shuhama T, de Lourdes M, et al. 2002. Iron derivatives from casein hydrolysates as a potential source in the treatment of iron deficiency. *J. Agric. Food Chem.* 50:871–77

Chen H, Ouyang W, Martoni C, Afkhami F, Lawuyi B, et al. 2010. Investigation of genipin cross-linked microcapsule for oral delivery of live bacterial cells and other biotherapeutics: preparation and in vitro analysis in simulated human gastrointestinal model. *Int. J. Polymer Sci.* 2010: 985137

Chen C, Remondetto GE, Subirade M. 2006. Food protein-based materials as nutraceutical delivery systems. *Trends Food Sci. Technol.* 17:272–83

Corcoran BM, Ross RP, Fitzgerald GF, Stanton C. 2004. Comparative survival of probiotic lactobacilli spray-dried in the presence of prebiotic substances. *J. App. Microbiol.* 96:1024–39

Day L, Seymour RB, Pitts KF, Konczak I, Lundin L. 2009. Incorporation of functional ingredients into foods. *Trends Food Sci. Technol.* 20:388–95

de Kruif CG, Weinbreck F, de Vries R. 2004. Complex coacervation of proteins and anionic polysaccharides. *Curr. Opin. Colloid Interface Sci.* 9:340–49

de Vos P, Faas MM, Spasojevic M, Sikkema J. 2010. Encapsulation for preservation of functionality and targeted delivery of bioactive food components. *Int. Dairy J.* 20:292–302

DeFelice SL. 1995. The nutraceutical revolution: its impact on food industry R&D. *Trends Food Sci. Technol.* 61:59–61 de Lorgeril M, Salen P, Martin JL, Monjaud I, Delaye J, Mamelle N. 1999. Mediterranean diet, traditional risk factors, and the rate of cardiovascular complications after myocardial infarction: final report of the Lyon Diet Heart Study. *Circulation* 99:779–85

Dewettnick K, Huyghebaert A. 1999. Fliudized bed coating in food technology. *Trends Food Sci. Technol.* 10:163–68

Dickson E. 2010. Food emulsions and foams: stabilization by particles. *Curr. Opin. Colloid Interface Sci.* 15:40–49

Doleyres Y, Lacroix C. 2005. Technologies with free and immobilized cells for probiotic bifidobacteria production and protection. *Int. Dairy J.* 15:973–88

Dong Z, Ma Y, Hayat K, Jia C, Xia S, Zhang X. 2011. Morphology and release profile of microcapsules encapsulating peppermint oil by complex coacervation. *J. Food Eng.* 104:455–60

Douglas LC, Sanders ME. 2008. Probiotics and prebiotics in dietetics practice. *J. Am. Diet. Assoc.* 108:510–21

Drusch S, Berg S. 2008. Extractable oil in microcapsules prepared by spray-drying: localization, determination and impact on oxidative stability. *Food Chem.* 109:17–24

Dziub M, Darewicz M. 2007. Food proteins as precursors of bioactive peptides: classification into families. *Food Sci. Tech. Int.* 13(6):393–404

Espin JC, Garcia-Conesa MT, Tomas-Barberan FA. 2007. Nutraceuticals: facts and fiction. *Phytochemistry* 68:2986–3008

Estruch R, Martinez-Gonzalez AM, Corella D, Salas-Salvado J, Ruiz-Gutierrez V, et al. 2006. Effects of a Mediterranean-style diet on cardiovascular risk factors: a randomized trial. *Ann. Intern. Med.* 145:1–11

Erlund I. 2004. Review of flavonoids, quercetin, hesperetin, and naringenin. Dietary sources, bioactivities, bioavailability, and epidemiology. *Nutr. Res.* 24:851–74

Faulks RM, Southon S. 2005. Challenges to understanding and measuring carotenoid bioavailability. *Biochim. Biophys. Acta* 1740:95–100

Fuchs M, Turchiuli C, Bohin M, Cuvelier ME, Ordonnaud C, et al. 2006. Encapsulation of oil in powder using spray drying and fluidized bed agglomeration. *J. Food Eng.* 75:27–35

Galland L. 2005. Functional foods: health effects and clinical applications. In *Encyclopedia of Human Nutrition*, 2nd ed., ed. B Caballero, pp. 360–66. London: Elsevier

Getz J, Adhikari K, Medeiros DM. 2010. Nutrigenomics and public health. *Food Technol.* 64(1):1–7

Gibson GR, Williams CM, eds. 2000. *Functional Foods*. Cambridge UK: Woodhead

Gillet L, Roger S, Bougnoux P, Le Guennec J, Besson P. 2011. Beneficial effects of omega-3 long-chain fatty acids in breast cancer and cardiovascular diseases: voltage-gated sodium channels as a common feature? *Biochimie* 93:4–6

Gonnet M, Lethuaut L, Boury F. 2010. New trends in encapsulation of liposoluble vitamins. *J. Control Release* 146:276–90

Gouin S. 2004. Micro-encapsulation: industrial appraisal of existing technologies and trends. *Trends Food Sci. Technol.* 15:330–47

Graves B, Weiss H. 1992. Encapsulation techniques. In *Encyclopedia of Food Science and Technology*, ed. YH Hui, pp. 620–27. New York: John Wiley & Sons, Inc.

Gregory JF, Quinlivan EP, Davis SR. 2005. Integrated the issues of folate bioavailability, intake and metabolism in the era of fortification. *Trends Food Sci. Technol.* 16:229–40

Gruenwald J. 2009. Fortification of beverages with products other than vitamins and minerals. In *Functional and Speciality Beverage Technology*, ed. P Paquin, pp. 71–91. Cambridge UK: Woodhead. **http://knovel.com/web/portal/browse/display?_EXT_KNOVEL_DISPLAY_bookid=2372&VerticalID=0**

Griffiths T. 2010. Promoting cereal grain and whole grain consumption: an Austrian perspective. *Cereal Chem.* 87(2):159–61

Guitierrez JM, Gonzalez C, Maestro A, Sole I, Pey CM, Nolla J. 2003. Nano-emulsions: new applications and optimization of their preparation. *Curr. Opin. Colloid Interface Sci.* 13:245–51

Gunasekaran S, Ko S, Xia L. 2007. Use of whey protein for encapsulation and controlled delivery application. *J. Food Eng.* 83:31–40

Hall RD. 2007. Food metabolomics: meta-phor: a new European research initiative. *AgroFOOD Industry* 18(1):14–16

Hartmann R, Meisel H. 2007. Food-derived peptides with biological activity: from research to food applications. *Curr. Opin. Biochem.* 18:163–69
Hasler CM. 2008. Health claims in the United States: an aid to the public or a source of confusion? *J. Nutr.* 138:1216–20
Hasler CM. 2002. Functional foods: benefits, concerns and challenges—a position paper from the American Council on Science and Health. *J. Nutr.* 132:3772–81
He K, Song Y, Daviglus ML, Liu K, Van Horn L, et al. 2004a. Accumulated evidence on fish consumption and coronary heart disease mortality: a meta-analysis of cohort studies. *Circulation* 109:2705–11
He K, Song Y, Daviglus ML, Liu K, Van Horn L, et al. 2004b. Fish consumption and incidence of stroke: a meta-analysis of cohort studies. *Stroke* 35:1538–42
Hedren E, Mulokozi G, Svanberg U. 2002. In vitro accessibility of carotenes from green leafy vegetables cooked with sunflower oil or red palm oil. *Int. J. Food Sci. Nutr.* 53:445–53
Hennekens CH, Buring JE, Manson, JE, et al. 1996. Lack of effect of long-term supplementation with beta carotene on the incidence of malignant neoplasms and cardiovascular disease. *N. Engl. J. Med.* 334:1145–49
Henrist D, Van Bortel L, Lefebvre RA, Remon JP. 2001. In vitro and in vivo evaluation of starch-based hot stage extruded double matrix systems. *J. Control Release* 75:391–400
Hu FB, Rimm EB, Stampfer MJ, Ascherio A, Spiegelman D, Willett WC. 2000. Prospective study of major dietary patterns and risk of coronary heart disease in men. *Am. J. Clin. Nutr.* 72:912–21
IFIC. 2009. Functional Foods/Foods for Health Consumer Trending Survey Executive Report. *Int. Food Inf. Counc. Rep.*, Washington, DC
IOM. 2010. *Strategies to Reduce Sodium Intake in the United States.* Washington, DC: IOM **http://www.iom.edu/Reports/2010/Strategies-to-Reduce-Sodium-Intake-in-the-United-States.aspx**
Inglett GE, Gelbman P, Reineccius GA. 1988. Encapsulation of orange oil. Use of oligosaccharides from α-amylase modified starches of maize, rice, cassava, and potato. In *Flavor Encapsulation*, ed. SJ Risch, GA Reineccius, pp. 1–5. Washington, DC: Am. Chem. Soc. Symp. Ser.
Ivanova E, Teunou E, Poncelet D. 2005. Encapsulation of water sensitive products: effectiveness and assessment of fluid bed fry coating. *J. Food Eng.* 71:223–30
Iyer C, Kailasapathy K. 2005. Effect of co-encapsulation of probiotics with prebiotics on increasing the viability of encapsulated bacteria under in vitro acidic and bile salt conditions and in yoghurt. *J. Food Sci.* 70(1):M18–23
Jacobs DR, Tapsell LC. 2007. Food, not nutrients, is the fundamental unit in nutrition. *Nutr. Rev.* 65(10):439–50
Jacobs DR, Steffen LM. 2003. Nutrients, foods, and dietary patterns as exposures in research: a framework for food synergy. *Am. J. Clin. Nutr.* 78(Suppl.):508–13
Janes KA, Calvo P, Alonso MJ. 2001. Polysaccharide colloidal particles as delivery systems for macromolecules. *Adv. Drug Deliv. Rev.* 47:83–97
Kailasapathy K. 2002. Microencapsulation of probiotic bacteria: technology and potential applications. *Curr. Issues Intest. Microbiol.* 3:39–48
Kailasapathy K. 2006. Survival of free and encapsulated probiotic bacteria and their effect on the sensory properties of yoghurt. *LWT* 39:1221–27
Kalt W. 2001. Health functional phytochemicals of fruit. *Hort. Rev.* 27:245–47
Kandile NG, Nasr A. 2011. Hydrogels based on a three component system with potential for leaching metals. *Carb. Polym.* 85:120–28
Kaput J, Noble J, Haipoglu B, Kohrs K, Dawson K, Bartholomew A. 2007. Application of nutrigenomics concepts to Type 2 diabetes mellitus. *Nutr. Metabol. Cardiovasc. Dis.* 17(2):89–103
Kim SK, Mendis E. 2006. Bioactive compounds from marine processing byproducts: a review. *Food Res. Int.* 39:383–93
Krasaekoopt W, Bhandari B, Deeth HC. 2003. Evaluation of encapsulation techniques of probiotics for yoghurt. *Int. Dairy J.* 13:3–13
Krasaekoopt W, Bhandari B, Deeth HC. 2004. The influence of coating materials on some properties of alginate beads and survivability of microencapsulated probiotic bacteria. *Int. Dairy J.* 14:737–43

Kritchevsky D, Chen SC. 2005. Phytosterols—health benefits and potential concerns: a review. *Nutr. Res.* 25:413–28

Lachance PA, Das YT. 2007. Nutraceuticals. *Comp. Med. Chem. II* 1:449–61

Leclercq S, Harlander KR, Reineccius GA. 2009. Formation and characterization of microcapsules by complex coacervation with liquid or solid aroma cores. *Flavour Fragr. J.* 24:17–24

Lesmes U, Barchechath J, Shimoni E. 2008. Continuous dual feed homogenization for the production of starch inclusion complexes for controlled release of nutrients. *Innov. Food Sci. Emerg. Technol.* 9:507–15

Lesmes U, McClements DJ. 2009. Structure function relationships to guide rational design and fabrication of particulate food delivery systems. *Trends Food Sci. Technol.* 20:448–57

Lindsay DG. 2000. Maximising the functional benefits of plant foods. See Gibson & Williams 2000, pp. 183–208

Lindshield BL, Erdman JW. 2010. Carotenoids. In *Nutrition and Health: Bioactive Compounds and Cancer*, ed. JA Milner, DF Romagnolo. New York: Springer Science+Business Media LLC

Livney YD. 2010. Milk proteins as vehicles for bioactives. *Curr. Opin. Colloid Interface Sci.* 15:73–83

Lockheart MSK, Steffen LM, Rebnord HM, Fimreite RL, Ringstad J, et al. 2007. Dietary patterns, food groups and myocardial infarction: a case-control study. *Br. J. Nutr.* 98:380–87

Lorenzo-Lamosa ML, Remunan-Lopez C, Vila-Jato JL, Alonso MJ. 1998. Design of microencapsulated chitosan microspheres for colonic drug delivery. *J. Control Release* 52:109–18

Lukaski HC. 2004. Vitamin and mineral status: effects on physical performance. *Nutrition* 20:632–44

Ma DWL, Seo J, Switzer KC, Fan YY, McMurray DN, et al. 2004. n-3 PUFA and membrane microdomains: a new frontier in bioactive lipid research. *J. Nutr. Biochim.* 15:700–6

Manarch C, Scalbert A, Morand C, Remesy C, Jimenez L. 2004. Polyphenols: food sources and bioavailability. *Am. J. Clin. Nutr.* 79:727–47

Mandel S, Packer L, Youdim MBH, Weinreb O. 2005. Proceedings from the third international conference on mechanism of action of nutraceuticals. *J. Nutr. Biochem.* 16:513–20

McClements DJ, Decker EA, Park Y, Weiss J. 2009. Structural design principles for delivery of bioactive components in nutraceuticals and functional foods. *Crit. Rev. Food Sci. Nutr.* 49(6):577–606

McClements DJ, Li Y. 2010. Structured emulsion-based delivery systems: controlling the digestion and release of lipophilic food components. *Adv. Colloid Interface Sci.* 159:213–28

Murtaugh MA, Jacobs DR Jr, Jacob B, Steffen LM, Marquart L. 2003. Epidemiological support for the protection of whole grains against diabetes. *Proc. Nutr. Soc.* 62:143–49

Onwulata CI, Smith PW, Craig JC Jr, Holsinger VH. 1998. Physical properties of encapsulated spray dried milkfat. *J. Food Sci.* 59:316–20

Ouwehand AC, Derrien M, de Vos W, Tiihonen K, Rautonen N. 2005. Prebiotics and other microbial substrates for gut functionality. *Curr. Opin. Biotechnol.* 16:212–17

Palafox-Carlos H, Ayala-Zavala JF, Gonzalez-Aguilar GA. 2011. The role of dietary fiber in the bioaccessibility and bioavailability of fruit and vegetable antioxidants. *J. Food Sci.* 76(1):R6–R15

Palzer S. 2009. Food structures for nutrition, health and wellness. *Trends Food Sci. Technol.* 20:194–200

Parada J, Aguilera JM. 2007. Food microstructure affects the bioavailability of several nutrients. *J. Food Sci.* 72(2):R21–R32

Peterson J, Dwyer J. 1998. Flavonoids: dietary occurrence and biochemical activity. *Nutr. Res.* 18(12):1995–2018

Qian C, McClements DJ. 2010. Formation of nanoemulsions stabilized by model food-grade emulsifiers using high-pressure homogenization: factors affecting particle size. *Food Hydrocoll.* 25:1000–8

Quigley EMM. 2010. Prebiotics and probiotics: modifying and mining the microbiota. *Pharma Res.* 61:213–18

Rastall RA, Maitin V. 2002. Prebiotics and synbiotics: towards the next generation. *Curr. Opin. Biotechnol.* 13:490–96

Rastall RA, Fuller R, Gaskins HR, Gibson GR. 2000. Colonic functional foods. See Gibson & Williams 2000, pp. 71–95

Rao AV, Rao LG. 2007. Carotenoids and human health. *Pharm. Res.* 55:207–16

Richardson DP. 2009. Health claims on foods: strength of the evidence and problems of proof. *Funct. Foods* 6(1):1–3

Roberfroid MB. 2000. Defining functional food. See Gibson & Williams 2000, pp. 9–27

Rioux V. 2011. Bioactive lipids, nutrition and health. *Biochimie* 93:v–vi

Rock CL, Natarajan L, Pu M, Thomson CA, Flatt SW, et al. 2009. Longitudinal biological exposure to carotenoids is associated with breast cancer–free survival in the women's healthy eating and living study. *Cancer Epidemiol. Biomark. Prev.* 18(2):486–94

Rock CL. 1997. Carotenoids: biology and treatment. *Pharm. Ther.* 75(3):185–97

Ros E, Mataix J. 2006. Fatty acid composition of nuts: implications for cardiovascular health. *Br. J. Nutr.* 96(Suppl. 2):S29–S35

Ruckman SA. 2008. Regulations for nutraceuticals and functional foods in Europe and the United Kingdom. In *Nutraceutical and Functional Food Regulations in the United States and Around the World*, ed. D Bagchi, pp. 221–38. Amsterdam: Elsevier/Academic

Sagalowicz L, Leser ME. 2010. Delivery systems for liquid food products. *Curr. Opin. Colloid Interface Sci.* 15:61–72

Sanders ME, Marco ML. 2010. Food formats for effective delivery of probiotics. *Annu. Rev. Food Sci. Technol.* 1:65–85

Saura-Calixto F. 2011. Dietary fiber as a carrier of anti-oxidants: an essential physiological function. *J. Agric. Food Chem.* 59:43–49

Scheepens A, Tan K, Paxton JW. 2010. Improving the oral bioavailability of beneficial polyphenols through designed synergies. *Genes Nutr.* 5:75–87

Schulze MB, Hoffmann K. 2006. Methodological approaches to study dietary patterns in relation to risk of coronary heart disease and stroke. *Br. J. Nutr.* 95:860–69

Schmitt C, Sanchez C, Lamprecht A, Renard D, Lehr C-M, et al. 2001. Study of α-lactoglobulin/acacia gum complex coacervation by diffusing-wave spectroscopy and confocal scanning laser microscopy. *Colloid Surf. B: Biointerfaces* 20:267–80

Shrubsole MJ, Lu W, Chen Z, Shu XO, Zheng Y, et al. Drinking green tea modestly reduces breast cancer risk. *J. Nutr.* 139:310–16

Siegrist M, Stampfil N, Kastenholz H, Keller C. 2008. Perceived risks and perceived benefits of different nanotechnology foods and nanotechnology food packaging. *Appetite* 51(2):283–90

Singh SS, Siddhanta AK, Meena R, Prasad K, Bandyopadhyay S, Bohindar HB. 2007. Intermolecular complexation and phase separation in aqueous solutions of oppositely charged biopolymers. *Int. J. Biol. Macromol.* 41:185–92

Shah NP. 2000. Probiotic bacteria: selective enumeration and survival in dairy foods. *J. Dairy Sci.* 83(4):894–907

Shah NP, Ravula RR. 2000. Microencapsulation of probiotic bacteria and their survival in frozen fermented dairy desserts. *Aust. J. Dairy Technol.* 55(3):139–44

Solans C, Izquierdo P, Nolla J, Azemar N, Garcia-Celma MJ. 2005. Nano-emulsions. *Curr. Opin. Colloid Interface Sci.* 10:102–10

Taylor PW, Hamilton-Miller MT, Stapleton PD. 2005. Antimicrobial properties of green tea catechins. *Food Sci. Technol. Funct. Foods* 2(7):71–81

Takei N, Unosawa K, Matsumoto S. 2002. Effect of the spray-drying process on the properties of coated films in fluidized bed granular coaters. *Adv. Powder Technol.* 13(3):333–42

Touhy KM, Probert HM, Smejkal CW, Gibson GR. 2003. Using probiotics and prebiotics to improve gut health. *DDT* 8(15):692–700

Ubbink J, Schoonman A. 2003. Flavor delivery systems. In *Kirk-Othmer Encyclopedia of Chemical Technology*, ed. K Othmer. New York: Wiley

Ubbink J, Kruger J. 2006. Physical approaches for the delivery of active ingredients in foods. *Trends Food Sci. Technol.* 17:244–54

Ubbink J, Mezzenga R. 2006. Delivery of functionality in complex food systems: introduction. *Trends Food Sci. Technol.* 17:194–95

U.S. Food and Drug Administration, Center for Food Safety and Applied Nutrition. Nutrient content claims, definitions and approved claims. **http://www.fda.gov/Food/GuidanceComplianceRegulatoryInformation/GuidanceDocuments/FoodLabelingNutrition/ucm056975.htm** van Kleef E, van Trijp HCM, Luning P. 2005. Functional foods: health claim-food product compatibility and the impact of health claim framing on consumer evaluation. *Appetite* 44:299–308

Vegarud GE, Langsrud T, Svenning C. 2000. Mineral-binding milk proteins and peptides: occurrence, biochemical and technological characteristics. *Br. J. Nutr.* 84(Suppl. 1):S91–S98

Velikov KP, Pelan E. 2008. Colloidal delivery systems for micronutrients and nutraceuticals. *Soft Matter* 4:1964–80

Versic RJ. 1988. Flavor encapsulation. In *Spray Drying of Food Flavors*, ed. SJ Risch, GA Reineccius, pp. 1–6. Washington, DC: Am. Chem. Soc. Symp. Ser.

Wang Y. 2009. Prebiotics: present and future in food science and technology. *Food Res. Int.* 42:8–12

Wang X, Li X, Chen L, Xie F, Yu L, Li B. 2011. Preparation and characterization of octenyl succinate starch as a delivery carrier for bioactive food components. *Food Chem.* 126:1218–25

Weinbreck F, Minor M, De Kruif CG. 2004. Microencapsulation of oils using whey protein/gum arabic coacervates. *J. Microencap.* 21(6):667–79

Wishart DS. 2008. Metabolics: applications to food science and nutrition research. *Trends Food Sci. Technol.* 19:482–93

Yuliani S, Torley PJ, D'Arcy B, Nicholson T, Bhandar B. 2006. Extrusion of mixtures of starch and D-limone encapsulated with β-cyclodextrin: flavour retention and physical properties. *Food Res. Int.* 39:318–31

Zeller BL, Saleeb FZ, Ludescher RD. 1999. Trends in development of porous carbohydrate food ingredients for use in flavor encapsulation. *Trends Food Sci. Technol.* 9:389–94

Zuidam NJ, Shimoni E. 2010. Overview of microencapsulates for use in food products or processes and methods to make them. In *Encapsulating Technologies for Active Food Ingredients and Food Processing*, ed. NJ Zuidam, V Nedovic, pp. 3–29. New York: Springer