8 Food Structures and Delivery of Nutrients

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8.1 INTRODUCTION

According to Codex, nutrient means any substance normally consumed as a constituent of food: (a) which provides energy; or (b) which is needed for growth, development and maintenance of healthy life; or (c) a deficit of which will cause characteristic bio-chemical or physiological changes to occur (Codex, 1987). Nutrients in human diet can be classified as essential and non-essential. An essential nutrient is defined as one whose absence from the diet will lead to growth impairment, organ dysfunction or failure to maintain nitrogen balance on an adequate intake of all other nutrients (Grimble,1993). This simple definition has proved useful in considering the roles of key nutrients like proteins, fat and carbohydrates and key vitamins and minerals. Research carried out in recent years has highlighted the importance of several physiologically functional nutrients such as, antioxidants, polyunsaturated fatty acids (e.g., omega 3 fatty acids), phytosterols and fibre. Although traditional diets and natural foods such as fruits and vegetables can supply both key and physiologically functional nutrients, the amounts of physiologically functional nutrients delivered are not sufficient to achieve significant health benefits. There are now a number of reasons that food processors are looking at delivering higher doses of specific nutrients to consumers. Some of these are:

- Enhanced scientific knowledge in discovery and development of new nutrients or nutrients with proven specific health benefits.
- Increased incidences of lifestyle diseases (such as obesity, diabetes and heart diseases) and consumer desire for prevention of these diseases through diet.
- Increased healthcare costs and desire to curb these costs.
- Evolution and easing of regulations allowing health claims for nutrients.

Although delivery of key nutrients through consumer food products such as milk, breakfast cereals, fruit juices and ready meals has long been in the food industries domain, desire to protect and deliver specific, physiologically functional nutrients to specific sites in the gastro intestinal (GI) tract is a relatively new phenomenon to the food industry. To achieve this the food industry has turned to the knowledge available in the pharmaceutical industry in the targeted delivery of drugs. However, due to the complex nature of food

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systems and the presence of several active and interactive ingredients, the knowledge gained in drug delivery has been found to be insufficient by the food industry and further research is currently underway at several research institutions around the world. Challenges are also faced by the food industry in maintaining the quality (safety, stability, flavour body and texture) prior to ingestion of physiologically functional nutrients as the food delivery systems are considerably different from those used in the pharmaceutical industry. In contrast to tablets and capsules, which are the pharmaceutical delivery systems, the food industry prefers to deliver through drinks, beverages and breakfast cereals. Therefore, research in specific food systems incorporating specific bioactive nutrients is required for successful protection and delivery in the GI tract.

The structure of food chosen for the delivery of nutrients not only affects the way the individual receives nutrients; it has been shown that there can be significant effect on the release of other molecules as well. In the last 5–10 years, considerable efforts have gone into understanding food structures that can effectively deliver high doses of nutrients to the appropriate target sites within the GI tract (Garti, 2008; McClements & Decker, 2009). Although most of the knowledge is still in the research arena, noticeable successes have been achieved commercially by companies such as Martek Bioscience (omega-3 fatty acids), Unilever (Phytosterols) and Biogaia (probiotics).

This review discusses various technologies for developing food structures that can protect and deliver sufficient quantities of nutrients in GI tract. In the future, it is likely that more emphasis will be placed on developing food structures based not only on properties of individual nutrients but also on the requirements for their site-specific delivery.

8.2 NUTRIENT DIGESTION AND ABSORPTION IN THE GASTROINTESTINAL TRACT

For development of robust and target-specific food structure for delivery of nutrients require an understanding of the physico-chemical and physiological processes that take place in the human GI tract (Faulks & Southon, 2008; McClements, 2008; 2010; Singh et al., 2009). A simplified process for the passage of food through the GI tract is presented in Figure 8.1. The upper digestive tract has a complex of control mechanisms which govern the entire process of ingestion and digestion. The main switches for these processes are oral stimuli, gastric stretch receptors, gut hormone responses to food in the GI tract and the systematic presence of absorbed nutrients (Faulks & Southon, 2008). The half-life of ingested food in the stomach is 60–90 min and most digestion and absorption occurs in the upper 30% of the small intestine. There are approximately 6 h available for the digestion and absorption of nutrients and any nutrient or food structure that is not digested is predominantly lost to the large intestine.

A simplified process of digestion of food and absorption of nutrients (Figure 8.1) within the GI tract can be described below (Kong & Singh, 2008a; McClements, 2010; Singh et al., 2009).

(1) Mouth: The mouth is the first point of contact for nutrient-containing substances unless the person is unable to swallow and tube-fed directly to the stomach. In the mouth, food is physically broken down into small pieces with the teeth and tongue and then swallowed. Some digestion, especially of simple carbohydrates, of food begins in the mouth with chewing and the action of saliva. Swallowed food is moved down the oesophagus by wavelike muscular contractions thus further mixing the contents.

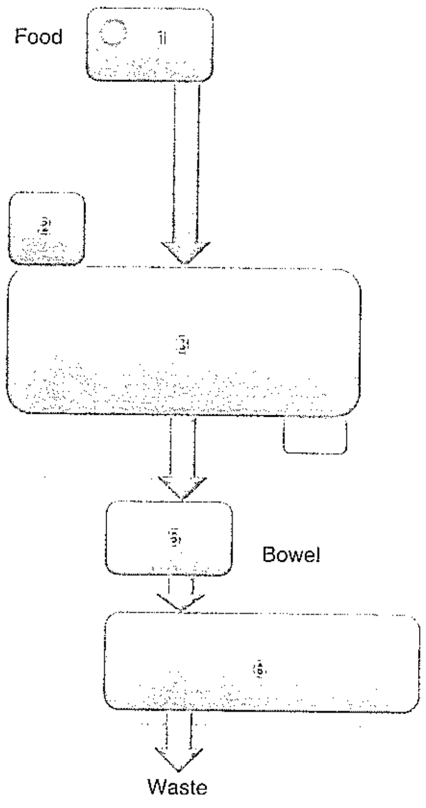
Figure 8.1 A simplified model for digestion and absorption of nutrients in human gastrointestinal (GI) tract.

(2) Stomach: Food passes from the mouth through the oesophagus into the stomach, where pH values of 1.5–3.5 depending on amount and type of food digested are prevalent (Fallingborg, 1999) and is then transported into the intestines. The stomach plays a significant role in the digestion of food material, thanks to its severely low pH which helps in breaking down macromolecular structure of food and releasing nutrients. The acids present in the stomach also destroy most bacteria (if any) in the food. During digestion, food is gradually turned into a liquid, which is released into the small intestine in small amounts. The stomach has three mechanical tasks. First, it stores the swallowed food and liquid. To do this, the muscle of the upper part of the stomach relaxes to accept large volumes of swallowed material. The second job is to mix up the food, liquid, and digestive juice produced by the stomach. The lower part of the stomach mixes these materials by its muscle action. The third task of the stomach is to empty its contents slowly into the small intestine. Several factors affect emptying of the stomach, including the kind of food and the degree of muscle action of the emptying stomach and the small intestine. Carbohydrates, for example, spend the least amount of time in the stomach, proteins stay longer, while fats remain the longest. As the food dissolves into the juices from the pancreas, liver, and intestine, the contents of the intestine are mixed and pushed forward to allow further digestion.

(3) Small intestine: The small intestine is a thin tube of up to 7 meters long, which is so ingeniously made, that it presents an enormous surface area from which it extracts nutrients from the partially digested mixture. This is where most of the nutrients are absorbed. Thus to achieve the physiologically functional benefits, nutrients need to be delivered in protected forms to the small intestine and be available for absorption. The small intestine is divided into three different sections, the duodenum, jejunum and the ileum with pH varying depending on the location in each section. When food enters the duodenum the pH is around 1.5–3.5, but increases rapidly to 6.2 through pancreas secretions. In the beginning of the jejunum the pH decreases slightly to around 6.1. Then the pH rises steadily as it passes through the jejunum and in the proximal part of the ileum the pH has risen to around 7.5. After that, pH decreases slowly to 7.1 in the distal part of the ileum. The small intestine is the site for absorption of most nutrients. Digested nutrients move across the small intestine wall into the bloodstream, where they are transported to the cells of the body, to be used for energy and building and repairing the body.

(4) Large intestine: The large intestine is about 1.5 meters long, containing undigested material including fibre, bacteria and other wastes that have been passed from the small intestine. It's here, that water is extracted (recycled) and the waste material is finally processed before elimination.

Although the human GI tract (*in vivo*) is the ultimate target for studying digestion, absorption and health benefits of nutrients, it is too complicated, inconvenient or expensive for the purpose of research and development of food structures. Hence, various *in vitro* laboratory models simulated to the GI tract for studying the digestion of food material and delivery of nutrients have been developed (Kong & Singh, 2008b; McClements, 2010). One such model was used recently for investigating the digestion and absorption of microencapsulated BSH Active Lactobacillus (Martoni et al., 2007). Although it is almost impossible to mimic the exact human physico-chemical and physiological conditions in simulated models, useful information can be obtained that can help in designing food structures for



Unit	Food processing functions	Time	Temperature	pH	Other main components
1. Mouth	Mastication, physical breakdown of solids, some breakdown of carbohydrates	2–40s	36–38°C	5–7	Digestive enzymes, saliva, salt
2. Liver	Production of digestive juice – bile, which helps in dissolving fat	–	–	–	–
3. Stomach	Digestion-churning and mixing with gastric juice (acid & enzymes); protein hydrolysis; protein denaturation, fat lipolysis, some absorption of small molecules and Vit B12	0.5 to 3.5 h	36–38°C	1–3; protein buffered 3–4	Enzymes (gastrin, pepsin, renin, lipase), HCL, mucus, salt
4. Pancreas	Produces enzymatic juice to break down the carbohydrate, fat, and protein in food	–	–	–	–
5. Small intestine	Majority of digestion and absorption. Digestion of protein, carbohydrates, absorption of amino acids, vitamins, glucose, fats etc.	30–60 min	36–38°C	7–9	Bile, pancreatic juice, enzymes (maltase, lactase, sucrase, trypsin. chymotrypsin.
6. Large intestine (colon)	Fermentation of fibre by gut bacteria, absorption of complex carbohydrates and plant fibre, formation of acids and gases	10–24 h	36–40°C	5.5–7	Water, minerals, insoluble fibre, enzymes, microorganisms

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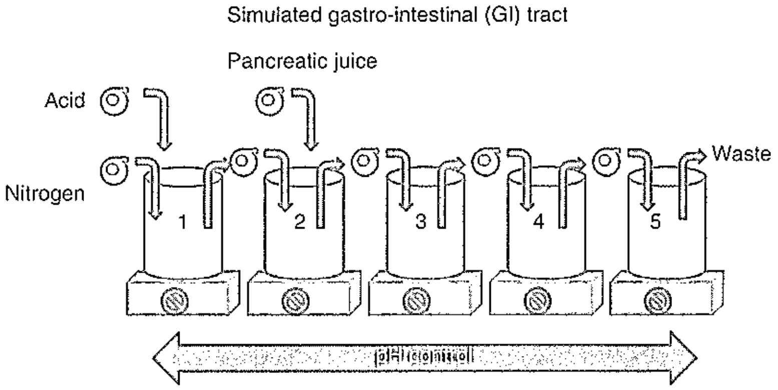

Figure 8.2 A simulated, computer-controlled dynamic human GI model. Bioreactor chambers in series representing stomach (Chamber 1), small intestine (Chamber 2), ascending colon (Chamber 3), transverse colon (Chamber 4), and descending colon (Chamber 5) (adapted from (Martoni et al., 2007).

protecting and selectively releasing nutrients. Ideally, a combination of *in vitro* and *in vivo* experimentations is required to establish technologies for protection and delivery of nutrients. A typical laboratory *in vitro* model for simulation of digestion and absorption includes series of chambers with physico-chemical conditions similar to that encountered in the human GI tract (Figure 8.2).

In such a model, conditions with regard to pH, temperature, bacteria, enzyme types and activities, volume and agitation are closely simulated to those in the human GI tract. Typically, the nutrients are delivered in appropriate food structure (e.g., encapsulated powders or emulsions) into chamber 1 which represents the stomach with pH 1–3 and contains gastric juices and mixed for 0.5 to 3.5 h at about 37°C. Digested material is then passed onto chamber 2 where the pH is raised to an alkaline pH and pancreatic juice is added. After mixing for about an hour, the digested material is passed on the three chambers in sequence representing ascending, transverse and descending colons of the large intestine. This is the longest part of the *in vitro* model and digested material is processed in this part for up to 24 h. The changes in the properties of the food structures and nutrient digestibility are measured throughout the process by analysing samples for particle size microstructure, change, denaturation and aggregation, and chemical composition (Martoni et al., 2007).

8.3 NUTRIENTS AND THEIR DELIVERY CHALLENGES

Functional nutrients such as omega-3 fatty acids and plant sterols are widely available as ingredients in the market. These nutrients can be delivered to the stomach either as dietary supplements such as pills, capsules and powders or as consumer functional foods such as drinks and beverages. Although delivery of these nutrients as dietary supplements is relatively easy, challenges exist for their delivery as food products. Some of the key nutrients with physiologically-functional benefits in the human body and the challenges in their delivery to the human body are discussed below.

8.4 ESSENTIAL FATTY ACIDS

Essential Fatty Acids (EFAs) are necessary fats that the human body is unable to synthesise, and must be obtained through diet. EFAs are long-chain polyunsaturated fatty acids derived from linolenic, linoleic, and oleic acids. There are two families of EFAs: Omega-3 and Omega-6 fatty acids. Fish oil is one of the richest sources of long-chain omega-3 poly unsaturated acids, (PUFAs) such as eicosapentaenoic acid (EPA, C20:5 n-3) and docosahexaenoic acid (DHA, C22:6 n-3), and widely used as a food and nutrition supplement. PUFAs have been extensively researched and are well known for their health benefits such as coronary heart disease, brain and eye functions in infants, joint heath, cancer, diabetes and mental health (Connor et al., 1996; Kolanowski et al., 2007; O'Shea, 2003). Health benefits of PUFA have also been recognised by food regulation authorities in US, Europe and Australia. Despite the knowledge of the health benefits of PUFAs, their intake by the human population has been slow. One of the reasons for the lower intake of PUFAs has been the unpleasant taste and poor oxidative stability of PUFA oils. Their delivery through diet into the human body has thus been a challenge for the food industry.

8.5 ANTIOXIDANTS INCLUDING VITAMINS AND MINERALS

Antioxidants can be defined as any substance that when present in low concentrations compared to that of an oxidisable substrate, significantly delays or inhibits the oxidation of that substrate (Halliwell & Gutteridge, 1985). Antioxidants include a vast range of food nutrients from plant extracts to vitamins such as Vitamin C (Table 8.1). Several studies have shown that both enzymatic and non-enzymatic antioxidants prevent cellular damage from chemical reactions that involve reactive oxygen species (ROS) (Halliwell, 1999; Knight, 2000; Young & Woodside, 2001). Although the ROS have important functions in cell metabolism, growth, and energy production, these can be damaging to different tissues due to their involvement in lipid peroxidation, DNA modification, carbohydrate oxidation and protein alteration (Sabliov & Astete, 2008). Several studies have demonstrated the damaging effects of ROS on health and disease including the effects on cardiovascular disease, cancers, diabetes, inflammatory responses, degenerative diseases, aging, liver damage etc. (Draper et al., 1984; Halliwell, 2000; Hazen, 2000; Hensley et al., 2000).

Relatively little has been published on changes in antioxidants, their interactions with other food components and the effect of these changes on food resistance against oxidation. The most important losses of antioxidant activity occur as a result of chemical changes in antioxidants present in food materials. Naturally, the most pronounced changes result from oxidation reactions occurring rapidly on heating or slowly in storage. Under these conditions, antioxidants are oxidised either by lipid oxidation products (mainly hydroperoxides) or directly by oxygen. For example, tocopherols have been oxidised by ferric ions and hydroperoxides even in absence of oxygen with formation of tocopherones and their mixed dimers with the polyunsaturated acid residue. Tocopherols and tocotrienols are partially destroyed (by about 25% in the case of α-tocopherol) during cooking and baking. In rye bread, prepared by traditional technology, a loss of 50% a-tocopherol was observed (Piironen et al., 1987). Losses of antioxidants rise moderately with increasing temperature and water content in food products during processing. Heat-sensitive vitamins can be

Table 8.1 Group of physiologically functional nutrients, their functions and potential challenge with their protection and delivery to the human body.

Nutrient class	Nutrients	Health benefits	Potential challenges in protection and delivery
Vitamins	Vitamin C (ascorbic acid)	Various functions, reduction in oxidative stress, supports immune functions	Stability to heat, light, moisture
	Vitamin E (tocopherols and tocotrienols)	a fat-soluble antioxidant, protection of cell membrane	Stability to heat, light, moisture
	Folate	Protection of DNA and neural tube defect in embryo	Instability in light, oxygen, heat
Carotenoids	Various such lutein, zeaxanthin, α-carotene, β-carotene and lycopene	efficient free-radical scavengers, immune functions	Instability to temperature, exposure to light, oxygen, and extremes in pH, and active surfaces
	Copper	Part of superoxide dismutases in protection of cell exposure to oxidation	Taste and flavour, insolubility
Elements	Selenium	Part of glutathione peroxidise in protection of organism from oxidative damage	Undesirable flavour, insolubility
	Iron	Oxygen transport and metabolism	Undesirable colour and taste, aggregation and precipitation of protein
	Zinc	functioning of immune system, digestion, control of diabetes, improves stress level,	Taste and stability in beverages
Peptides	Glutathione, anti-hypertensive peptides	reduce blood pressure and hypertension	Bitter flavour, interactions with proteins and minerals
Phyto-chemicals (food components of plant origin)	Isoflavones e.g. genistein and daidzein	Reduce the risk of hormone-dependent diseases	Bitterness, beany off-flavour and brown colour
	Flavonols/flavonoids e.g. quercetin and kaempferol	Onset of diseases (such as cancer) induced by free radicals	Insolubility and off flavour
	Polyphenols e.g. rosmarinic acid	May reduce the risk of cardiovascular disease and cancer.	Poor stability and low bioavailability
	Anthocyanins	Benefits in cardiovascular diseases	Colour degradation with light and heat
	Catechins e.g. epigallocatechin gallate (EGCG)	Benefits in cancer, aging and neurological diseases inflammation diabetes	Bitter flavour
	Indoles	Benefits in heart diseases and cancer	Faecal odour
	Lignans (similar to isoflavones)	anti-inflammatory, anti-cancer, and immune stimulators	Poor solubility
	Sulphides (various allyl sulphides)	Immune functions	Unpleasant odour
	Glutathione	Cell protection from oxidative stress	An unpleasant odour due to the influence of heat, oxygen, or light, consequently, the quality of glutathione is deteriorated.
Zoo-chemicals (food components of animal origin)	Ubiquinone (coenzyme Q_{10})	Involved in essential cellular processes	Poor solubility

destroyed significantly at high temperatures during food processing. Losses of ascorbic acid and vitamin A of up to 50% occur depending on the time and moisture content of the food held at elevated temperatures.

The minerals can also be classified as either essential or non-essential, depending on whether or not they are required for human nutrition and have metabolic roles in the body. Uptake of certain minerals from food can be affected by other components of the diet such as phytic acid and phytates in cereals which can inhibit absorption of iron and zinc. The same effect can be caused by oxalate in certain vegetables. Iodine absorption can be limited by sulphur-containing compounds known as goitrogens, which occur in certain plants, such as some brassicae and cassava. If an essential element is at a low level in the diet, a nutritional deficiency may occur, with specific symptoms. Thus an inadequate intake of iron can cause anaemia when there is insufficient haemoglobin to meet the needs of the body or oxygen transport. A deficiency of iodine can lead to goitre when the body tries to compensate for a low production of the iodine-containing thyroid hormone by increasing the size of the thyroid gland. Inadequate zinc may result in growth failure in children.

8.6 PROBIOTIC BACTERIA

Probiotic bacteria, especially the genus lactobacillus, are currently the focus of much scientific and commercial interest due to a myriad of health-promoting effects in the GI tract (Kailasapathy, 2002; Naidu et al., 1999; Young, 1998). In recent years, various lactobacilli strains have proven to lower total or low-density lipoprotein cholesterol (LDL-C) in humans (Anderson & Gilliland, 1999; Bukowska et al., 1997). This effect can at least partially be attributed to the assimilation of cholesterol by bacterial cells and the enzymatic deconjugation of bile salts (Schaafsma et al., 1998). Bile salt hydrolase (BSH), the enzyme responsible for bile salt deconjugation in the intestine, has been detected and characterised in several intestinal lactobacillus species. It has also been suggested that BSH activity is a requirement in the selection of cholesterol lowering microorganisms, as non-deconjugating organisms do not appear to have any significant cholesterol removal ability in culture medium. However, insufficient survival when passing from the mouth to the intestine has limited the potential of many probiotics for clinical or commercial use (Huang & Adams, 2004).

8.7 PLANT STEROLS

Plant sterols and stanols, also called phytosterols and phytostanols, have chemical structures resembling that of cholesterol and are available in small quantities to humans through plant foods such as vegetable oils, nuts, seeds, cereals, legumes, fruits and vegetables. Plant sterols, such as stanol esters have recently been allowed cholesterol-lowering health claims in US, Europe and Australia. Experiments with plant stanol esters have shown to lower serum cholesterol consistently by about 10–15% and LDL-cholesterol by about 20% in patients with high serum cholesterol levels as well as in normal individuals (Gylling et al., 1997). Similar effects have been seen with plant sterol esters but at least 1 g/day of plant sterols need to be consumed (Hendricks et al., 1999). Consequently, they require extraction and addition to foods. Several patented processes for extraction and incorporation of phytosterols have been reviewed recently (Kamal-Eldin & Moazzami, 2009). The main destroyed significantly at high temperatures during food processing. Losses of ascorbic acid and vitamin A of up to 50% occur depending on the time and moisture content of the food held at elevated temperatures.

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8.8 FOOD STRUCTURES AND TECHNOLOGIES FOR PROTECTION AND DELIVERY OF NUTRIENTS

The bioavailability of dietary nutrients can be either increased or decreased by manipulating the microstructure and/or physicochemical properties of the foods that contain them. Thus, an improved understanding of the relationship between food matrix and structure and its influence on *in vitro* and *in vivo* digestion and absorption would facilitate rational designing and fabrication of foods with improved nutrient absorption properties. Knowledge gained here could be used to design food matrices that protect bioactive components during storage, transport, and utilisation but then release them at specific sites within the gastrointestinal (GI) tract, or that can either increase or decrease the bioavailability of specific nutrients. Improving our understanding of the influence of food structure on the bioavailability of nutrients has also been stressed as an important part of establishing health claims since bioactive compounds might have reduced bioavailability in some food matrices as they move through the GI tract.

8.9 PROTEIN-BASED STRUCTURES FOR NUTRIENT DELIVERY

Protein-based structures for delivery of nutrients have recently been reviewed by Chen and others (Chen, 2009; Chen et al., 2006). Apart from their own nutritional value, proteins offer an excellent platform for delivery of nutrients as the proteins are widely accepted food ingredients and are generally recognised as safe (GRAS). Milk is a classic example where the role of proteins as a delivery system for milk fat and fat-soluble vitamins can be demonstrated. Through the process of homogenisation, milk proteins are able to coat the fat droplets thereby providing protection from aggregation, heat and light oxidation. The key functional properties of proteins in developing structures are the emulsification and gelation. The emulsifying properties are exploited for the development of emulsion-based delivery systems while gelation properties are useful in the development of protein hydrogels.

8.9.1 Protein hydrogels

A hydrogel is a three-dimensional hydrophilic polymer network that can swell in water and hold a large amount of water while maintaining a stable network structure. This three-dimensional network is formed by cross-linking protein polymer chains through covalent bonds, hydrogen bonding, van der Waals interactions, or physical entanglements (Kamath & Park, 1993). Over the past decade, hydrogels have been studied extensively in biomedical and pharmaceutical applications, due primarily to their ability to protect drugs from hostile environments and to deliver them in response to environmental stimuli such as pH and temperature (Qiu & Park, 2001). Protein hydrogels are formed through denaturation and gelation of protein molecules followed by network formation mediated by cations such as calcium and iron (Figure 8.3). Gel mechanical properties and microstructural analyses show

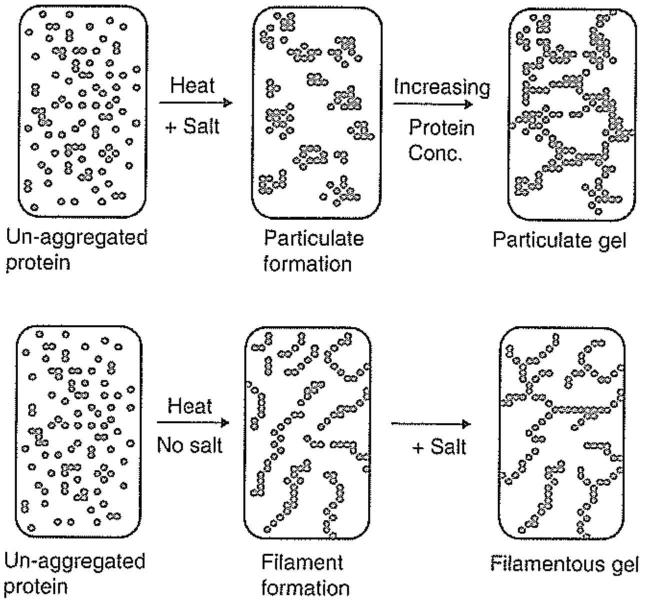

Figure 8.3 Protein based hydrogels suitable for delivery of nutrients.

that two types of protein hydrogels can be obtained, depending on cation/protein ratio; at a lower cation concentration, 'filamentous' gels composed of more or less flexible linear strands making up a regular network characterised by elastic behaviour and high resistance to rupture are formed, while at a higher cation concentration, 'particulate' gels composed of large and almost spherical aggregates characterised by less elastic behaviour and lower rupture resistance are obtained.

Numerous studies have been carried out demonstrating varied gelation properties of globular proteins such as those from egg white, soy and whey (Bryant & McClements, 1998; Clarke et al., 2001; Ziegler & Foegeding, 1990). The hydrogels formed by gelation of globular proteins have the ability to carry and deliver both water- and fat-soluble nutrients (Chen et al., 2006). The ability of hydrogels made from such proteins to entrap both fat-soluble and water-soluble nutrients and to maintain their activity could contribute to the development of innovative functional solid foods.

Protein hydrogels can be used to deliver cationic nutrients such as calcium and iron. Recently, cold-set protein hydrogels were obtained by adding a ferrous salt to solutions of denatured β-lactoglobulin (Remondetto et al., 2002). The filamentous form is created by linear aggregation of structural units maintained by hydrophobic interactions, whereas the aggregate form is produced by random aggregation of structural units essentially controlled by van der Waals forces. Release studies showed that these microstructures would have a major impact on iron delivery, due to their different sensitivities to environmental conditions such as pH and digestive enzymes and that filamentous gels show promise as matrices for transporting iron and promoting its absorption (Remondetto et al., 2004). Modulation of gel microstructure and functional properties by cold gelation should allow tailoring of water-soluble delivery devices for nutraceutical and functional food system development.

8.10 MICROENCAPSULATION

Microencapsulation is one the most successful stories for the delivery of nutrients in commercial ingredients and food products. Microencapsulation involves packaging nutrients in solid, liquid or gas within a secondary material, known as the matrix or shell in the form of small capsules. The core material (also called the internal phase or 'fill') is the particulate mass to be encapsulated (Kim & Baianu, 1991). The coating material has also been referred to as the 'shell' or 'wall' material in the literature. These shells, called microcapsules, may range in size from several tenths of a micron to a few thousand microns, and are, ideally, spherical. The shell structures protect the core material from moisture, light, oxygen and other. The nutrients within the capsule are protected from the surrounding environment and are released in response to triggers such as temperature, shear, pH or enzyme action, thus enabling their controlled and timed delivery to a targeted site.

Microencapsulation is a rapidly expanding technology that promises a variety of new applications in the food industry. Nutrients delivered by microencapsulation include omega-3 fatty acids (Earnest et al., 2009), iron (Lysionek et al., 2001); probiotic bacteria (Weinbreck et al., 2010); and antioxidants (Huang et al., 2009). Food products with encapsulated nutrients such as omega-3, probiotics and phytosterols include infant formula, juices, drinks and beverages.

Selection of coating material remains a critical factor for successful protection and delivery of nutrients using microencapsulation. A range of materials have been investigated including carbohydrates, proteins, lipids, surfactants and co-polymers (Augustin & Hemar, 2009). The use of protein-based wall materials in the food industry for sensitive ingredients is limited because proteins are generally unstable with heating and damaged by low pH and other organic solvents. However, combinations of proteins with other polymers have been successfully utilised. A study investigated the use of protein crosslinking agents on the ability of proteins to encapsulate fish oil. Soy protein isolate (SPI)-based microcapsules containing fish oil were prepared using a modified coacervation method followed by crosslinking treatments (Gan et al., 2008). The procedure yielded 95–98% microcapsules containing 0.5–0.6 g fish oil/g capsule with a volume mean diameter ranged from ~260 to ~280 μm. The study concluded that SPI may be used as a microencapsulating agent in developing microcapsules for controlled-release and oxidative-stability enhancement of fish oil. Compared to the use of ribose, the use of MTGase to cross-link SPI did not satisfactorily yield sufficient protection to the fish oil. Nevertheless, more studies are needed in order to achieve the level of release that is desired in nutraceutical applications.

8.11 FLUIDISED BED COATING

Fluid-bed technology was developed during the 1950s, and mainly applied for various purposes in chemical industries. Its application to particle and powder coating is relatively recent and was developed to satisfy the growing demand of pharmaceutical, chemical, agrochemical, cosmetic, food and feed industries (Gouin, 2004). Fluidised bed technology remains a batch, expensive, and time-consuming process, which is mostly used in pharmaceutical and cosmetic industries that are able to compensate the cost of the process by the high price of their final product. Its application to coating food nutrients is actually limited to some high value products, because of the cost and availability of alternative technologies such as spray drying (a well-established technology). This technique also suffers from serious shortcomings, such as exposure of the active agent to a vigorous hot air stream that may result in active nutrients oxidising under such conditions.

8.12 SPRAY DRYING

Spray drying is one of the most adopted techniques for dehydration and concentration of nutrients. It also accounts for drying of the majority of commercial encapsulated materials in food products (Reineccius, 2004). The process involves an extremely rapid spontaneous evaporation of water from mist of fine particles produced by atomising nutrients in liquid-concentrated forms into a spray dryer chamber through a nozzle or a rotary spinning disc. The dryer chamber is supplied with co-current or counter-current hot air which instantly dries the fine mist of nutrient material into a powder with moisture contents below 5%. Prior to spray drying the nutrients are coated and protected by other encapsulation techniques such as emulsification or microencapsulation. The coating materials used in spray drying include vegetable gums (e.g., Gum Acacia), starches and modified starches, dextrins (including cyclodextrins), sugars (e.g., sucrose and dextrose), proteins (e.g., casein, whey, gelatine and soy protein), and combinations of these materials. Studies have demonstrated that nutrients sensitive to oxidation such as omega-3 fatty acids can be encapsulated via Maillard reaction products formed during heating a mixture of proteins and carbohydrates followed by spray drying (Augustin et al., 2006; Rusli et al., 2006). The spray drying process is relatively well established, and the encapsulated nutrients can be delivered into dry products and powders where the encapsulated nutrients are released upon contact of the product with water, which dissolves the spray-dried capsules. Depending on the coating material, the delivery of the nutrients can be controlled in the GI tract.

Spray drying is one of the most cost-effective and widely used techniques in the food Industry. Spray drying can be used as an encapsulation technique to microencapsulate a wide range of nutrients including vitamins, minerals and omega 3 fatty acids (Augustin & Hemar, 2009). The advantages of spray drying over other encapsulation techniques are: well established range of equipment, ease of scalability, low processing costs and easy manipulation of processing conditions. Spray drying also leads to the development of encapsulated nutrients with extended shelf life for transport, storage and delivery. Despite the wide availability of spray drying technology, the technique may not be suitable for delivery of nutrients that are sensitive to heat, such as heat labile vitamins.

8.13 SPRAY CHILLING

Spray-chilling is another form of technique available to the food industry (Gouin, 2004). In the process, a molten matrix of hydrogenated or fractionated vegetable oils with low melting point (32–40°C) containing active nutrient is atomised through a nozzle into a vessel, similar to the process of spray drying. However, in spray chilling cold air is used instead of the hot air to enable instant solidification of the particle. The major draw backs of spray-chilling include interactions between the fat and the active nutrient, volatilisation of lipid-soluble materials over time, and loss of volatile materials during processing.

8.14 EXTRUSION

An alternative process for protection of nutrients is melt extrusion. In this process, a melting system such as an extruder is employed to form the nutrient carrier melt in a continuous process which is followed by solidification (Augustin & Hemar, 2009). Extrusion-encapsulated nutrients can be incorporated into dry products or powders, and the active nutrients are released upon contact of the product with water. Although extrusion is mainly used for encapsulation of flavours, technique can also be applied for encapsulation of omega-3 fatty acids.

8.15 NANOPARTICLES AND EMULSIONS

Nanotechnology refers to the development of food structures at a length scale of less than 100 nm. Although the applications of nanotechnology in therapeutic systems have been well documented and various systems have been designed for intelligent, modulated, and selective delivery of drugs to specific areas in the body in order to maximise drug action and minimise side effects, nanotechnology is relatively new in the food industry (Acosta, 2009; Huang et al., 2010). Due to their sub-cellular size, nanoparticles offer promising means of improving the bioavailability of physiologically functional nutrients, especially poorly soluble substances such as functional lipids (e.g., carotenoids, phytosterols, u-3 fatty acids), natural antioxidants, and numerous other compounds that are widely used as active ingredients in various food products (Chen et al., 2006; Liu & Wu, 2009). For controlled release and targeted delivery, nano-particles can offer advantages. Nanotechnology can dramatically prolong nutrient residence time in the GI tract by decreasing the influence of intestinal clearance mechanisms and increasing the surface available for interactions with the support material (Kawashim, 2001; Peppas, 1995).

One method of formation of nano-particles is by mixing the bioactive nutrients such as vitamins and antioxidants in polymer solutions followed by encapsulation with surfactant molecules (Figure 8.4).

There are several advantages of using polymeric material for the delivery vehicle because the nutrient is well protected against severe conditions in the stomach such as the low pH, enzymatic and microbial degradation. Nutrients such as antioxidants and vitamins are also protected from any extracellular interactions and their absorption is improved (Sabliov & Astete, 2008). Recently Kwon and others successfully demonstrated the use of poly(methyl methacrylate) (PMMA) as a medium for delivery of nanoencapsulated antioxidant coenzyme Q_{10} (Kwon et al., 2002). The surfactants used for the preparation of nanoparticles were poly vinyl alcohol and sodium dodecyl sulphate. This technique of encapsulation proved to be suitable for protection of coenzyme Q_{10} against UV and high temperature induced inactivation compared with traditionally used oil-based formulation. In another study on the application of nanoencapsulation, the nanoparticles were made from chitosan and β–lactoglobulin for the oral delivery of physiologically functional nutrients. In such systems the protein protected the nutrient from pepsin and acid degradation (Chen & Subirade, 2005). The authors also concluded that nanoparticles based on chitosan and β–lactoglobulin were suitable for protection of nutrients from conditions encountered in the food processing and the GI tract thus improving their chances of absorption in the body.

Nanoemulsions-based delivery systems have been proved to be one of the best platforms to enhance the oral bioavailability and biological efficacies (that is, anti inflammation,

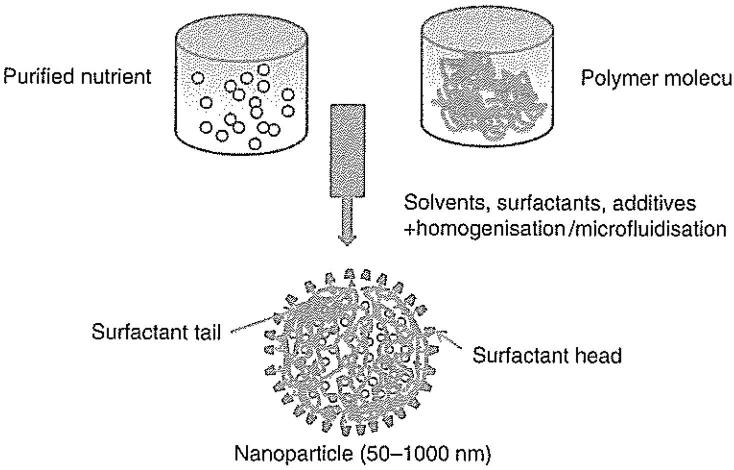

Figure 8.4 Development of nanoparticle structure for delivery of nutrients.

anticancer, and so on) of different phytochemicals (Huang et al., 2009). They are especially appealing to food industry because there are many food-grade lipids and emulsifiers available. They are simpler and easier to prepare compared with other lipid-based delivery systems, such as multiple emulsions and solid lipid nanoparticles. In addition, human body has different lipases ready to digest these lipids, therefore, the potential toxicity of these phytochemical nanoemulsions may be minimal.

8.16 FOOD STRUCTURE AND BIO-ACCESSIBILITY OF NUTRIENTS

The bio-accessibility of nutrients is affected by several factors such the food structure, food processing conditions and the digesting environment conditions (Parada & Aguilera, 2007). In order for the nutrient to be bio-available, it needs to be released from the food matrix and turned into a chemical form that can bind to and enter the gut cells or pass between them. One of the most important challenges remains the understanding of the proportion of nutrients that can be released from the food matrix and therefore potentially available for absorption within the GI tract.

The cell walls of certain plant foods reduce nutrient bio-accessibility by hindering the release of nutrients available for digestion. For example, intact cell wall of starch-rich grains can act as a physical barrier to the action of α-amylase thereby hindering the rate and extent of starch digestion (Ellis et al., 2004). The natural structure of the starch components, amylose and amylopectin also plays a crucial role in their digestion and absorption. Due to the more compact structure of amylose than amylopectin, its breakdown is slower in the GI tract and thus food rich in amylose (e.g., beans, lentils and basmati rice) tend to have lower glycaemic index compared with foods rich in amylopectin (e.g., potatoes, pasta, rice). Further processing such as cooking can increase or decrease the bio-accessibility and the rate of digestion (Hoebler et al., 1999). For example, although raw carrots and spinach are good sources of dietary fibre, cooking them allows the human body to also extract a much larger fraction of the carotenoids (Rock et al., 1998).

Studies have shown that the consumption of whole grain foods has a protective effect against the development of diet-related disorders such as cardiovascular disease, type-2 diabetes, and certain types of cancers. The beneficial influence has been linked to the high phytochemical content of whole grains (Anderson, 2004). In wheat grain (*Triticum aestivum* L.), the majority of the health-beneficial phytochemicals are present in bran and germ. Hemery et al. (2010) demonstrated that ultrafine grinding improved the bioaccessiblity of phytochemicals from wheat bran when used in breads.

Colle et al. (2010) investigated the effect of high pressure homogenisation and thermal processing on *in vitro* bioaccessibility of lycopene in tomato pulp. Increasing the homogenisation pressure resulted in the breakdown of the tomato cell aggregate structures but also improved the strength of the fibre network which resulted in a decrease in *in vitro* bioaccessibility of lycopene. Thermal processing (30 min at 90°C), subsequent to high pressure homogenisation, was not able to sufficiently decrease the strength of the fibre network of homogenised tomato pulp in order to improve the lycopene *in vitro* bioaccessibility.

8.17 CONCLUSIONS AND FUTURE DIRECTIONS

Due to the increased incidences of lifestyle diseases such as obesity, stress, diabetes and cardiovascular diseases, there is considerable interest in developing nutrient-rich ingredients and foods that can help control these diseases. Most of the knowledge used in developing food structures suitable for delivery of physiologically functional nutrients has been adapted from the pharmaceutical, agro-chemical or the cosmetics industries. This includes a number of technologies such as microencapsulation and nano-technology which have been adapted in developing suitable food structures. In doing so researchers have realised that food systems are far more complicated than pharmaceutical or agro-chemical systems due to the potential for complex ingredient interactions. They have also realised that the food structure for delivery of nutrients within the human GI tract needs to be far more robust and adaptable to the harsh conditions during processing and storage and within the stomach. Structures for delivery of nutrients, based on microencapsulation technology have been relatively more suitable than those from other technologies. In future, advances in research may allow us to develop food structures that offer the release of a specific nutrient at a specific site for a specific period and at a specific time interval. For example, this would involve developing food formulations where each nutrient is individually protected in a matrix and combined with other nutrients that are also protected individually. This will require understanding of the interactions of the protecting material not only with its own active component but also with other protective materials under the conditions encountered at various stages of digestion and absorption. Such foods, which can also be called functional foods may be considered alternatives to medicines where the diet is used as a means to control specific diseases or maintain certain health conditions.

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