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Health-Promoting Food Ingredients and Functional Food Processing

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1. Introduction

One of the greatest challenges food research is facing in this century lies in maintaining sustainable food production and at the same time delivering high quality food products with an added functionality to prevent life-style related diseases such as, cancer, obesity, diabetes, heart disease, stroke. Functional foods that contain bioactive components may provide desirable health benefits beyond basic nutrition and play important roles in the prevention of life-style related diseases. Polyphenols and carotenoids are plant secondary metabolites which are well recognized as natural antioxidants linked to the reduction of the development and progression of life-style related diseases. This chapter focuses on health-promoting food ingredients (polyphenols and carotenoids), food structure and functionality, and bioavailability of these bioactive ingredients, with examples on their commercial applications, namely on functional foods. Thereafter, in order to support successful development of health-promoting food ingredients, this chapter contributes to an understanding of the relationship between food structures, ingredient functionality, in relation to the breakdown of food structures in the gastrointestinal tract and its impact on the bioavailability of bioactive ingredients. The overview on food processing techniques and the processing of functional foods given here will elaborate novel delivery systems for functional food ingredients and their applications in food. Finally, this chapter concludes with microencapsulation techniques and examples of encapsulation of polyphenols and carotenoids; the physical structure of microencapsulated food ingredients and their impacts on food sensorial properties; yielding an outline on the controlled release of encapsulated bioactive compounds in food products.

2. Overview on health-promoting food ingredients and food processing technology

2.1 Health-promoting food ingredients from plant sources

A great number of research activities in the field of health related dietary aspects have demonstrated a significant link between the regular intake of phytochemicals (e.g. polyphenols, carotenoids, phytosterols), and the prevention of life-style related diseases, such as cancer, obesity, diabetes and cardiovascular complications (Greselea, 2011). As a natural source of these phytochemicals, especially the consumption of whole foods (e.g.

coloured fruits and vegetables), has been suggested to be of health benefit (Liu, 2003). Research studies have shown that a polyphenol mixture including anthocyanins, proanthocyanidins and flavonols, naturally occurring in certain red and blue berry fruits, had a stronger activity against cancer cells than purified polyphenols (Herring & Albrecht, 2005). Similar to this finding, the consumption of purified lycopene resulted in a minimal protection against prostate cancer in rats, whereas the consumption of tomatoes lowered this risk more successfully by 26% (Boileau et al., 2003). The potent antioxidant and anticancer activities can be assumed to be due to the additive and synergistic effects of phytochemicals and nutrients, when occurring in a complex mixture in fruits and vegetables (Liu, 2004). This may also explain why no single antioxidant can replace natural compounds in fruits and vegetables to achieve similar health benefits. Early epidemiological surveys indicated that regular consumption of fruits and vegetables can reduce cancer risk, which has been demonstrated through comprehensive studies linked to cancer prevention (Block et al., 1992). Furthermore, the clinical studies have also shown that commonly applied dietary supplements do not have the same health benefits as a natural diet with a large percentage of fruits and vegetables, which has demonstrated to inversely affect tumor formation and cardiovascular diseases (Hertog et al., 1993; Verhoeven et al., 1996). Functional foods, which aim to amplify these positive attributes by the addition of certain purified phytochemicals, have to undergo a paradigm change based on research findings. The beneficial effect of purified phytochemicals is commonly reduced, in comparison with a mixture of phytochemicals in their natural food matrix. Hence, the isolated compounds either lose their bioactive function or can not react in the same way as when they are present in their natural matrix, possibly due to the extraction and purification processes applied. On the other hand, the application of bioactive ingredients sourced from plants, e.g. extracts rich in isoflavones, lycopene and ingredients from herbs, nuts and fibres, has been documented in cancer prevention, however the market for these supplements and potential health claims is currently still widely unregulated (Watson & Preedy, 2010).

2.1.1 Polyphenols

Polyphenols are a group of dietary antioxidants found naturally in fruits and vegetables. They primarily consist of flavonoids including flavanols, flavones, isoflavones, flavonols, flavonones and anthocyanins, and non-flavonoid polyphenolics including phenolic acids, lignans and stilbenes. Polyphenol functionality lies in the prevention of e.g. oxidative, inflammatory, microbial and viral assaults, and therefore in their potential to reduce chronic diseases (Leifert & Abeywardena, 2008a,b; Rimando & Suh, 2008). The mechanisms of antioxidant activity of polyphenols can be characterized by direct scavenging or quenching of oxygen free radicals and inhibition of oxidative enzymes that generate reactive oxygen species (Terao, 2009). Potential mechanisms for the anticarcinogenic actions of polyphenols have been reviewed by Lea (2010), in which one of the most common recognized mechanism is that polyphenols cause the excessive production of hydrogen peroxide and the defense of the cancer cell may be overwhelmed, leading to an inhibition of proliferation and death in the cell. However, polyphenols may also function mutagenic and thus increase carcinogenesis, as they enhance the formation of reactive oxygen species under some specific circumstances (Watson & Preedy, 2010), causing further DNA damage.

The challenges for applications of polyphenols in food system are the initial protection of the bioactivity of the polyphenols, as they may lose their antioxidative properties or bioactive functionalities during processing of food, due to their sensitivity to oxygen, temperature, light (Ottaway, 2008), and to the gastrointestinal tract environment (pH, enzymes) (Bell, 2001); furthermore the development of appropriate formulations to increase solubility of polyphenols according to a specific food matrix. Examples for polyphenols from food sources, with some of their properties are presented in Table 1. Plant extracts frequently produced from regular foods which are rich in polyphenols, are for example, grape seed or pine bark, lemon balm, green tea, olive, rooibos, and aloe vera, etc. Among these, functionality in the prevention of lipid peroxidation has been reported for grape seed extract and maritime pine bark extract (Buchwald-Werner et al., 2008). However, not every commercially available plant extract complies with the regulatory requirements governing their application in foods. The approval of food status for any ingredient depends on the traditional use of the plant as a food, the form in which it is presented to the consumer (i.e. a pill versus a candy) and its physiological functionality, as well as on the processes which are involved in the extraction of the ingredient. In addition to these legal aspects, other technological properties such as stability and solubility are also important for a successful application in food. The plant extracts should not interfere with the product characteristics, such as colour or taste, and they have to be stable within in the food matrix to prevent unwanted precipitation. When included in a food product, the polyphenolic compounds may impart an astringent or bitter taste, or introduce a degree of brown colouring. For example, grape seed extracts are difficult to incorporate into functional foods due to their dark brown colour and low water solubility. Therefore, it is a crucial step during the product development process, to investigate the sensorial impacts of bioactive compounds on foods before their application. Certain methods can help to avoid these issues, e.g. a modified food formulation using microencapsulation technique could be a possibility to mask an unpleasant flavour from the bioactive extracts. The most successful applications of plant extracts containing polyphenols are beverages, including water or tea-based functional drinks, as well as dairy products or other novel product groups such as "smoothies" while the most popular plant extracts used in this type of beverages is green tea extract followed by rooibos extract.

2.1.2 Carotenoids

Carotenoids are natural occurring pigments in plants. There are more than 600 known carotenoids, which can be categorized in two groups: provitamin A carotenoids (α-carotene, β-carotene, β-cryptoxanthin), and non-provitamin A carotenoids (lycopene, lutein, zeaxanthin, astaxanthin), where the former can be metabolized by humans into retinol, and the later exhibit no function of vitamin A in humans (Bohn, 2008). Carotenoids can not be synthesized by our bodies and have to be obtained from food sources, such as fruits, vegetables, certain types of fish or shell fish (Table 2). The potent antioxidant activities of carotenoids and their health beneficial functionality, such as maintaining eye health, and prevention of chronic diseases have been widely investigated. Although, a recent study showed that β-carotene increases the risk of lung cancer in smokers when it was administered as a purified food supplement (Goodman et al., 2004), the health benefits and cancer preventing properties of carotenoids, when occurring in a natural diet of fruits and vegetables, cannot be denied. For example, data collected from 1993 case subjects with first primary incident of adenocarcinoma of the colon, strongly suggested that lutein was inversely associated with colon cancer in both men and women, when incorporating

Polyphenols	Main compounds	Food sources	Properties
Anthocyanidins	Malvidin, cyanidin, delphinidin, pelargoindin, peonidin, peltunidin and their glycosides	Red wine, all kinds of berries, red grape, orange, aubergine, avocado	Highly sensitive to temperature, oxidation, pH, and light; water soluble
Flavanones	Hesperetin, hesperidin, naringenin, naringin, homoeriodictyol	Citrus, such as, grapefruit juice, orange juice	Sensitive to oxidation, light and pH; aglycones insoluble but glycosides soluble in water
Flavones	Apigenin, luteolin	Fruit and vegetables, such as, celery, oregano, parsley	Sensitive to oxidation and pH; aglycones slightly soluble but glycosides soluble in water
Flavonols	Kaempferol, myricetin, quercetin, and their glycosides	Fruit and vegetables, such as, apples, onions, tea, red wine	Sensitive to oxidation, lights and pH; aglycones slightly soluble but glycosides soluble in water
Flavan-3-ols	Catechin, epicatechin, gallocatechin, epigallocatechin	Tea (green/black), red wine, dark chocolate	Sensitive to oxidation and pH; astringent and bitter; slightly soluble in water
Isoflavones	Daidzein, genistein, genistein	Soy beans, peas, peanuts	Sensitive to temperature, oxidation, lights and pH; astringent and bitter; soy smell; water soluble
Hydroxybenzoic acids	Gallic acid, *p*-hydroxybenzoic, vanillic acid	Berries, tea, wheat	Sensitive to temperature, oxidation, lights and pH; soluble in water
Hydroxycinnamic Acids	Caffeic acid, ferulic acid, *p*-coumaric acid, sinapic acid	Fruits, oats, rice	Sensitive to oxidation and pH; most slightly soluble in water
Lignans	Pinoresinol, podophyllotoxin, steganacin	Flaxseed, sesame, whole grain wheat bread, rice, cashew nuts, sunflower seeds	Relatively stable under normal conditions; unpleasant flavour; water soluble
Tannins	Castalin, pentagalloyl glucose, procyanidins	Tea, berries, wines, chocolate, black walnuts, black/red beans	Sensitive to high temperature and oxidation; astringent and bitter, water soluble

Table 1. Polyphenols from food sources and their properties (adapted from Ottaway, 2008; Watson & Preedy, 2010)

spinach, broccoli, lettuce, tomatoes, oranges and orange juice, carrots, celery, and greens into the diet (Slattery et al., 2000). In vitro studies, it has been suggested that carotenoids (β-cryptoxanthin, lycopene) stimulated bone formation and mineralization, and may prevent osteoporosis development (Yamaguchi & Uchiyama, 2004). Zeaxanthin and lutein might possess the function of preventing age-related macular degeneration (Sajilata et al., 2008). Epidemiological evidence has indicated that lycopene may protect individuals from colorectal cancer and men from prostate cancer (Schwarz et al., 2008).

In the last few decades efforts have been made to develop genetically modified food sources with an increased carotenoid content. Golden Rice is one of the well-known examples, which is a crop product that has 1.6 mg/g total carotenoids in the rice endosperm (Ye et al., 2000). This already posed a significant increase to the values found in natural rice varieties, e.g. 0.02 µg/g for pale varieties and a highest value of 0.13 µg/g for a dark variety (Frei & Becker, 2004). A later developed variety of golden rice (Paine et al., 2005) contains up to 37 mg/g of total carotenoids and recent clinical trials have shown that this functional product is a good source of vitamin A for humans (Tang et al., 2009).

At present, carotenoids are most often used as food colouring substances in commercial products. β-carotene, lycopene, astaxanthin, lutein, and zeaxanthin are also consumed as dietary supplement in human nutrition. Physically, carotenoids are almost insoluble in the aqueous phase, but slightly soluble in the lipid phase (0.2 g/L). However, the stability and solubility of carotenoids can be considerably improved with encapsulation technology during food processing, which will be discussed later in this chapter.

2.2 Food structure, functionality and bioavailability

The functionality and bioavailability of bioactive compounds are strongly affected and determined by their chemical properties, in terms of solubilisation and depolymerisation (Lesmes & McClements, 2009). Also further processing of the food material may dramatically affect the bioavailability of nutrients and phytochemicals, as do the environmental conditions during its passage through the gastrointestinal tract (GI).

The influence of heat and mass transfer in food processing affects food microstructures. The complexity of food matrix determines both food texture and also the release of functional components. It has been suggested that quantitative structure function relationships (QSFR) can help the rational design and efficient production of such functional food system (Lattanzio et al., 2009). However, currently the knowledge base on bioactive ingredients and food structure is very limited. Future studies should provide further data which can aid in the understanding of bioavailability of specific compounds and hence an improved description of food processes (Armand et al., 1997; Lesmes & McClements, 2009), as not only the bioavailability, of selected micronutrients and phytochemicals, but also the general ingredient stability is affected by the food matrix. For example, it has been found that only a minor part of the carotenoids in raw fruits or vegetables is absorbed in the intestines, probably due to the fact that carotenoids in most plant foods exist as crystals or are bound to proteins. In contrast, carotenoids dissolved in vegetable oils show a higher bioavailability (Parker, 1997). Incorporation of carotenoids into micro and nano structures in food matrices may influence their solubility and crystallinity, and thus their absorption. After formulating carotenoids into particulate systems which allow for sufficient solubility and release during digestion, they may be more easily delivered into cellular compartments, improving their bioavailability.

The current knowledge of the effects of processing methods on the bioavailability of individual food components has been reviewed by Faulks & Southon (2008). The understanding of the following considerations are crucial for the development of novel products with added health beneficial value, and they could aid in predicting the absorption rate, metabolism and bioavailability of bioactive compounds within the human organism: (i) original compounds might be present in a form which is not directly available in the human digestive system; (ii) the food matrix has a significant effect on the release and availability of bioactive ingredients; (iii) compounds might need an additional carrier substance to aid solubility; (iv) released ingredients might not be fully absorbed; (v) functional responses to bioactive compounds may vary throughout the population according to their genetic makeup. Faulks & Southon (2008) concluded that interactions of foods with the human body are extremely complex, due to the large variety of physicochemical processes, their effect on food structure and also the individual's metabolism characteristics. There is also still a lack in the understanding of how single food components are digested. Current developments in the area of functional food have already demonstrated that the bioavailability of bioactive ingredients can be improved by the selection and development of a delivery and protection method for bioactive ingredients. Plant sterol absorption, for example, differs greatly throughout various food matrixes, with milk being a good carrier, being up to three times

Carotenoid species	Food sources	Potential health benefits
β-carotene	Carrots, sweet potatoes, apricots, cantaloupes, peaches, dark green leafy vegetables	Most potent pro-vitamin A form, maintains healthy eyes; vision cycle, reduces the risk of cancers and heart diseases
Lycopene	Tomatoes, watermelon, red peppers, pink Grapefruit	Against many types of cancers, prevention of cardiovascular disease
β-cryptoxanthin	Peppers, pumpkin, squash, peas, chilli, sweet corns	Prevention of vitamin A deficiency, prevention of colon cancer; improves lung function
Lutein	Spinach, kale, collard greens, turnip greens, lettuce, broccoli	Prevention of macular degeneration
α- carotene	Sweet potatoes, carrots, kales, spinach, turnip greens, winter squash, collard greens, cilantro, fresh thyme, cantaloupe, lettuce, broccoli	Prevention of vitamin A deficiency, heart disease prevention
Zeaxanthin	Sweet corn, persimmon, spinach, egg yolk, green peas, brussel sprouts, citrus fruits, peaches, apricots, papayas	Prevention of macular degeneration
Astaxanthin	Salmon, shrimp, trout, seabream, lobster, fish eggs	Maintains healthy eyes

Table 2. Main dietary carotenoids and their major food sources (adapted from Wildman, 2007)

Functional ingredients	A	B	C	D	E	F	G	H	I	J
Carotenoids	x		x		x					
Plant sterols	x							x		
Saponines	x	x			x			x		
Glucosinolates	x	x						x		
Polyphenols	x	x	x	x	x	x	x		x	
Protease inhibitors	x		x						x	
Terpenes	x									
Phyto-estrogens	x		x							
Sulfides	x	x	x	x	x	x	x	x		x
Phytic acid	x		x		x			x	x	
Dietary fibre	x				x			x	x	x
Substances from fermented foods	x	x			x			x		

A – anticancerogenous; B – antimicrobial; C – antioxidant; D – antithrombotic; E – immunomodulatory; F – anti-inflammatory; G – blood pressure regulation; H – cholesterol level lowering; I – blood glucose lowering; J – digestive improvements

Table 3. Examples of food ingredient functionality (adapted from Watzl & Leitzmann, 1999)

more efficient than bread or other cereal products (Jones & Jew, 2007). With future studies and increased understanding on the normal human GI system, it will be possible to develop further functional foods with enhanced nutritional value, bioavailability and specific health beneficial functionality (Salminen et al., 1998).

2.3 Gastrointestinal physiology of functional foods

A most crucial part in the utilisation of food and bioactive ingredients, after the required processing and formulation of food, is the behaviour of food during gastrointestinal passage, i.e. the way it is processed by the human body. Due to initial chewing and further movements of the food matter, the structure is exposed to physical fragmentation, and in addition to pH changes, changes in the moisture content and exposure to acid /enzymatic activity, and bioactive ingredients are more or less released from the structure and made available for absorption into the blood stream. The time of digestion is depending, among other factors such as the amount consumed, on the original food structure and its breakdown, as these factors determine how fast digestive enzymes can penetrate into the food matrix. Furthermore, the food composition plays an important role, as the digestion rate will also depend not only on the physical food structure, but also on the type and concentrations of food molecules (e.g. proteins, carbohydrates, minerals, dietary fibre, etc.), how these are interacting with each other, allowing the release of fragments or bioactive ingredients (Norton et al., 2006).

To demonstrate novel methods of approaching a better controlled availability of nutritional components, a study by Augustin et al. (2011) showed that the use of microencapsulation for improved bioavailability of marked bioactive compound (radiolabeled [14C]-trilinolenin or [14C]-tributyrin and [3H]-resveratrol) did not alter the time needed for the gastrointestinal passage, but significantly improved the absorption into the blood system. This proved the potential suitability of microencapsulation as a delivery vehicle for bioactive substances. Parallel to the approach of delivering certain bioactive phytochemicals to a specific point of release in the human GI tract, another similar approach lies in the delivery of certain microorganisms. As the human body and health status is not only influenced by the nutrient supply, but also by the GI microbial flora, based on the ability of these organisms to transform food components, influence the absorption of bioactive molecules, it may be of interest to release certain organisms into the GI tract after their stomach passage, e.g. in microencapsulated form. The need for further studies on how the normal human intestinal flora with all aspects, e.g. fermentation, immune system, functions, and the effect of wanted modifications via the use of prebiotics and probiotics, was also stated by Salminen et al. (1998).

2.4 Food processing

2.4.1 Development of centralized food production

The human diet undergoes traditionally changes, both in nutritional composition and preparation methods, and these circumstances require linking the understanding of health beneficial nutrition to the development of novel food products. Throughout history, several significant steps of variations can be noted, starting with anthropological investigations on the diets of our ancestors, and leading to the analysis of a modern diet driven by health concerns and fashion. As humans developed on a natural diet on the basis of a hunter and gatherer society, the sourcing and preparation of suitable food was the major activity on a day-to-day basis. Obtained goods had to be prepared and mostly consumed immediately, as prolonged storage was often not possible.

The appearance of settlements, larger societies, and a further specialisation of individuals on their activities for the community, also determined the need for food preservation and storage, and so an enablement of the group to plan future activities, e.g. procurement of winter supplies. These early food processing methods all aimed at the preservation of food and consisted of simple activities, e.g. sorting suitable items, cleaning, drying, salting, smoking, packaging and if possible, a controlled storage to minimize spoilage. These inventions were made solely by observation, by trial and error. Also the application of biotechnology in food production and preservation can be ascribed to the early stages of modern societies.

Since those times, food production methods had to be more and more specialised on different products and food groups. The rise of these specialised activities formed traditional professions, e.g. bakers, butchers, cheese makers, or brewers, in addition to supporting professions, e.g. coopers, the first engineers to produce food processing equipment and packaging technology.

As the first heat sterilization plant in France was developed by Appert in the early 1800s (Throne, 1986), the second half of the 19th century saw another major step and development of food processing, the birth of technologies and food factory set-ups as we know them today. The industrial revolution, as an example in Central Europe, with its relocation of large parts of the population from country side rural life style into city dwellings and full time activities apart from food sourcing, and also the need for a country to be able to supply the food needs of large armies, needed new methods and procedures, both in food preparation and packaging.

A major achievement of these developed production methods, with many processes adapted from other industrial fields, was certainly the increased food safety. However, the application of industrial processes with their sometimes harsh conditions in terms of handling, cleaning or temperature treatments, also led to a certain amount of depletion of nutrients from the so preserved food products. The industry was able to produce safe food, with good storage properties, however, the need of guaranteeing a healthy and nutritional balanced diet still lied within the consumer's responsibility and malnutrition could occur due to a consumer's lack of knowledge when limiting the diet to highly processed products and ingredients, e.g. refined sugar, white flour, convenient products such as canned vegetable and fruits. Nowadays, the average consumer is much better informed and with the wide options of food products and choices available to us, with growing concern about malnutrition and the knowledge of related health risks, the need and demand for a diet of nutritionally high value is greater than ever.

2.4.2 Overview on food processing

An overview about common food processing technologies is presented in Table 4. According to the desired products, several production steps are necessary in order to produce a food product from raw ingredients, change the physical and chemical appearance of the product, ensure food safety, consistent quality, shelf-life and supply. A typical processing step, to be found in many solid and liquid products is heat treatment, which can be applied either to prepare the product (i.e. cook the product for added bioavailability of nutrients, denaturise proteins, modify carbohydrates and starches), to develop desired flavours, aroma and colour components (e.g. Maillard reaction), modify the food structure (e.g. texture changes due to ingredient modifications or drying processes), or to preserve or sterilize the food by heat induced inactivation of microorganisms, toxins and enzymes (e.g. heat sterilisation of canned food products, blanching of vegetables, to inactivate enzymes). As can be expected, the heat treatment regimes, and also other principal food processing steps, often lead to a loss of bioactivites of native ingredients, which are essential for the human diet. Fruit and vegetable products, as these are a major source of important phytochemicals, have to be protected during processing, packaging and storage, to ensure their availability for the human diet.

Beside the method of adding bioactive ingredients specifically to food items and so creating or re-creating the desired nutritional value of the product, which is explained later in this chapter, the modern way of food processing aims at preserving native bioactive ingredients in the raw food as much as possible. In order to achieve this, novel food processing methods have been developed, are under deployment, or are in the investigative stage and close to an industrial application. Examples for these novel methods are listed in Table 5, and their aim of preserving and protecting food nutrients and native bioactive ingredients can easily be understood, especially in the area of non-thermal treatments. In this approach, the advantages of a heat treatment, e.g. microorganism inactivation or a textural modification, are achieved by non-thermal methods, e.g. ultra high pressure treatment or the use of enzymatic reactions. Nott et al. (2000) and Zhong et al. (2004) demonstrated that through ohmic heating and microwave technology, a suitable food product could be manufactured with the same level of safety as by production with conventional heat treatment processes, but with improved organoleptic properties.

The reduction of quality degradation due to food processing by high pressure processing and application of pulsed electric fields, both methods characterized as non-thermal treatments, was shown by Matser (2004). These approaches in novel food processing have certainly advantages in terms of human nutrition and health, as well as improving food quality. However, having also to consider the other reasons for food processing, such as guaranteeing sufficient inactivation of spoilage microorganisms, these methods have their limitations, including the ability to process large volumes, processing costs.

2.4.2.1 Functional food processing

By definition, functional foods are food products, both natural occurring or processed food, which contain bioactive compounds with a functionality beyond the essential daily nutritional requirements to improve the human health. Fruits and vegetables are well recognized functional foods, however, their beneficial ingredients also can be extracted, purified and used as dietary supplements and consumed in concentrated form, or after addition to a different food product exert an added dietary value. However, these methods of a simple addition may result in an unwanted and negative change of sensory and structure of food products. With the aid of novel processing technologies (such as microencapsulation), these effects could be minimized or avoided, e.g. through microstructural modifications (Palzer, 2009). These novel technologies differ from the traditional food processing methods and have certain advantages in their capacity to prevent the inactivation of bioactive ingredients. In order to provide a greater amount and variety of functional foods, beside the traditional natural products, food manufacturing companies are working continuously on the development of novel products. This can either be in the form of modified raw ingredients, e.g. vegetables with increased amount of phytochemicals, or in the form of adding desired bioactive ingredients to other food. The fortification of food is a well established production method and can be found in application in numerous products, for example breakfast cereals with added vitamin (e.g. folic acid), minerals or fruit juices fortified with ω3-fatty acids. Producers have to consider, if the product is able to simple contain the added ingredient within its natural matrix, or if further process modifications are needed (e.g. encapsulation). This approach could include delivery of the protected bioactive ingredients to their target site and release under certain trigger factors (enzymes, pH, salts, etc.) (Chen et al., 2006).

	Aim of the process	**Principle of operation**	**Typical application examples**	**Equipment examples**
Mechanical Processes				
Size classification	Dividing a mix of particles according to size	Sieving and size classification	Grain processing / milling applications	Sifting machines / air separator
Sorting	Dividing a mix of particles according to other characteristics than size, e.g. specific density	Sorting according to differences in density, magnetic susceptibility, electric conductivity	Grain processing / processing of herbs and other plant parts	Stone separator / magnetic separator
Filtration	Separation of a liquid / solids mixture	Separation of solid particles from suspension by a filtration media	Beverage industry / dairy industry / ingredient manufacture	Filtering machines, e.g. fixed bed filtration / membrane filtration unit
Centri-fugation	Separation of suspensions with smallest particle sizes	Centrifugation forces	Dairy industry / beverage industry / fruit and vegetable processing / oil manufacturing	Centrifuge / separator
De-foaming	Removal of unwanted stable foam during process operations	De-stabilisation of foam by mechanical fixtures, separating gas / liquid	Beverage industry / dairy industry	Mechanical fixtures within process machinery / tanks
De-dusting	Removal of fine solid particles from gaseous phase, e.g. avoidance of dust explosions	Centrifugation forces / filtration media	Milling-, baking-, powder-, ingredient industry	Aerocyclone / air seperator
Flotation	Separation of solid particles from liquids	Attachment of particles to gas bubbles, followed by foam separation	Beverage industry	Flotation reaction vessel
Mixing	Homogenous mix / particle distribution in solid/solid or solid/liquid mixes	Mechanical mixing	Applications throughout the industry	Various mixing vessels and machines
Dispersion	Homogenous mix of liquid/liquid system	Mechanical mixing / homogenisation	Oil/water mixtures, e.g. mayonnaise	Mixing vessels

	Aim of the process	Principle of operation	Typical application examples	Equipment examples
Disag-gregation	Production of smaller particle sizes, solids	Mechanical combination	Milling of food ingredients	Milling / crushing machines
Spraying	Production of smaller particle sizes, liquids	Spraying of liquids through nozzles by pressure	Dairy industry, ingredient industry	Spray dryers / coating applicators
Ag-glomeration	Production of larger particles from powder mixes	Affinity of particles	Ingredient industry, pellet and tablet production	Pelletisation drum / tablet press
Thermal Processes				
Heating	Support of other processes by change of rheological/chemical properties; pasteurisation; sterilisation; denaturation; flavour development	Food is exposed to heat energy, in different applications and by various methods (steaming, boiling, roasting, indirect heating, micro-wave, etc)	Throughout all food production processes	Cooking vessels, autoclaves, reaction vessels, continuous liquid sterilisation (UHT), drying machines
Cooling	Temperature control of product	Removal of heat energy, by active or passive cooling	Throughout all food production processes	Equipment similar to heating applications
Evaporation	Reduction of liquid phase / increase of solid content	Heating (under modified pressure) to evaporate solvent (water, etc.)	Beverage industry / powder and ingredient manufacture	Evaporation tower
Crystal-lisation	Separation of solids from liquids	Temperature changes induces crystallisation of solid in high concentrations	Sugar industry / ingredient industry	Crystallisation reactor
Osmosis	Separation of liquid solid mixes	Pressure difference across a separation membrane	Fruit and vegetable juices / protein and lactose production	Ultrafiltration unit / reverse osmosis

Table 4. Mechanical and thermal processes common to food processing

2.4.2.2 Functional food design and safety

When considering the aspects of functional food development, one need to understand the food structure and the related product characteristics, as the structure primarily determines the behaviour of food within the human GI tract. (Davis & Gordon, 1982). The challenge in functional food product development lies in maintaining the desired and traditional sensory attributes, in terms of flavour and texture, while maintaining the functionality of the added active ingredient. The targeted consumer group and their consumption habits have to be taken into account and a tailored product needs to fulfil the consumer's requirements, in order to achieve a positive market response. If this addition of the ingredient is achieved with a satisfying result on the product's appearance, the next crucial step lies in the assurance of the ingredients' functionality. Besides in vitro and in vivo (animal and human) studies on the bioavailability of the bioactive compounds, researchers and scientists can apply mathematical models (Ottino, 2005), including current understandings of ingredient activity, release mechanisms and human metabolism, to follow and predict the ingredients' functionality and hence justify the its addition to the product. Currently, research activities in product microstructure design for process modelling in mouth behaviour and other sensorial characteristics, such as, taste development or physical sensation (e.g. mouth feeling) (Malone et al., 2003) are building up support data for these functionality studies. A recently developing area in functional food development considers the interactions between foods and nutrient supplements and an individual's genome and its effect on nutritional needs, (nutrigenomics). The main idea of nutrigenomics, is that a dietary recommendation for one individual might be inappropriate to another. This emerging science might be able to provide individual tailored nutrition for population groups or individuals, and could be a major step in reducing diet related illnesses and resulting health care costs. Functional ingredients, either embedded as ingredients in other food products or as enriched nutritional supplements, are generally considered as safe, due to their origin from natural food sources, however, as shown earlier for the β-carotene supplements, even dietary supplements ought to be evaluated carefully.

2.5 Microencapsulation in functional foods

Similar to traditional encapsulation methods where a shell material protects a sensitive core, e.g. chocolate covered peanuts to reduce exposure to surrounding oxygen and occurring rancidity, microencapsulation shows the same technological advantages for ingredients on a much smaller scale. Also here, the same technological advantages which are achieved by microencapsulating certain ingredients, are that the capsule protects the core material against degradation, or reaction with other ingredients, and at the same time protects the food from any unwanted flavour of the ingredient. Furthermore, encapsulated ingredients, either in dry or liquid form (e.g. solid dry powders or structured emulsions), can easily be added to food items during most processes and achieve a homogeneous distribution. Another technological advantage is the possibility of a delayed or controlled release of the ingredient from the capsule, which can be triggered by various methods (e.g. time, pressure, temperature, pH, water activity, physical force / chewing, time, enzymes, etc) (de Vos et al., 2010). Food structures can be used directly as a delivery vehicle for a functional ingredient, if the bioactive substance can be included and is protected sufficiently. If further protection is required, the active molecule can first be encapsulated (in solid or liquid form) and then be added to the food system (Ubbink & Krüger, 2006). However, the use of these functional ingredients should not alter the product's structural properties, and so a specifically developed ingredient is needed for each individual product. (de Vos et al.,2010). In order to overcome the technological issues related to added bioactive ingredients in food products, microencapsulation is now a state-of-the-art technology for manufacturers. The successful encapsulation of active nutrients or non-nutrients in powder or liquid form, as it has been initially developed by the pharmaceutical and chemical industry to protect pharmaceutical active ingredients or other chemical compounds, has been demonstrated (Palzer, 2009).

2.5.1 Overview on microencapsulation technology

In the same way as food packaging methods are designed to protect a food item against any unwanted spoilage, and microencapsulation is essentially a packaging technology on a smaller scale, a microencapsulated food ingredient has to be adapted and developed to suit the product conditions, in terms of chemical composition, processing factors, application and storage methods. With the range of different encapsulating methods and materials available, it is possible to develop and manufacture a great range of functional ingredients. Table 6 gives an overview of shell materials applied in common microencapsulated ingredient products. By applying different shell materials and encapsulation methods, the microcapsules can be produced with specific attributes, e.g. particle size, shape, point and trigger of intended core release (Kirby, 1991). However, it is typical that the capsulation process for each intended application has to be designed specifically, and this is determined by the functionality of the ingredient and the surrounding matrix. The food product itself, the suitable coating material, the point and trigger of core release, the environmental conditions the capsule must be able to withstandand the suitable size of the capsule determine a technological viable application (Chen, 2004). Being widely applied in the pharmaceutical industry, the much smaller profit margins in the food industry are also playing an important role when considering the use of an encapsulated ingredient. The coating material itself has to demonstrate certain properties, which allows it to be applied in a coating process in terms of temperature resistance and rheological properties (Drush, 2011).

Furthermore the encapsulant, i.e. the coating material needs to be inert to the core material and at the same time be able to protect the core during processing or storage. One of the aspects of highest importance when choosing a coating material is its acceptance in a food product, in other words, the coating material should not lead to a negative effect on the food product and it has to be food grade throughout its production and application (Gibbs, 1999).

Technologies	Benefits	Applications	Limitations
High pressure treatment / ultra high pressure treatment	No formation of unwanted compounds (products from heat treatment); Best preservation of natural nutritional value, flavour, appearance, texture; possible production of safe food	Successful treatment (sterilisation) of products which are highly prone to spoilage and damage through processing (e.g. fresh dairy products, meat, seafood, fruit and vegetable)	High process costs (Investment and maintenance); Available equipment mostly batch processes

	(microbiological safety) with highest quality (nutritional and sensorial)		
Freeze drying	Good preservation of products characteristics and applicable to a large product range	Applied in products with fragile texture where natural ingredients (e.g. flavours) need to be protected. E.g. fruits as ingredients for high value applications	Formation of certain heat induced substances; Limited microbiological safety; High production costs
Pulsed electric field	Gentle processing, though cell disintegration (if desired); No formation of unwanted compounds (products from heat treatment);	Applications for wide product range, solid and liquid product processing	Missing heat treatment limits microbiological safety (spores); Missing enzyme inactivation; Cooled storage is required
Membrane filtration / ultrafiltration	No formation of unwanted compounds (products from heat treatment);	As additional treatment in milk pasteurisation (overall smaller temperature treatment possible)	Only for liquid products; High energy costs

Table 5. Examples for novel food processing methods

Ingredient category	**Coating materials**	**Widely used methods**	**References**
Carbohydrates	Starch, maltodextrins, chitosan, corn syrup solids, dextran, modified starch, cyclodextrins	Spray and freeze drying, extrusion, coacervation, inclusion complexation	Godshall,1988; Flink & Karel, 1970; Reineccius & Coulter, 1989; Reineccius, 1989 Reineccius, 1991
Cellulose	CMC (Carboxymethylcellulose, methyl cellulose, ethylcellulose, celluloseacetate-phthalate	Coacervation, spray drying, edible film coatings	Greener & Fennema, 1989a; 1989b;
Gums	Gum acacia, agar, sodium alginate, carrageenan	Spray drying, gel beads	Dziezak, 1991
Lipids	Wax, paraffin, beeswax, diacylglycerols, oils, fats	Emulsion, liposomes, film formation	Kampe & Fennema, 1984; Kim & Baianu, 1991
Protein	Gluten, casein, gelatin, albumin, peptides	Emulsion, spray drying	Ono, 1980

Table 6. Examples for applied coating materials used for functional food ingredients (adapted from Desai & Park, 2005)

In the production of these ingredients, certain attention has to be paid to the encapsulation itself and how the coating material is applied onto the core. Only an intact capsule can protect and hold the core sufficiently and often this shell is applied in multiple layers. In order to form this suitable shell, the coating material has to be applied by a specific process, designed for the coating material (Kim & Baianu, 1991). Typical processes for encapsulating functional micronutrients and bioactive ingredients are listed in Table 7. In general, the applied processes of encapsulation can include emulsification and extrusion, coacervation, liposome entrapment, spray drying, spray cooling, spray chilling, fluidized bed coating, etc. (Desai et al., 2005). The variety of food ingredients can range from ingredients which are important for the food processing and production, e.g. microorganisms, flavours, sweeteners, colorants, lipids, micro / macro nutrients, enzymes, but also more and more novel ingredients with positive effects on human health are produced for functional foods. Functionality of time delay can also be desired to achieve a slow release.

2.5.2 Physical structure of microencapsulated food ingredients

The appearance of an encapsulated food ingredient can be described as a core material (the functional ingredient, usually purified and/or stabilised by another carrier substance), which is surrounded by a mono or multi layer shell of a suitable material (Bakan, 1973; Shahidi & Han, 1993). The bulk ingredient can be in liquid, paste or solid / dry powder form, according to the nature of the core ingredient, the shell material, the applied production method and intended usage, and range in size from submicrometer to several millimetres. The protection is given by certain membranes and a multiple protective layer. In this case, the shell protects the inner core and environment to some extent against mechanical damage and also against environmental conditions. These microcapsules may have a multitude of different shapes, depending on the materials and methods used to prepare them (Dziezak, 1998).

An example for the technical process of encapsulation in the dry form is the encapsulation of bioactive compounds into powder form by spray granulation. Herein, the bioactive compounds, e.g. carotenes as colourant, are in liquid solution and sprayed onto inert core particles, e.g. sugar crystals with a specific size classification, where the solution then dries and forms layers around the solid particle. An additional protection layer can be applied. For the encapsulation of lipophilic vitamins (A, D, E, K), spray chilling is widely used. The bioactive compounds, being dissolved in oil and emulsified with a gelatine solution, is sprayed onto a powder bed, fluidized by cooled air, and solidified around the particles. The obtained particles are then further dried in a fluidized bed dryer/cooler. Other ingredients, e.g. hydrophilic substances, demand different processing conditions where heat energy is applied in order to form a dry coating of the sprayed liquid onto the particles by removal of the solvent, e.g. water. In the production of these various particles, also agglomeration has to be controlled, as it has to be avoided or it is intended to take place. For instance, the addition of fine starch powder into the fluidized bed after encapsulation does function against agglomeration. Beside these methods for producing dry powder particles, also liquid / semisolid capsules have their applications and one common example for their production is coacervation. In order to achieve this, the bioactive ingredient is mixed in liquid phase and blended with a second liquid, containing a shell-forming material such as alginates and other ingredients which are prone to gel formation. The spontaneously formed capsules or micro spheres are for further processing by spray chilling or spray drying for easy handling (Desai & Park, 2005).

2.5.3 Microencapsulation of polyphenols and carotenoids

With the development of microencapsulation and its adaption to the food industry, polyphenols and carotenoids as bioactive ingredients are readily available for a wide range of products and with various purposes. The main trend for growing and at this time relevant application of bioactive compound encapsulation is to deliver health-beneficial ingredients to functional foods. An important role for consumer health, disease prevention and even treatment is being played by nutraceuticals of a natural source of especially phytochemicals (Howells, et al., 2007).

In the determination of a suitable encapsulation method for carotenoids, the specific food system determines the initial basis on which to decide. The specific food production process has to be taken into account, as well as the food characteristics (dry / liquid product), sensory aspects, production costs, bioavailability of the carotenoids after storage, and consumption. Furthermore, the market requirements and local legislation have to be taken into account. Several encapsulation methods have demonstrated their suitability to encapsulate carotenoids (including β-carotene, lycopene, astaxanthin, zeaxanthin and lutein, which are common ingredients used for food coloration and added nutritional value due to their antioxidant behaviour), e.g. various emulsification processes, high pressure homogenisation, liposome entrapment, micro beads production, spray drying and freeze drying (Ribeiro et al., 2010). Studies have shown that the encapsulation of polyphenols does protect their functionality and stability, and furthermore can induce a health benefit by tailoring the encapsulation / release mechanism for an increased bioavailability (de Vos et al., 2010). For example, Lycopen has been encapuslated using emulsion technology to enhance to solubility and bioavailability. As with other functional food ingredients, which are currently in the focus of attention due to their health beneficial properties, most encapsulation methods available have been adapted successfully to polyphenols and an extensive summary of these methods is given by Fang & Bhandari (2010). These produced ingredients result in a wide variation of possible morphologies, structures and characteristics and so yield a great range of possible applications.

Polyphenols, carotenoids, and also other food components with the potential to constitute further upcoming nutraceuticals, in relation to the growing knowledge on their functional properties and health benefits, will play an important role in the development of novel food products with an added health benefit. Further improvements in their manufacturing technologies, stabilization and controlled bioavailability will aid to a growing number of health food products in the future. Research and development activities will most likely focus on adapting and exploiting further delivery methods, encapsulated products with ingredient combinations tailored to nutritional needs, and a cost efficient production for a mass market.

2.5.4 Controlled release mechanism and delivery of bioactive ingredients

The advantage of supplying a food, fortified with a bioactive ingredient, has been described earlier and the advantage of a controlled release has been stated. As the extensive

Ingredient Category	Substance examples / Food ingredient	Preferred encapsulation method	Food applications / Benefits
Acidulants	Lactic acid, glucono-δ-lactone, vitamin C, acetic acid, potassium sorbate, sorbic acid, calcium propionate, sodium chloride	Fluidized-bed coating, extrusion	Applied to assist in the development of colour and flavour in meat emulsions, dry sausage products, uncooked processed meats and other meat containing products. Acids and baking soda is used in wet and dry mixes to control release of carbon dioxide during processing in the bakery industry.
Flavouring agents	Citrus oil, mint oils, onion oil, garlic oil	Inclusion complexation, extrusion, spray drying	To transfer liquid flavourings into easy to handle and stable free flowing powders.
Sweeteners	Sugars, artificial sweeteners (e.g. aspartame)	Co-crystallization, fluidized-bed coating	To reduce hygroscopicity, resulting in an improved flowability. Prolonged sweetness perception.
Colorants	Annatta, β-carotene, turmeric	Extrusion, emulsion	For easier handling and improved solubility. Protection from oxidation and improved application in dry mixing.
Lipids	Fish oil, linolenic acid, rice brain oil, egg white powder, sardine oil, palmitic acid	Spray drying, freeze drying, vacuum drying	To prevent ingredient from oxidation during storage and processing.
Vitamins and minerals	Vitamin A, D, E, K (fat soluble) Vitamin C, B1, B2, B6, B12, niacin, folic acid (water soluble)	Coacervation, inclusion complexation, spray drying, liposome	Reduction of off-flavours. To control release time. To enhance stability. To protect from interaction with other ingredients.
Enzymes and microorganisms	Lipase, invertase, *Brevibacterium linens, Penicillium roqueforti*	Coacervation, spray methods, liposome	To improve stability and control time and point of release.

Table 7. Examples for microencapsulated food ingredients (adapted from Desai & Park, 2005).

knowledge base generated by the pharmaceutical industry during the development of drug delivery systems is of great advantage to the development of food grade delivery systems, these systems can be specifically designed in order not to negatively affect the food product properties. At the same time, they will be able to deliver the desired compound to the specific point within the human body, e.g., mouth, stomach, small intestine or colon (McClements et al., 2008; McClements et al., 2009a; Ubbink et al., 2008). As bioactive ingredients, encapsulation materials and the food matrix can alter considerably during processing, storage, consumption and digestion, e.g. changes caused by pH, ionic strength, surface activities, enzymatic activities (lipases, proteases, amylases), force and flow profiles (pressure, disruption, agitation) associated with chewing, stomach and intestine passage (Armand et al., 1997, 1999; Van Aken, 2007), the ingredient may benefit from associate changes such as degradation due to acid pH, cleavage by enzymes such as deglycosylase, complexation by other dietary ingredients, and other related physiochemical changes. Furthermore, one of these digestive impacts can be applied as the trigger for the release of the encapsulated bioactive ingredient. For example, pancreatic proteases may act as an agent dissolving a capsule designed to resist acidic pH and pepsin in the stomach.

To describe these food and drug delivery methods, several mathematical models have been developed (Pothakamury & Barbosa-Canovas, 1995; Siepmann, J. & Siepmann, F., 2008) and with detailed knowledge of parameters such as particle size, active ingredient concentration within the particle and in the surrounding matrix, and diffusion coefficients, these models can be applied to aid in the understanding of the process kinetics. The amount of empirical data available for drug delivery is vast, however, similar databases for food ingredients are still missing and relevant data is just emerging (Sereno et al., 2009). Controlled release of phytochemicals from encapsulated stages has been reported (Augustin et al., 2001; Augustin, M. A. & Sanguansri, L., 2008; Chen et al., 2006; Narayanan et al., 2009; Weiss et al., 2008; Dziezak, 1998).

Designing food structure to control stability, digestion, release and absorption of lipophilic food components and the available release mechanisms allow a wide range of applications in the development of functional food ingredients (McClements et al., 2008). the context is with the previous and next sentence together, that these are all points for future consideration in product development. The developed knowledge, together with deeper understanding of the relations between food properties and bioactive ingredient adsorption, is aiding in the design of food materials and encapsulation methods which, after protecting the ingredient, give controlled release at specific points in the gastrointestinal tract (Augusin et al., 2011; Hejazi & Amiji, 2003; McClements, et al., 2009b).

3. Conclusion

The world continues to face the increasing burden of dietary and life-style related diseases and of the increasing aging population. This results in increased interest and consumer demand for fortified healthy food products. Phytochemicals as natural sources of health-promoting ingredients have been extensively studied by scientists. Great opportunities for developing foods fortified with these active ingredients are rapidly arising for food manufacturers, including ADD. Although, these future food products, with fortified bioactive ingredients, can improve and maintain a nutritional balance, the use of phytochemicals, nutraceuticals and functional foods requires a deep knowledge and understanding of the complex physicochemical processes that occur within food and on effective strategies to design foods that can increase the bioavailability of valuable bioactive ingredients. Scientists, food and pharmaceutical industries are not only required to address quality and stability of functional foods, but also to improve the consumer education on the efficiency and safety of dietary supplements and functional foods, which claim to be health promoting. These are still existing issues that functional food designers and manufacturers need to face.

From the perspective of food technology, and as well as far as functional food products are concerned, the future research lies in novel food processing methods, food design and the understanding of the relations between bioactive ingredients release (specifically aimed at microencapsulation development for bioactive compounds to meet specific needs of food applications), personalized nutrition, processing technology with improved efficiency, sustainable production, while environmental friendly packaging also is of concern. The key findings of these activities provide an opportunity to engineer functional foods with increased health-promoting benefits.

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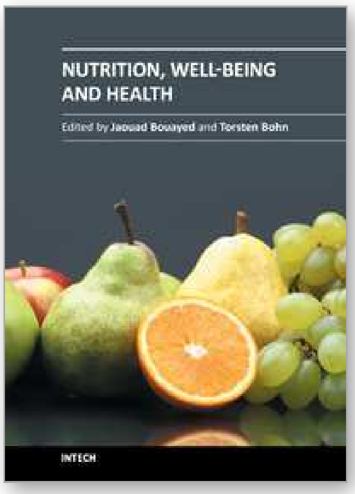

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