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Overview of Nano- and Microencapsulation for Foods

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1.1 Introduction

Nano- or microencapsulation technology is a rapidly expanding technology offering numerous beneficial applications in the food industries. Nano- or microencapsulation technology is the process by which core materials enriched with bioactive compounds are packed within wall materials to form capsules. This method helps to protect many functional core compounds, such as antioxidants, enzyme, polyphenol, and micronutrients, to deliver them to the controlled target site and to protect them from an adverse environment (Gouin, 2004; Lee *et al*., 2013). Based on the capsule size, the name and the technology of the encapsulation are different: the capsules which range from 3 to 800 μm in size are called microcapsules and the technology is called microencapsulation technology (Ahn *et al*., 2010). If the particle size ranges from 10 to 1,000 nm, these are called nanospheres and the technology involved to encapsulate the bioactive compounds within the nano size range is termed nanoencapsulation technology (Lopez *et al*., 2006). Nanocapsules differ from nanospheres when the bioactive systems are dispersed uniformly (Couvreur *et al*., 1995). The development of the nanotechnology on the nanometer scale has led to the development of many technological, commercial, and scientific opportunities for the industry (Huang *et al*., 2010).

Application of nanotechnology in the food industry involves many characteristic changes on the macroscale, such as texture, taste, and color, which have led to the development of many new products. This also improves many functions, such as oral bioavailability, water solubility, and the thermal stability of functional compounds (McClements *et al*., 2009). It is claimed that the functional compounds provide many health benefits in the prevention and treatment of many diseases, and these compounds can easily be seen on the market in various forms. However, the sustainability of the

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Table 1.1 Nano-encapsulation techniques of various functional materials.

Techniques	Functional compounds	Coating materials	Particle size (nm)	References
Emulsification	Pine seed oil (L)	W: Eudragit L 100-55	457–1,288	Averina and Allémann., 2013
	d-Limonene (L)	W: maltodextrin; E: modified starch (Hi-Cap 100)	543–1,292	Jafari *et al.*, 2007
	Flax seed oil (L)	E: Tween-40	135	Kentish *et al.*, 2008
	Sunflower oil (L)	E: Tween-80, Span-80, and sodium dodecyl sulfate	40	Leong *et al.*, 2009
	Salmon oil (L)	O: marine lecithin, α-tocopherol, quercetin, chloroform, methanol, diethylic ether, hexane	160–207	Belhaj *et al.*, 2010
	Curcumin (L)	E: Tween-20, ethyl acetate	125–1083	Souguir *et al.*, 2013
	MCT (L)	W: OSA starch, chitosan, and lambda-carrageenan	130	Preetz *et al.*, 2008
Inclusion complexation	DHA (L)	W: beta-lactoglobulin and low methoxyl pectin	100	Zimet and Livney, 2009
	Curcumin (L)	W: β-cyclodextrin	260–300	Sun *et al.*, 2013
	Linoleic acid (L)	W: α- and β-cyclodextrin	236	Hadaruga *et al.*, 2006
Emulsification–solvent evaporation	α-Tocopherol (L)	E: Tween-20	90–120	Cheong *et al.*, 2008
	Quercetin	W: poly-d,l-lactide	170	Kumari *et al.*, 2010
	Quercetin	W: poly-d,l-lactide and polyvinyl alcohol	250	Kumari *et al.*, 2011
	Phytosterol (L)	E: Tween-20; other materials: hexane, isopropyl alcohol, ethanol, and acetone	50–282	Leong *et al.*, 2011
	Astaxanthin	E: sodium caseinate	115–163	Anarjan *et al.*, 2011
	β-carotene (L)	E: Tween-20	9–280	Silva *et al.*, 2011
Coacervation	Capsaicin (L)	W: gelatin, maltodextrin and tannins; E: Tween-60; other material: glutaraldehyde	100	Wang *et al.*, 2008
	BSA (H)	W: gelatin, acacia, and tannins; E: Tween-60; other material: glutaraldehyde	200–580	Gan and Wang, 2007
	Curcumin (L)	E: palmitic, myristic	<300–500	Chirio *et al.*, 2011
	Capsaicin (L)	W: gelatin, acacia, and tannins; E: Tween-60; other material: glutaraldehyde	100	Jincheng *et al.*, 2010

delivery of functional bioactive compounds to the target site is very low, particularly lipophilic compounds. Improving the availability of the functional compounds enhances the absorption of the functional compounds in the gastrointestinal tract, which is a critical requirement. The development of nano- or microencapsulation technologies offers possible solutions to improve the bioavailability of many functional compounds (Chau *et al*., 2007). The methods used to develop the encapsulation technologies, to enclose the functional compound encapsulated along with its applications in food, and its regulatory framework are described in various chapters in this volume.

1.2 Nano- or microencapsulation as a rich source of delivery of functional components

Nano- or microencapsulation techniques are one of the most interesting fields in that they can act as a carriers or delivery systems for functional components, such as antioxidants, flavor, and antimicrobial agents (Wissing *et al*., 2004; Sanguansri and Augustin, 2006; McClements *et al*., 2009; Weiss *et al*., 2008). The major functional compounds that often need to be incorporated in foods can be divided into four categories: (1) fatty acids (e.g., omega three fatty acids); (2) carotenoids (e.g., β-carotene); (3) antioxidants (e.g., tocopherol); and (4) phytosterols (e.g., stigmasterol). Table 1.1 shows a list of functional compounds that have been encapsulated into nano- or microemulsion systems, their expected benefits, and their fields of application. Applications of the nano- or microencapsulation technologies in the food industries are mainly based on the stability of the capsules. During various environmental conditions, such as chilling, freezing, and thermal processing, which commonly occur during food processing, the capsules are susceptible to instability. The properties of physical stability are at different levels during the encapsulation process, such as stability required in the food ingredients or in the food matrix. Furthermore, stability also varies with the type of food system in which it is incorporated (McClements *et al*., 2009).

1.3 Wall materials used for encapsulation

Nano- or microencapsulation techniques are mainly used in the delivery of functional compounds to the target sites and largely depend on the carrier wall materials used. The effectiveness of the functional compounds wholly depends on the preservation of the compounds (Chen *et al*., 2006). Microencapsulation greatly helps in the delivery with a suitable wall material, however, reducing the particle size to the nanosize greatly increases the delivery properties due to the increase in surface area per unit volume (Shegokar and Muller, 2010). Based on solubility, the functional compounds used for encapsulation can be classified as either lipophilic or hydrophilic. Water-soluble functional compounds which are insoluble in lipids or organic solvents are termed hydrophilic functional compounds. The hydrophilic functional compounds are listed as polyphenols, ascorbic acids (Lakkis, 2007; Dube *et al*., 2010). Functional compounds which are insoluble in water and soluble in lipids and organic solvents are termed lipophilic which includes lycopene, and β-carotene (Zimet and Livney, 2009; Leong *et al*., 2011). In the polymeric matrix system, the solubility also determines the release rate of their functional compounds. A hydrophilic compound shows a faster release rate and low permeability, which is absorbed by active transport. Lipophilic compounds show high permeability through the intestine and are absorbed by active transport, and facilitate diffusion with a lower release rate (Varma *et al*., 2004; Kuang *et al*., 2010). Various kinds of wall materials are used in the delivery of functional lipophilic or hydrophilic compounds for nano- or microencapsulation techniques. The polymers, such as albumin, globulin, maltodextrin, chitosan, ethylcellulose gelatin, starch, and chitosan are used in the delivery systems (Reis *et al*., 2006). Bioavailabilities of functional compounds were greatly increased with the development of the nanocarrier system, such as whey protein. Nanotechnology also greatly increases the delivery of vitamins and minerals to the mucosal systems (Chen *et al*., 2006).

1.4 Techniques used for the production of nano- or microencapsulation of foods

Functional compounds and wall material properties, such as particle size, size distribution, encapsulation efficiency, shape, and solubility, are altered by the techniques used for the encapsulation. Therefore, it is important to select the proper technique based on the requirement of either nano- or microencapsulation. Nanoencapsulation techniques are more complex than the microencapsulation process. Numerous techniques have been used in the preparation of the microencapsulation process (Figure 1.1). However, coacervation, nano-precipitation, inclusion complexation, and supercritical fluid

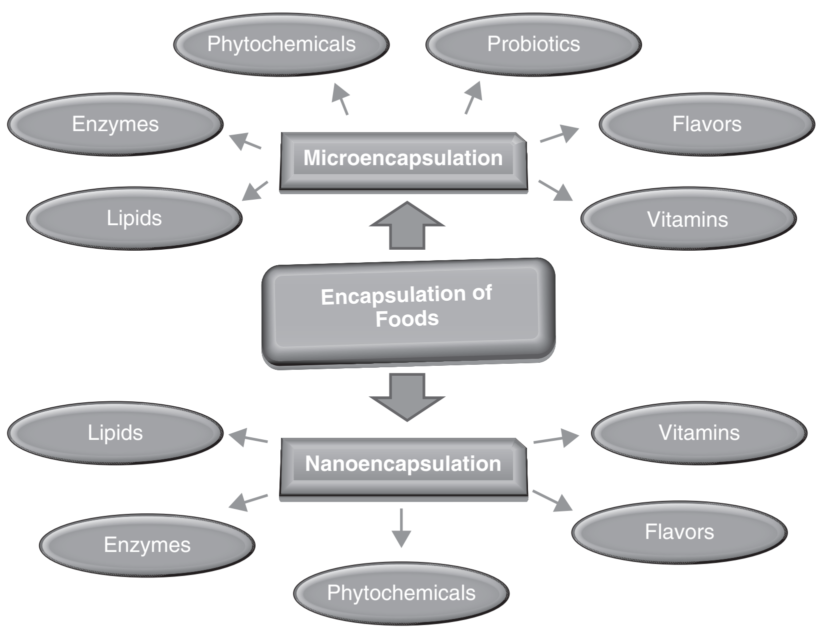

Figure 1.1 Schematic representation of encapsulation of foods.

extraction techniques are considered the nanoencapsulation techniques which can produce capsules in the nano range. The size reduction of the capsules is mostly achieved by the emulsification and emulsification solvent evaporation which has no impact on any other factor, such as pH and temperature. Coacervation, the supercritical fluid technique, and the inclusion complexation also help size reduction; however, it largely depends on other factors, such as pH and temperature. Coacervation and supercritical fluid extraction are used for encapsulation of both hydrophilic and lipophilic compounds, whereas emulsification-solvent evaporation and inclusion complexation are largely used for the lipohilic compounds (Reis *et al*., 2006; Leong *et al*., 2009). The major problems of the micro- or nanocapsules are irreversible aggregations and leakage of functional compounds, and that it is necessary to dry the compounds for better stability of these compounds. Freeze-drying and spray-drying techniques are the most commonly used techniques for the stable release of functional compounds (Choi *et al*., 2004). Drying increases greater stability compared to the original suspension, and it can sustain the functional compounds for long storage periods (Guterres, 2009).

1.5 Characterization of nano- or microencapsulated functional particles

Characterization of nano- or microcapsules is an important way to understand the functional aspects of the bioactive compounds. A number of techniques are involved in the characterization of both kinds of capsules, such as high performance liquid chromatography (HPLC), field flow fractionation, laser diffraction, online photon correlation spectroscopy, mass spectrometry, scanning electron microscopy (SEM), transmission electron microscopy (TEM), etc. Every technique has its own advantages and disadvantages in the characterization of the capsules. Laser techniques can be used to measure the particle size and particle size distribution in a wide range from 0.02 μm to a few millimeters with rapid accuracy. A dynamic light scattering technique (DLS) is usually applied to measure the particle size of emulsions, micelles, polymers, proteins, nanoparticles, or colloids in the range from 5–1000 nm. Acoustic spectroscopy is able to determine the particle size of nano- and microcapsules at high concentrations from 1 to 50% (v/v) depending on the nature of the system, due to the use of sound waves, which interact with particles in a similar manner to light, but have the advantage that they can travel through concentrated suspensions. Nuclear magnetic resonance (NMR) is a powerful and complex analytical tool that allows the study of compounds in either a liquid or a solid state, and serves equally in quantitative as in structural analysis. Small-angle X-ray scattering (SAXS) is a technique for the study of structural features of colloidal size particles where the elastic scattering of X-rays in a sample that has non-homogeneities in the nanometric range, is recorded at very low angles (typically 0.1–10°). The morphology of both nano- or microcapsules is observed by various microscopy techniques which have various limitations on the size view, such as an optical microscope that has a resolution limit of about 100–200 nm, and TEM has a resolution limit of <1 nm to ~ 100 nm. Thus, imaging techniques enable the various sizes of the nano- or microcapsules to be measured accurately. Detailed characterization of nano- or microcapsules is listed in Chapter 4.

1.6 Fortification of foods through nano- or microcapsules

Nano- or microtech companies are trying to enhance their food products with nano- or microencapsulated nutrients; the taste and appearance are enhanced by the nano- or microencapsulated functional ingredients or by reducing the original nutrient content of fat or sugar and by improving the mouth feel of the product. The fortification of foods with functional food ingredients will soon be seen on the market with an increase in nutritional claims, such as medically beneficial nano- or microcapsules as alternative healthy foods. Nanoparticles will also enable the production of healthy junk foods, that now are rich in fats, such as ice-cream and chocolate, by preventing the absorption of fats and sugar. They can enhance the market share of calorie-rich foods fortified with vitamins and fibre-fortified as a health enhancer by weight reducing (Miller, 2008). Most food polymers are nanosized, which include lipids and polysaccharides composed of linear polymers, whereas proteins are of globular polymers of a size of 1–10 nm. Their functionality is greatly enhanced by the encapsulation or reduction of their size to nanoforms of self-assembled nanostructures (Chen *et al.*, 2006). Recently nanoceuticals have claimed to have more health benefits in the food industries; some recent health claims includes fortification of carotenoids' nanoparticles in fruit drinks, enhancement of selenium intake by Chinese nanotea, and enhancement of mineral uptake by nanosilver or nanogold. Although nano- or microencapsulation technologies have been used for several years in other sectors, food utilization is very limited and it is compromised by the very limited array of functional, generally recognized as safe (GRAS) encapsulating agents and technologies.

1.7 Nano- or microencapsulation technologies: industrial perspectives and applications in the food market

Over the last few decades, nano- or microencapsulation technology has developed into a large-scale business, becoming a multimillion market with the impact of nano- or microtechnology. It will employ more than 1.5 to 2 million workers and the expected business trade will come to about 0.5 to one trillion U.S. dollars by 2015 (Neethirajan and Jayas, 2011). From the evidence of various analyses, patent applications, and paper reports, the nano- or microencapsulation technologies have a large impact on different food aspects and associated industries (Neethirajan and Jayas, 2011). Research also differs based on the companies and location, according to the research by Lux, the nanotechnology industry was expected to grow about 2.6 trillion US$ in manufactured products by the year 2014. According to the U.S. Department of Agriculture (USDA), the global impact of nanoproducts will be 1 trillion US$ annually by 2015. In the food and drink sector, it might reach about 3.2 billion US$ in 2015 (UK, 2010). A recent report suggested that there may be about 400 companies involved in the nanosize production of food materials (Neethirajan and Jayas, 2011). This number was expected to reach about 1000 by 2015 (Joseph and Morrison, 2006). The sale, the growth, the types, and the benefits of functional food are shown in Figures 1.2, 1.3 and 1.4. Nano- or

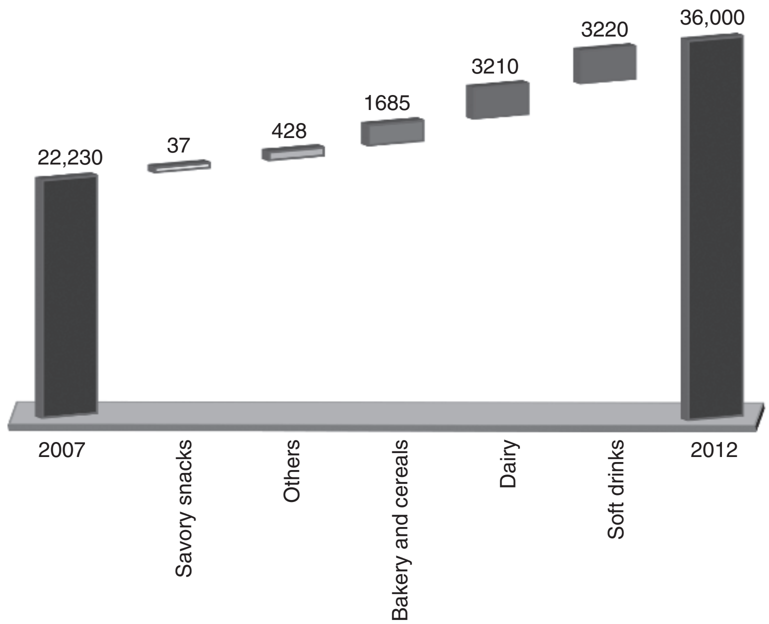

Figure 1.2 Varieties of functional food sales growth from 2007 to 2012 (US$).

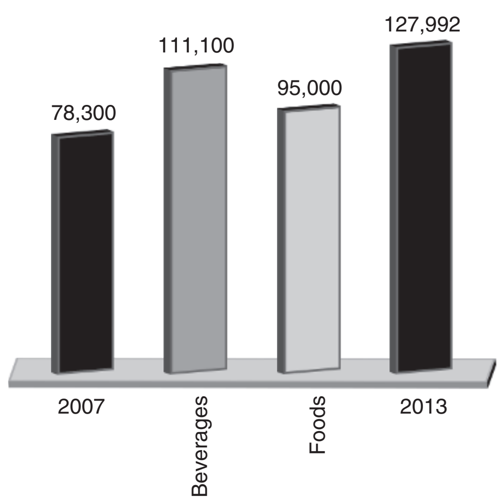

Figure 1.3 Type of functional food sales growth from 2007 to 2012 (US$).

microencapsulation production for the encapsulation of various functional compounds is one of the emerging fields in encapsulation applied to the food industry. Some of the applications are given below and detailed studies are provided in the chapters in this volume. Various functional compounds, such as vitamins A and E, isoflavones, phytosterols, lycopene, and lutein are available (NutraLease, 2011a). Their main technology involves the self-assembled nanoemulsions for their higher bioavailability to the human

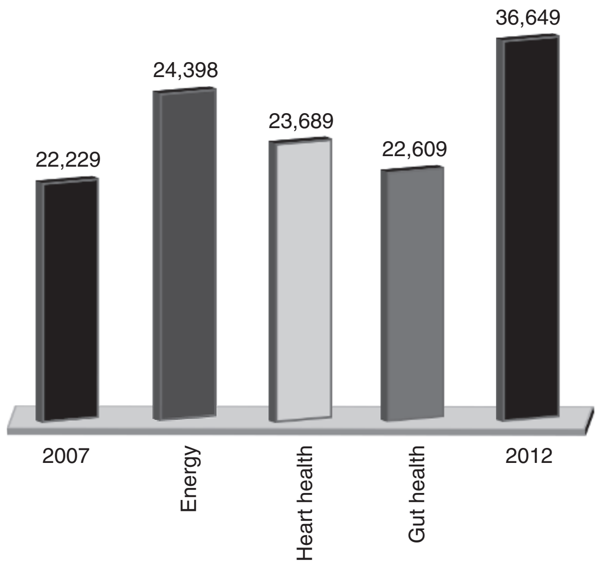

Figure 1.4 Benefit from functional foods sale growth from 2007 to 2012 (US$).

body, and better encapsulation can be achieved (NutraLease, 2011b). In addition to the availability of their functional compounds, nanotechnology can also protect the flavor compounds under various pHs and temperatures with higher stability (NutraLease, 2011c). Another company called Aquanova has produced novel beverage solutions with healthy functional compounds rich in co-enzymes, vitamins, and natural colorants. The novel encapsulated beverages are also stable under various environmental conditions with the standardized additive concentrations. Some multinational companies, such as Nestlé and Unilever, which are well known worldwide, are also developing functional foods using the encapsulation technologies, and their well-known products are low fat ice cream with 1% fat content.

In spite of various nano- or microencapsulation technologies being applied in the nano-industries, various countries lack regulatory systems and a framework in relation to the nanomaterials. The reason for most concern is their minute scale which can make them go deeper into the human body, thus being unable to be detected. Before various health risks from consumption of nanoproducts surface, the countries where regulations are still lacking regarding these technologies should be identified. Even though legislation is still being adapted, other actions may be taken to improve consumer trust in the food encapsulated with nano-sized particles.

1.8 Overview of the book

There have been very few publications available on the nano- or microencapsulation of bioactive and nutraceutical compounds in food, and the characterization of nanoencapsulated foods, therefore, toxicity studies, and their regulations have not received much research attention. This book is therefore unique as it also extensively covers bioactivity, toxicity, and the regulations regarding nano- or microencapsulated foods by internationally renowned scientists who are at the forefront of research into nano- or microencapsulated foods and their toxicity and regulations. It represents the best available current knowledge and up-to-date information written by world authorities and experts in the field of nano- or microencapsulation of various functional compounds.

This book will be of interest to readers around the world, including health-conscious consumers, students, and scientists who are looking for valuable scientific information on functional compound encapsulations with regards to health benefits. It not only contains rich compilations of a variety of current research data on nano- or microencapsulation for foods, but it also describes the functional compounds' benefits to health in consumption. Other integral aspects of regulations and toxicity are also included, such as the regulations on nano- or micro encapsulation of functional compounds in food in various countries.

Part I presents an overview of nano- or microencapsulation of various functional food materials, the wall materials used for the encapsulation, its characterization and its application in various food types. This part covers the rationales and concepts used in nanomaterials, nano- or microencapsulation of foods.

Chapter 2 by Jingyuan Wen, Guanyu Chen, and Raid G. Alany focuses on the concepts involved in nano- or microencapsulation for food, to present up-to-date references, research data, and scientific information in the field of encapsulation of food ingredients with respect to those beneficial to health. They discuss the technology, its significant advantages, the commonly used materials, fabrication techniques, and the factors influencing delivery system optimization for nutraceuticals. Some representative studies of nano- and microencapsulation of food ingredients via different delivery routes are reported.

Chapter 3 by Sundaram Gunasekaran and Sanghoon Ko discusses the rationales for the use of nano- or microencapsulation for foods.

Chapter 4 by Minh-Hiep Nguyen, Nurul Fadhilah Kamalul Aripin, and Hyun-Jin Park deals with common techniques used for determining the characteristics of nanoencapsulation. In particular, techniques, such as laser diffraction, dynamic light scattering, acoustic spectroscopy, sedimentation, microscopy, or image analysis, can be applied to measure particle size and particle size distribution. Electrophoretic light scattering and the electroacoustic technique are commonly used to determine the zeta potential of nano- and microcapsules. In addition, optical microscopy, confocal laser scanning microscopy, transmission electron microscopy, or scanning electron microscopy can be applied to observe the morphology of nano- and microcapsules. On the other hand, the membrane flexibility can be measured using fluorescence anisotropy, extrusion, or electron spin resonance. Moreover, the methods used to determine the stability of nano- and microcapsules are also discussed in this chapter. Finally, to measure encapsulation efficiency, there are two major steps (separation and analysis). However, the separation stage, in which nano- and microcapsules are separated from unencapsulated active ingredients, is usually more difficult than the analysis stage. Therefore, common techniques used in separation, such as centrifugation, filtration, size exclusion chromatography, and dialysis, are also introduced in this chapter. This chapter not only supplies general information about the common techniques used in the characterization of nano- and microcapsules, but also indicates that each technique has its advantages and disadvantages.

Chapter 5 by Mi-Jung Choi and Hae-Soo Kwak deals with the current strategies involved in the development of nano-materials, nano- or microencapsulation of foods. It presents an overview of current and projected applications of nano- or microencapsulation for food ingredients in the food and agricultural sectors. Overall, Part I deals with the encapsulation development from the micro-size to the nano-size from its beginnings to the current technologies used in its applications.

Part II looks closely at the various functional compounds for encapsulation, such as phytochemicals, probiotics, minerals, vitamins, and flavors and its application in various food products. Chapter 6 by Sung Je Lee and Marie Wong deals with the current trends in the encapsulation of phytochemicals and their application in the development of various functional beverages without affecting their physicochemical properties. Chapter 7 by Kasipathy Kailasapathy deals mainly with the microencapsulation of probiotics and its potential applications in various food products, including beverages, dairy products, meat products, and some vegetarian foods. Since probiotic bacteria are micro-sized, this chapter focuses mainly on microencapsulation. The current microencapsulation trends reduce the main problem of the survival rate of the microbes and in the near future these will overcome this and open the door to the marketing of these products. Chapter 8 by Florentine M. Hilty and Michael B. Zimmermann is mainly focused on the nanostructured minerals used in food and nutritional applications. Mineral deficiencies (e.g. iron, zinc, and calcium) are major global health problems affecting both low- and high-income countries. Correction of these deficiencies through food fortification and/or supplementation requires the application of mineral compounds that are stable when added to reactive food matrices and that are well absorbed. Nanostructuring of minerals may provide these performance characteristics. For example, the nanostructuring of poorly soluble iron compounds that cause little color change in foods, such as iron and zinc-containing phosphates, and oxides, sharply increases their solubility and their iron bioavailability. Similarly, nanostructured selenium and calcium compounds have characteristics that may allow them to be used as food fortificants and nutritional supplements. However, for most nanostructured minerals, there is a lack of data on potential gastrointestinal toxicity as well as long-term shelf-life in potential food vehicles. Future research will clarify whether these nanostructured minerals will prove useful for nutritional applications.

Chapter 9 by Ashok R. Patel and Bhesh Bhandhari covers the encapsulation of vitamins in foods. The encapsulation and stabilization of micronutrients, such as vitamins, have received increased attention from academic researchers and in particular from industrial scientists, due to their ease in industrial feasibility. In today's modern scenario, with increased consumer awareness and resultant increase in the demands for modern fortified food products, nano- and microencapsulation are considered an integral part of the product development in the food manufacturing industries. In this chapter, an overview of the formulation and delivery challenges associated with vitamins is discussed with respect to the need for their encapsulation in micro-/nanostructures. In addition, some of the latest developments in encapsulation of vitamins are detailed with the help of illustrated examples.

Flavor plays an important role in the appeal of food: It motivates us to eat and provides satisfaction during food consumption. Chapter 10 by Kyuya Nakagawa deals with the engineering aspects of nano- and microencapsulation of flavors in food systems. Flavor control is a challenge in food engineering; specifically, it is difficult to maintain the flavor at a desired level during processing and storage and to release it with the desired kinetics during consumption. Therefore, we must study the relationships between the nano- and microstructures in food systems and the flavor components. These investigations cover a wide variety of topics, including the chemistry of encapsulates and flavor molecules, the physical chemistry of the substances, the transport phenomena of flavors, the rheology of food systems, etc. We must also develop a technique to incorporate these functionalities into industry. In this chapter, methods of flavor stabilization in food nano- and microstructures first are reviewed, and then, mass transfer models that can be adapted to flavor components are explained. Finally, on the basis of practical encapsulation processes (i.e., spray-drying, freeze-drying, and coacervation), the relationships between nano- and microstructure formation and flavor retention are discussed.

Chapter 11 by Hae-Soo Kwak, Mohammad Al Mijan, and Palanivel Ganesan deals with the application of encapsulated food ingredients in the dairy foods industry. Dairy foods are a large sector where the application of encapsulated foods is employed. For the past few decades microencapsulated dairy foods have been well known in the world. Recently nanoencapsulated foods provide greater benefits by reaching the target site without affecting their properties. This chapter deals with the application of various plant-, and animal-derived functional ingredients in dairy foods, such as milk, yogurt, and cheese. However, still this field has some limitations due to toxicity and it is still at an early stage of development.

Chapter 12 by Loong-Tak Lim deals with the application of nano- and microencapsulated materials to food packaging. It covers the broad range of materials that are involved in packaging to protect the food materials with longer shelf-life, enhanced flavoring and color of the food product. Even though innovative technologies are involved in the smart packaging of the food, a regulatory framework is still needed to prevent toxic effects. Overall, Part II is the core section of this book and covers encapsulated food ingredients in a variety of its applications in the food industry.

Part III covers the controlled release, bioactivity, toxicity and regulation of nanomaterials and nano- and microencapsulated ingredients and discusses the regulations of nanoencapsulated foods in the major developed countries in the world. This provides an international perspective on the current knowledge of regulations for nano-supplemented foods in various countries. Chapter 13 by Sanghoon Ko and Sundaram Gunasekaran mainly deals with the controlled release of functional compounds to various target sites. The controlled release may be triggered by one mechanism, but it is involved in complex reactions and these are presented in full.

Chapter 14 by Soo-Jin Choi deals with recent development of nano- and microencapsulation systems for functional ingredients and nutraceuticals, focusing on enhancement of their oral bioactivity and bioavailability *in vivo*. Diverse materials and techniques have been applied to improve the oral absorption and the physiological functions of bioactive molecules that are generally insoluble in water and rapidly excreted from the body, though most studies have been limited to demonstrating physico-chemical characterization and *in vitro* stability experiments of the prepared nano- and microencapsulated nutraceuticals. This chapter will provide a new perspective on the design of efficient food ingredient delivery systems to enhance the bioavailability of functional food components.

Chapter 15 by Guanyu Chen, Soon-Mi Shim, and Jingyuan Wen is the only chapter which mainly deals with the toxicity of food ingredients loaded with nano- and microfood particles. Some basic factors can influence the toxicity of nano- and microparticles, such as the size, shape, solubility, and chemical components of the particles. Second, it discusses the behavior and health risk of nano- and microparticles in the gastrointestinal tract, including the behavior of the particles in the processes of absorption, distribution, metabolism, and elimination that influence toxicity. Third, the potential health implications associated with the use of nano- and microtechnology in the nutraceutical sector with representative *in vitro* and *in vivo* toxicity studies are reported. Lastly, the risk assessment of nano- and micromaterials in food applications, including hazard identification, hazard characterization and risk characterization, is also reviewed. However, as methods for detection and characterization of nano- and microencapsulation of food ingredients are not readily available, therefore, the claimed nano- and microscale character of the applications in the nutraceutical field cannot be verified, and the knowledge regarding recent products made with nano- and microencapsulated food ingredients relies on information provided by the producers or manufacturers.

In Chapter 16, Hyun-Kyung Kim, Jong-Gu Lee, and Si-Young Lee present the current knowledge of regulations of nanomaterials in the food systems in the world. The regulations differ between nations and these are clearly described in this chapter. Most regulations for nanomaterials will need to be unified across the different nations of the world in future.

In conclusion, this book highlights recent innovations in nano- or microencapsulation and the various functional ingredients in the food systems. In addition, it also provides some regulations developed for the encapsulation of functional ingredients in various food systems. Furthermore, it describes the controlled release mechanisms of functional ingredients encapsulated at various sizes in the food systems. This book also presents the future new possibilities of encapsulation of functional ingredients which will have a lot of economic implications in modern food processing technologies.

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References

Ahn, S.I., Chang, Y.H., and Kwak, H.S. 2010. Optimization of microencapsulation of inonotus obliquus extract powder by response surface methodology and its application into milk. *Korean Journal for Food Science of Animal Resources* 30, 661–668.

Anarjan, N., Mirhosseini, H., Baharin, B.S., and Tan, C.P. 2011. Effect of processing conditions on physicochemical properties of sodium caseinate-stabilized astaxanthin nanodispersions. *LWT-Food Science and Technology* 44, 1658–1665.

Averina, E. and Allémann, E. 2013. Encapsulation of alimentary bioactive oils of the Baikal Lake area into pH-sensitive micro- and nanoparticles. *LWT-Food Science and Technology* 53, 271–277.

Belhaj, N., Arab-Tehrany, E., and Linder, M. 2010. Oxidative kinetics of salmon oil in bulk and in nanoemulsion stabilized by marine lecithin. *Process Biochemistry* 45, 187–195.

Chau, C.F., Wu, S.H., and Yen, G.C. 2007. The development of regulations for food nanotechnology. *Trends in Food Science and Technology* 18, 269–280.

Chen, H., Weiss, J., and Shahidi, F. 2006a. Nanotechnology in nutraceuticals and functional foods. *Food Technology* 60, 30–36.

Chen, L.Y., Remondetto, G.E., and Subirade, M. 2006b. Food protein based materials as nutraceutical delivery systems. *Trends in Food Science and Technology* 17, 272–283.

Cheong, J.N., Tan, C.P., Man, Y.B.C., and Misran, M. 2008. α-Tocopherol nanodispersions: Preparation, characterization and stability evaluation. *Journal of Food Engineering*, 89(2), 204–209.

Chirio, D., Gallarate, M., Peira, E., Battaglia, L., Serpe, L., and Trotta, M. 2011. Formulation of curcumin-loaded solid lipid nanoparticles produced by fatty acids coacervation technique. *Journal of Microencapsulation*, 28(6), 537–548.

Choi, M.J., Briancon, S., Andrieu, J., Min, S.G., and Fessi, H. 2004. Effect of freeze-drying process conditions on the stability of nanoparticles. *Drying Technology* 22, 335–346.

Couvreur, P., Dubernet, C., and Puisieux, F. 1995. Controlled drug delivery with nanoparticles: Current possibilities and future trends. *European Journal of Pharmaceutics and Biopharmaceutics* 41, 2–13.

Dube, A., Ken, N., Nicolazzo, J.A., and Ian, L. 2010. Effective use of reducing agents and nanoparticle encapsulation in stabilizing catechins in alkaline solution. *Food Chemistry* 122, 662– 667.

Gan, Q. and Wang, T. 2007. Chitosan nanoparticle as protein delivery carrier: Systematic examination of fabrication conditions for efficient loading and release. *Colloids and Surfaces B: Biointerfaces* 59, 24–34.

Gouin, S. 2004. Microencapsulation: Industrial appraisal of existing technologies and trends. *Trends in Food Science and Technology* 15, 330–347.

Guterres, S.S. 2009. Spray drying technique to prepare innovative nanoparticulated formulations for drug administration: A brief overview. *Brazilian Journal of Physics* 39, 205–209.

Hadaruga, N.G., Hadaruga, D.I., Paunescu, V., Tatu, C., Ordodi, V.L., Bandur, G., and Lupea, A.X. 2006. Thermal stability of the linoleic acid/α- and β-cyclodextrin complexes. *Food Chemistry* 99, 500–508.

Huang, Q., Yu, H., and Ru, Q. 2010. Bioavailability and delivery of nutraceuticals using nanotechnology. *Journal of Food Science* 75, R50–R57.

Jafari, S.M., Assadpoor, E., Bhandari, B., and He, Y. 2008. Nanoparticle encapsulation of fish oil by spray drying. *Food Research International* 41, 172–183.

Jafari S.M., He Y., and Bhandari, B. 2007. Encapsulation of nanoparticles of d-limonene by spray drying: Role of emulsifiers and emulsifying techniques. *Drying Technology* 25, 1079–1089.

Jincheng, W., Xiaoyu, Z., and Siahao, C. 2010. Preparation and properties of nanoencapsulated capsaicin by complex coacervation method. *Chemical Engineering Communication* 197, 919–933.

Joseph, T. and Morrison, M. 2006. Nanotechnology in agriculture and food, Düsseldorf, Germany. Available at: http://www.nanoforum.org/dateien/temp/nanotechnology%20in%20agriculture%20and%20food.pdf?08122006200524 (accessed 10 May 2013).

Kentish, S., Wooster, T.J., Ashokkumar, M., Balachandran, S., Mawson, R., and Simons, L. 2008. The use of ultrasonics for nanoemulsion preparation. *Innovative Food Science and Emerging Technologies* 9, 170–175.

Kuang, S.S., Oliveira, J.C., and Crean, A.M. 2010. Microencapsulation as a tool for incorporating bioactive ingredients into food. *Critical Reviews in Food Science and Nutrition* 50, 951–968.

Kumari, A., Yadav, S.K., Pakade, Y.B., Kumar, V., Singh, B., Chaudhary, A., and Yadav, S.C. 2011. Nanoencapsulation and characterization of Albizia chinensis isolated antioxidant quercitrin on PLA nanoparticles. *Colloids and Surfaces B: Biointerfaces* 82, 224–232.

Kumari, A., Yadav, S.K., Pakade, Y.B., Singh, B., and Yadav, S.C. 2010. Development of biodegradable nanoparticles for delivery of quercetin. *Colloid Surface B: Biointerfaces* 80, 184–192.

Lakkis, J.M. 2007. *Encapsulation and Controlled Release Technologies in Food Systems*. Ames, Iowa: Blackwell.

Lee, Y.K., Mijan, M.A., Ganesan, P. and Kwak, H.S. 2013. The physicochemical properties of yoghurt supplemented with a possible functional ingredient microencapsulated peanut sprout extract. *International Journal of Dairy Technology* 66, 417–423.

Leong, T.S.H., Wooster, T.J., Kentish, S.E., and Ashokkumar, M. 2009. Minimising oil droplet size using ultrasonic emulsification. *Ultrasonics Sonochemistry* 16, 721–727.

Leong, W.F., Lai, O.M., Long, K., Yaakob, B., Mana, C., Misran, M., and Tan, C.P. 2011. Preparation and characterisation of water-soluble phytosterol nanodispersions. *Food Chemistry* 129, 77–83.

Lopez, A., Gavara, R., and Lagaron, J. 2006. Bioactive packaging: turning foods into healthier foods through biomaterials. *Trends in Food Science and Technology* 17, 567–575.

McClements, D.J., Decker, E.A., Park, Y., and Weiss, J. 2009. Structural design principles for delivery of bioactive components in nutraceuticals and functional foods. *Critical Review in Food Science and Nutrition* 49, 577–606.

Miller, G. 2008. Nanotechnology – the new threat to food. Available at: http://www.globalresearch.ca/PrintArticle.php?articleId=10755 (accessed October 30, 2008).

Neethirajan, S. and Jayas, D.S. 2011. Nanotechnology for the food and bioprocessing industries. *Food and Bioprocess Technology* 4, 39–47.

NutraLease (2011a). Available at: http://www.nutralease.com/Nutra/Templates/showpage.asp?DBID=1andLNGID=1andTMID=84and FID=767 (accessed 10 February 2013).

NutraLease (2011b). Available at: http://www.nutralease.com/Nutra/Templates/showpage.asp?DBID=1andLNGID=1andTMID=84and FID=769 (accessed 10 April 2013).

NutraLease (2011c). Available at: http://www.nutralease.com/Nutra/Templates/showpage.asp?DBID=1andLNGID=1andTMID=84and FID=768 (accessed 10 April 2013).

Preetz, C., Rube, A., Reiche, I., Hause, G., and Mader, K. 2008. Preparation and characterization of biocompatible oil-loaded polyelectrolyte nanocapsules. *Nanomedicine: Nanotechnology, Biology and Medicine* 4, 106–114.

Reis, C.P., Neufeld, R.J., Ribeiro, A.J., and Veiga, F. 2006. Nanoencapsulation I: Methods for preparation of drug-loaded polymeric nanoparticles. *Nanomedicine: Nanotechnology, Biology and Medicine* 2, 8–21.

Sanguansri, P. and Augustin, M.A. 2006. Nanoscale materials development:A food industry perspective. *Trends in Food Science and Technology* 17, 547–556.

Shegokar, R. and Muller, R.H. 2010. Nanocrystals: industrially feasible multifunctional formulation technology for poorly soluble actives. *International Journal of Pharmaceutics* 399, 129–139.

Silva, H.D., Cerqueira, M.A., Souza, B.W. S., Ribeiro, C., Avides, M.C., Quintas, M.A.C., Coimbra, J.S.R., *et al*. 2011. Nanoemulsions of β-carotene using a high energy emulsification–evaporation technique. *Journal of Food Engineering* 102, 130–135.

Silva, H.D., Cerqueira, M.A., and Vicente, A.A. 2012. Nanoemulsions for food applications: development and characterization. *Food Bioprocess Technology* 5, 854–867.

Souguir, H., Salaün, F., Douillet, P., Vroman, I., and Chatterjee, S. 2013. Nanoencapsulation of curcumin in polyurethane and polyurea shells by an emulsion diffusion method. *Chemical Engineering Journal* 221, 133–145.

Sun, X.Z., Williams, G.R., Hou, X.X., and Zhu, L.M. 2013. Electrospun curcumin-loaded fibers with potential biomedical applications. *Carbohydrate Polymers* 94, 147–153.

Varma, M.V.S., Kaushal, A.M., Garg, A., and Garg, S. 2004. Factors affecting mechanism and kinetics of drug release from matrix-based oral controlled drug delivery systems. *American Journal of Drug Delivery* 2, 43–57.

Wang, J.C., Chen, S.H., and Xu, Z.C. 2008. Synthesis and properties research on the nanocapsulated capsaicin by simple coacervation method. *Journal of Dispersion Science and Technology* 29(5), 687–695.

Weiss, J., Decker, E., McClements, D., Kristbergsson, K., Helgason, T., and Awad, T. 2008. Solid lipid nanoparticles as delivery systems for bioactive food components. *Food Biophysics* 3, 146–154.

Wissing, S.A., Kayser, O., and Müller, R.H. 2004. Solid lipid nanoparticles for parenteral drug delivery. *Advanced Drug Delivery Reviews* 56, 1257–1272.

Zimet, P. and Livney, Y.D. 2009. Beta-lactoglobulin and its nanocomplexes with pectin as vehicles for ω-3 polyunsaturated fatty acids. *Food Hydrocolloid* 23, 1120–1126.