# An Introduction to Food Nanotechnology 34

Chi-Fai Chau

## Contents



**Abstract**

Nanotechnology has been touted as the next revolution in many industries. It has offered enormous opportunities and provided new possibilities to many industries such as chemistry, materials science, medicine, and engineering. This emerging technology has also opened up a whole universe of new possibilities in the development and applications of nanotechnology in the food sectors. Considerable research efforts have highlighted the potential of nanotechnology in a wide range of food applications. While most nanotechnology-derived food products and applications are still at the early

C.-F. Chau (✉)
Department of Food Science and Biotechnology, National Chung Hsing University, Taichung, Taiwan, Republic of China
e-mail: chaucf@nchu.edu.tw



P.C.K. Cheung, B.M. Mehta (eds.), *Handbook of Food Chemistry*,
DOI 10.1007/978-3-642-36605-5_25

stage of research and development, food packaging and nanodelivery systems are relatively closer to be the promising sectors of the food industry. The diverse industrial applications in food and nutrition sciences may include the enhancement of uptake and bioavailability of nutrients and supplements, promotion of food safety and security, innovative tastes and textures, and preservation of quality and freshness. Future developments are limited only by the imagination. However, as novel properties and characteristics pose novel risks, uncertainty and risks of exposure for consumers to free engineered nanomaterials are emerging. Yet little is known about the impact of nanotechnology, especially engineered nanomaterials, on human health. From the food industry and public safety standpoints, it is anticipated that more scientific research in food nanotechnology will be conducted worldwide to fill the knowledge gaps and give more support to regulation and policy development for the safety and health of consumers and the environment.

## Introduction

Nanoscience and nanotechnology are the engineering and manipulation of materials at the molecular scales, far smaller than a cell. They are so small that they cannot be seen under a regular microscope. In the 1980s, the word nanotechnology was initially referring to an ability to build machines from the bottom-up approach on the scale of molecules. The highly enlarged surface area per mass compared with bigger-sized particles of the same chemistry might render nanosized particles more biologically and chemically active (Oberdörster et al. 2005). Properties of the nanosized particles materials can be very different from those at the larger scale and potentially useful: for instance, gold nanoparticles are red and melt at a much lower temperature than bulk gold.

Since nanometer-scale technology has become an accepted concept, the word nanotechnology gained popularity across different science fields, such as chemistry, biology, physics, materials science, medicine, and engineering. Nanotechnology is likely to be under research in a number of areas, for example, bio-nanotechnology is a fusion of biology and nanotechnology and refers to the functional applications of biomolecules in nanotechnology. It encompasses the diverse applications in food and nutrition sciences, biomedicine, agriculture, and other fields. Scientists in the field of food and nutritional sciences have also tried to explore the possibility to apply the tools of nanotechnology in their research. From many futuristic ideas to more down-to-earth applications, there is much ongoing research about how nanotechnology could help enhance nutritional benefits and absorption of bioactive compounds. There is also much work being done to take advantage of nanotechnology to develop new delivery devices (i.e., liposomes), create new packaging materials, extend food storage, and improve food safety, taste, and texture.

## An Overview of Food Nanotechnology

The National Nanotechnology Initiative (NNI) in the USA is a federal research and development program established to create a framework for understanding and controlling matter at the nanoscale. Nanotechnology leads to a revolution in technology and industry and is creating scientific advances. New products that are smaller, stronger, lighter in weight, and more reliable have been made. It is changing the world and the way we live.

An appropriate definition for nanotechnology should be broadly applicable to a wide range of products that include nanomaterials or otherwise involve nanotechnology. NNI describes nanotechnology as the understanding and control of matter at dimensions between approximately 1 and 100 nanometers (nm) with novel properties which are not feasible when working with bulk materials. It generally describes the fabrication of structures and devices where at least one dimension is less than 100 nm. Here are some examples of materials at the nanoscale in different dimensions: one dimension (thin coatings), two dimensions (nanowires and nanotubes), and three dimensions (nanoparticles or fine powder preparations).

Over the past few decades, several different definitions of nanotechnology have been discussed. These definitions have been generated for different purposes. In general, the term nanotechnology commonly refers to particles nanoscale in size or having at least one dimension falling within the size range of roughly 1–100 nm. Some other factors such as shape, charge, surface area to volume ratio, function, and other physical or chemical properties have also been considered as parameters to define nanoparticles. To consider whether a product contains nanomaterials or involves the application of nanotechnology, the ability of nanomaterials to exhibit novel properties or phenomena may be a consideration point even if their dimensions fall outside the nanoscale range (up to 1 μm) (FDA 2011). That means the size range (approximately 1–100 nm) may not be the only criteria in different cases. Therefore, the underlying scientific concepts of these technologies are more important than merely the semantics of a definition. It should be noted that one definition may offer meaningful guidance in one context, whereas it may be too broad or narrow to be of use in another. As different definitions and ongoing controversy on the implications of nanotechnology exist, it is understandable that an agency would choose not to arbitrarily offer a rigid and size-based regulatory definition to avoid any change or conflict as science evolves.

Regarding the size (between approximately 1 and 100 nm) as mentioned above, nanoparticles are also found in nature. Many natural food substances and ingredients have nanostructures in nature and have been eaten safely for generations. Broadly speaking, nanotechnology and nanomaterials are a natural part of food processing and conventional foods. Beta-lactoglobulin, α-lactalbumin, casein micelles, and recrystallized amylose are typical examples of food materials which may undergo structural changes at the nano- and micrometer scales during normal food processing (Sekhon 2010). Moreover, the characteristics and property of many foods may rely on their nanosized components such as foams and nanoemulsions.

Milk is an example of nanoemulsion in which incredibly small droplets of fat are suspended in water. In nature, protein, lipid, and starch molecules are extremely small down to a few nanometers in size. Scientists have tried to explore the possibility to apply the concept of nanotechnology in food and nutritional sciences. The application of nanotechnology or even microtechnology in food systems opens up many new possibilities for the food industry.

Nanotechnology, in its original sense, refers to the engineering and fabrication of functional systems at the molecular scale from the bottom up. As used today, this term also refers to a broader collection of mostly disconnected fields. Scientists in different fields have tried to explore the possibility to apply this emerging technology in their research. To date, much of the work being done under the name of nanotechnology is not nanotechnology in the original meaning of the word. As we have seen, the application of nanotechnology in food research is quite different from the approach and concept of molecular manufacturing in its original sense. However, it poses the question that the general definition of nanotechnology may not be completely applicable to food materials as well as the development of food nanotechnology, or in other word “nanofoods.”

## Applications of Nanotechnology in Food Industry

After a couple decades of steady progress in nanotechnology research and development, scientists around the world have a much more clear view of how to create nanoscale materials with properties never envisioned before. Huge investment has been made in a global race to apply nanotechnologies in both academia and private industry. It is undeniable that this emerging technology has also introduced new chances for innovation in the food industry. There has been an increasing interest in the development and applications of nanotechnology in the food sectors. Considerable research efforts have highlighted the prospect that nanotechnology could be potentially used in a wide range of food applications, including food processing, water purification, improving supplements, delivery of bioactive compounds, food packaging and storage, food safety, deodorization, and increasing the variety of food textures, colors, and tastes (Chau et al. 2007; Cushen et al. 2012; Sanguansri and Augustin 2006; Sekhon 2010; FAO/WHO 2010).

Recent research has explored the possible applications of nanotechnology in food production and processing. That research and their applications in relation to the term “nanotechnology” can be summarized into two categories including (1) engineering materials and structures and (2) natural materials and structures. Different from the scenarios in the other nonfood sectors (e.g., electronic, lighting, robotics, atomic design. etc.), many applications in the food sectors are referring to the handling of natural nanostructures of some naturally occurring substances (e.g., proteins, starches, lipids, and sugars). The research of food nanotechnology might involve the changes in natural nanostructures at the nano- and micrometer scales during food processing, recrystallization of gelatinized amylose molecules into nanoscale structures, enhanced efficiency of nanosized starch particles as an adhesive, and study of the nanostructure of homogenized milk droplets (Sekhon 2010).

The engineered nanomaterials used in different food applications may include both inorganic and organic substances. Different inorganic engineered nanomaterials such as nanosilver, nanosilica, nanozinc oxide, nanotitanium dioxide, nanocalcium, nanoiron, nanomagnesium, and nanoselenium have been widely used in the food industry. Common examples may include nanosilver and nanozinc oxide for antimicrobial action, nanosilica for food package and surface coating, nanotitanium dioxide for ultraviolet (UV) protection, and nanocalcium, nanoiron, nanomagnesium, and nanoselenium for the categories of health supplements. In addition to the uses of engineering nanoparticles or nanocomposites in food production and processing, many food nanotechnology applications in fact involve the development of nanostructures in foodstuffs. Nanostructured foods include many different forms such as nanoemulsions, liposomal nanovesicle, nanoencapsulation, emulsion bilayers, micelles, surfactant micelles, and reverse micelles (Weiss et al. 2006). Nanoemulsions have received much attention and have shown great promise in the nanotexturing of foodstuffs like beverage, mayonnaise, spreads, cream, and also a synthetic nanosized form of lycopene (FAO/WHO 2010; Hoppe et al. 2003). Commercially available nanostructured food products are, however, still limited in the marketplace.

There are two main ways of nanomaterial manufacture such as top-down and bottom-up approaches. Bottom-up manufacture usually includes crystallization, self-assembly, microbial synthesis, aggregation of substances, or biomass reactions (Cushen et al. 2012). In the food sectors, mechanical top-down approaches such as wet milling, dry milling, and homogenization have been commonly used to produce fine particles or suspensions. Currently, it should be noted that the number of food products using nanotechnology of any kind is still small.

## Food Packaging and Storage

While most nanotechnology-derived food products and applications are still at the R&D and laboratory stage, applications for food packaging are relatively closer to being a promising sector of the food industry. This emerging packaging technology has the potential to change the atmosphere surrounding the food in the pack and delay oxidation. It can also help control microbial growth, respiration rates, and volatile flavors or aromas (Brody et al. 2008). The application of nanomaterials (e.g., metal and metal-oxide) in food packaging is a rapidly growing field and has led to the development of improved or novel food packaging materials. It forms the largest share of the current market for nano-enabled products in the food sector. Some example applications include the incorporation of nanoclay in plastic polymers as a gas barrier, nanosilver and nanozinc oxide for antimicrobial action, nanotitanium dioxide for ultraviolet (UV) protection, nanosilica for surface coating, and nanotitanium nitride for mechanical strength and as a processing aid. Furthermore, inorganic nanomaterials such as nanosilver, nanozinc oxide, or nanomagnesium oxide may also be used as effective surface biocides or antimicrobial agents in food contact materials including plastics, rubber, and silicones (Bradley et al. 2011; Sekhon 2010).

Inclusion of nanocomposites (e.g., nanoclays, carbon nanoparticles, nanoscale metals and oxides, and polymer matrix) in packaging materials may improve their mechanical properties. This approach could be able to improve the barrier properties of packaging materials against oxygen, carbon dioxide, ultraviolet radiation, moisture, and volatiles, hence helping control moisture migration and reducing the possibly of food spoiling or drying out (Smolander and Chaudhry 2010). The use of nanocomposites can also provide some promising functionalities such as antimicrobial activity and antioxidant ability, thus promoting the prolongation of the shelf life of packaged food products. A known example is a transparent plastic film (called Durethan) embedded with an enormous number of silicate nanoparticles of clay. The use of functionalized nanocrystals in food packaging (e.g., beer bottles) has created an effective molecular barrier to gasses or moisture. The barrier can increase the shelf life effectively by reducing the entry of oxygen and minimizing the loss of carbon dioxide (Sorrentino et al. 2007). Nanosensors integrated in food packaging will be an innovative packaging technique to detect allergen proteins to avoid adverse reactions as well as to eventually improve food quality and safety (Brody et al. 2008). There is an expectation that nanosensors will be an important tool for food quality and safety in the future.

In many products and applications, such as plastic materials for food packaging, nanomaterials are claimed to be incorporated in a fixed, bound, or embedded form. It is possible that some novel applications may pose unknown or serious risks of exposure for consumers to free engineered nanomaterials. For example, carbon nanotubes have been reported to exhibit remarkable antimicrobial effects by puncturing the *Escherichia coli* cells and causing its cellular damage upon an immediate direct contact (Kang et al. 2007). It is not an easy task to make broad generalizations as to whether such a nanotechnology is good or bad in the food sector. An improved understanding of the benefits and the additional risks to consumer health or the environment may be needed.

## Delivery of Bioactive Compounds

In addition to food packaging, nanodelivery systems based on encapsulation technology are perhaps another potential area of nanotechnology application in the food sectors. This technology has been used to develop nanostructured carriers for the controlled release of nutrients, additives, and supplements. These nanodelivery systems can be used for having a better dispersion of encapsulated ingredients, preserving core ingredients during processing and storage, masking unpleasant tastes and flavors, and controlling the release of core ingredients. While nanocarriers facilitate the delivery of a substance into the bloodstream, they could enhance the absorption and bioavailability of the encapsulated substance

(Chen et al. 2006; Shegokar and Müller 2010). The enormously increased biological activity, compared with conventional bulk equivalents, with the application of nanostructured carriers may require a risk assessment.

Nanoencapsulation evolved from the well-established microencapsulation process, but it involves much smaller particle sizes. It can be considered to be the miniaturization of microencapsulation. The nanoencapsulation technique is used to coat food ingredients or certain substances within another material at sizes on the nanoscale, in order to provide protective barriers, flavor and taste masking, increased bioavailability, controlled release, and better dispersion in aqueous systems (Chaudhry et al. 2008; Mozafari et al. 2006). For example, casein and hydrophobically modified starch can be used to produce nanostructured micelles as a natural nanovehicle for encapsulating hydrophobic active ingredients; α-lactalbumin nanotubes which are formed by the self-assembly of hydrolyzed milk protein α-lactalbumin possess a nanoscale cavity to encapsulate food components and nutrients (e.g., vitamins or enzymes) or to mask undesirable flavor or aroma compounds (Graveland-Bikker and de Kruif 2006; Srinivas et al. 2010).

Nanoemulsion and nanoliposome are the common examples of how nanoencapsulation techniques can be applied to an existing process in the food industry. Some low-fat products such as nanostructured spreads, mayonnaise, and ice creams are claimed to be as creamy as their full fat alternatives (Chaudhry and Castle 2011). The nanoemulsification technique may reduce the need for stabilizers in food products. Scientists believe that lipid-based nanoencapsulation systems (i.e., nanoemulsions, nanoliposomes) can be used as carrier vehicles of nutrients, nutraceuticals, enzymes, food additives, and antimicrobial agents (Mozafari et al. 2008). The applications of nanoemulsions could improve the stability and oral bioavailability of certain bioactive compounds such as polyphenols (Sekhon 2010). The formulation of nanoemulsions using some stabilizers can also allow natural fat-soluble colorants to be used in a novel way. Nanostructured lipid carriers may allow an oil-soluble pigment such as beta-carotene to be easily dispersed and stabilized in aqueous-based foods or beverages (Astete et al. 2009). Nanoemulsion techniques are expected to play a future role in revolutionizing the making of these products; however, they are still in developmental stages.

## Food Safety

An overview of the existing research findings as well as the current and futuristic applications of nanotechnology for the food industry indicates that they can potentially offer a variety of benefits. The diverse industrial applications in food and nutrition sciences may include the following: enhanced uptake and bioavailability of nutrients and supplements, innovative tastes and textures, promotion of food safety and security, preservation of quality and freshness, and reduced dietary intake of fat, salt, and food additives. Novel techniques have paved the way for detecting foodborne pathogens and developing various nano-based sensing approaches for pesticides, toxic anions, and ripening gas. However, the barrier of commercializing detectors and methods for rapid screening of analytes at low levels with accuracy and precision is still a challenge for real-world applications to the food industry (Nugen and Baeumner 2008; Valdés et al. 2009).

Taking food packaging, a promising sector, as an example, there are questions about the possible migration of nanomaterials from packaging into food. Knowledge gaps still remain as to whether nanoparticles could migrate from the packaging materials into food products. The highly increased surface area and chemistry of nanomaterials could possibly give rise to unwanted and also unexpected chemical reactions. It may pose unknown risks and uncertainties to consumers. Previous studies have shown that some nanomaterials could induce cell death in eukaryotic cells (Nel et al. 2006) and cytotoxicity in prokaryotic cells (Brayner et al. 2006; Thill et al. 2006). Universal analytical measuring tools, reliable technology, and protocols are also needed for arriving at solutions. Owing to the limited information of the potential toxicity of nanomaterials, risk assessment and management are therefore urgently required for existing products available on the market around the world. Some regulatory regimes including the European Union and the USA have required the pre-market approval with a safety assessment for the constituents of plastic food packaging materials.

## Potential Risks of Nanotechnology

Although nanotechnology has introduced new opportunities for innovation in the food industry, it has also provoked public concern and debate. It is well known that nanomaterials are chemically and physically more reactive than larger particles of the same chemical composition. They may behave differently and interact with the living systems accordingly, causing unexpected toxicity (Das et al. 2009). The potential health risks of nanomaterials may depend on their properties including composition, particle size, shape, solubility, reactivity, and other physicochemical parameters (Chau et al. 2007).

The extent to which nanoparticles enter the body and their possible accumulation and translocation may determine their potential risks to the human health. It is generally believed that the scale ($<100$ nm) of nanoparticles could make it easier for nanomaterials to pass through biological barriers. Some studies have shown that particles less than 70 nm could even penetrate into nuclei and cause cellular damage (Geiser et al. 2005). However, particles up to 300 nm were also reported to be taken up by individual cells (Garnett and Kallinteri 2006). Little is yet known about the occurrence, bioaccumulation, fate, and toxicity of nanoparticles. As novel properties and characteristics pose novel risks, uncertainty and health concerns about the uses of nanomaterials are emerging. The safety concerns of different nanomaterials are different, and some nanomaterials may be more harmful than others.

## Possible Routes of Exposure to Nanomaterials

In general, there are three main routes of exposure to nanomaterials, including dermal contact, inhalation, and ingestion.

The ability of nanomaterials to penetrate through the outer protective layers such as the epidermis or dermis determines their impact on health (Maynard 2006). The stratum corneum may act as a barrier layer (about 10 μm thick) to cutaneous absorption of most chemicals, ionic compounds, and water-soluble molecules (Hoet et al. 2004). It was reported that nanoparticles could penetrate into the dermis and translocate via the lymph to regional lymph nodes (Oberdörster et al. 2005). Titanium dioxide nanoparticles (~20 nm) were capable of passing through the skin and interacted with the immune system (Kreilgaard 2002). As yet, there is still limited information on the potential hazards of nanomaterials to the skin. Discussions about the health consequences of contacting nanomaterials and possible mechanisms of interaction are rather speculative, and further studies are needed.

In terms of aerodynamics, small particles less than 10 μm can pass through the nasal cavity into the lungs. With particles smaller than 4 μm, more than 50 % may penetrate more deeply into the alveolar region. The smaller the fine particles, the deeper they are drawn into the lungs (Hoet et al. 2004). While inhaled, titanium dioxide nanoparticles and carbon nanotube might accumulate in the lungs and induce chronic diseases such as pulmonary inflammation, pneumonia, pulmonary granuloma, and oxidative stress (Kim et al. 2003; Nel et al. 2006). Given our current state of knowledge, it is still not possible to reach generic conclusions on the toxicity of inhaled particles solely based on the consideration of size alone. As the overall surface of intestinal lumen available to nutrient absorption is more than 200 $m^2$, the safety assessment of nanomaterials entering the body by ingestion becomes important. A particle translocation experiment has demonstrated that 34 % and 26 % of polystyrene nanoparticles (about 50 and 100 nm, respectively) could be absorbed, but polystyrene particles larger than 300 nm were absent from the blood, heart, or lung tissue (Jani et al. 1990). It has been reported that the smaller the particle, the faster it would penetrate across the intestinal mucus barrier. However, particles larger than 1 μm were unable to pass through the intestinal mucus barrier (Szentkuti 1997).

## Safety Assessments

Nanomaterials such as titanium dioxide, aluminum oxide, zinc oxide, silica, and silver, which exhibit some novel properties not observed at the macroscale, may result in unpredictable safety problems and risks. For instance, aluminum oxide which is used in dentistry due to its inertness could spontaneously explode at nanoscale. Some in vivo experiments have shown that instillation of multiwalled and single-walled carbon nanotubes may agglomerate and cause pulmonary inflammation, interstitial fibrosis, granulomas, and death in rodents (Lam et al. 2004; Muller et al. 2005). Some other studies have observed that carbon nanoparticles diffused from the lungs to the surrounding blood vessel system and resulted in further vascular diseases (Brown et al. 2000; Nemmar et al. 2002). The inhalation of titanium dioxide nanoparticles (~20 nm) also resulted in significant pulmonary inflammatory responses (Oberdörster et al 1994). It was reported that titanium dioxide nanoparticles might penetrate through the skin barrier and cause intracellular damage (Oberdorster 2001). The genotoxicity of nanosilver particles themselves is found to be weak, but particles like silver nanopowder, silver/copper nanopowder, and colloidal silver might bind with DNA and affect the replication fidelity of genes (Yang et al. 2009).

The potential applications of engineered nanomaterials in food packaging have been and are being widely studied. For instance, engineered carbon nanotubes were added into food packaging with the purpose to improve its mechanical properties. Carbon nanotubes were also shown to be able to exhibit powerful antimicrobial effects on immediate direct contact with nanotube aggregates. The tiny nanotubes punctured *Escherichia coli* and caused cellular damage to bacterial cells (Kang et al. 2007). In such applications, nanomaterials may be incorporated in a fixed, bound, or embedded form in the packaging materials. The entry of these manufactured nanoparticles into food chain, however, may result in any unexpected bioaccumulation and harmful effects. Other applications, including certain foods and beverages containing free nanoparticles, may pose a greater risk of exposure for consumers to free engineered nanomaterials. Likewise, precautions are also required for the uses of nanostructured carriers to enhance the absorption and bioavailability of a given chemical substance. An enormous increase in bioavailability and/or tissue distribution of the substance (e.g., vitamin A), compared with conventional bulk equivalents, may not be desirable as it can exhibit a toxic effect given a large enough dose. It seems that even the use of nanostructured carriers to enhance the nutrient absorption may require a risk assessment.

Most of the existing toxicology research and safety assessments of nanotechnology are basically focusing on inorganic and nonfood materials or consumer products. Yet little is known about the impact of nanotechnology, especially engineered nanomaterials, on human health. Toxicological profiles of nanomaterials cannot be judged by extrapolation from data on their equivalent larger forms. It is probably wise to take a precautionary principle (e.g., a case-by-case approach) to deliberate the possible regulatory control as a proactive approach. It should be understood that engineered nanomaterials could be considered for use in food products or production only on the circumstances that they are deemed safe by intensive toxicology research which are practically limited, especially in the food sector.

## Regulation of Nanotechnology

Like other new or modern technologies, there is a long-standing debate about the ethics and social issues involved in the development of nanotechnology. It has the potential to bring significant benefits but may also pose potential risks to human health and the environment. Broadly speaking, many of the issues are not particular to nanotechnology, but in fact are part of ongoing discussion about how different technologies are used in our society. The risks arising from the exposure to various nanoparticles are not yet completely understood. It is important for governments and international agencies to collaborate to fill the knowledge gaps by conducting research related to the health and safety risks of nanomaterials, particularly the engineered nanomaterials that are deliberately introduced into the food chain (Reilly 2010).

As nanotechnology develops, countries and regions have begun to develop regulatory framework for foods. As a step toward developing the regulatory standards, it is necessary to envision that the emerging technology may offer diverse applications that will involve multiple regulatory agencies. It also requires government or regulatory agency to consider different criteria such as clear definitions, food safety assessments, public debate, and the need for regulation. Conflicting definitions of nanotechnology and blurry distinctions among different fields have complicated the development of a global harmonized regulatory framework. A precautionary principle should be taken to deliberate proper regulatory controls that address the definition and standard as well as regulate the labeling of food products.

In 2006, the US Food and Drug Administration (FDA) formed the Nanotechnology Task Force to address concerns and determine regulatory approaches that encourage the continued development of innovative, safe, and effective FDA-regulated products that use nanotechnology materials. Nanotechnology is an emerging technology that falls within the FDA's mission. It has the potential to be used in a broad array of FDA-regulated products. Nanotechnology products may be appropriately regulated by the product-focused, science-based regulatory policy (FDA 2013). The European Union (EU) policy on nanotechnologies is to take an "integrated, safe, and responsible approach" to their developments. The efforts include the review and adaptation of EU laws, monitoring of safety issues, and participation in dialogue with national authorities, stakeholders, and citizens. Since 2006, the European Food Safety Authority (EFSA) has been involved in the development of nanotechnology (EFSA 2013). EFSA has been asked by the European Commission to provide independent scientific opinion on the knowledge and potential risks of application of nanotechnology with regard to food and feed. The advice focuses on the use of nanotechnology, especially engineered nanomaterials, in the food and feed chain. The scientific advice then helps the European Commission to consider appropriate measures and assess existing legislation by considering EFSA's opinions. However, limitations in exposure data and a lack of validated methodologies make the risk assessments of nanomaterials difficult and subject to a high degree of uncertainty. EFSA's Scientific Committee has concluded that a case-by-case approach would be broadly applicable to protect the consumer.

## Conclusion and Future Directions

From the food industry and public safety standpoints, this chapter is to give a general discussion on the development, applications, and risk of nanotechnology in relation to foods. Some food scientists would claim that the industry has already embraced nanotechnology, but in fact, applications and available products in this area are still very scarce. Most developments of nano-derived food ingredients which are expected to be nearing the market are still in their formative stage in many regards. Unlike the development and applications of engineered nanomaterials, many claims of nanotechnology applications in the food industry, as a matter of fact, are basically a description of the characteristics and structure of naturally occurring food components at nanoscale level. Without a universal definition, some food components are regarded as nanomaterials simply because their particles or structures have at least one dimension falling within the nanoscale range from approximately 1–100 nm. Many food components such as protein, starch, phospholipids, lipid, and sugar possess nanostructures in nature. In fact, food proteins are true nanoparticles, and the molecules of starch and lipids may have one-dimensional nanostructures less than 1 nm in thickness. Casein micelles, emulsion in mayonnaise spreads, and foam in ice cream are also considered as nanostructured food components. The nanostructures of some nanomaterials in the food sectors existed naturally even before the word "nanotechnology" was used to describe the process for producing these structures. However, it should be understood that the uses of nanostructures of biological origin such as proteins, starch, phospholipids, lipids, etc. in food processing should not be considered as a manipulation of nanotechnology. The food sectors are only at an initial stage, and the future developments are limited only by the imagination.

It is worth noting that a number of nanomaterials found in literature are not likely to be used for any food-related applications. For example, there are some applications of carbon nanotubes in the areas of packaging or water treatment, but these engineered nanomaterials are basically manufactured for a diversity of nonfood applications (FAO/WHO 2010). Their functionalities in relation to the enhanced mechanical strength and electrical conductivity are of little relevance to the potential use in food products. To date, there are many different types of nanomaterials, whereas it should be understood that not all of them could be considered for uses in food products or production. From a food safety perspective, it therefore poses a question of whether these artificially engineered nanomaterials could be used in any food-related research and applications. It is anticipated that more scientific research in food nanotechnology will be conducted worldwide. This research will be used to fill knowledge gaps and give more support to regulation and policy development for the safety and health of consumers and the environment.

## Cross-References

► Applications of Nanotechnology in Developing Biosensors for Food Safety
► Advances of Nanomaterials for Food Processing

## References

Astete CE, Sabliov CM, Watanabe F, Biris A (2009) $Ca^{2+}$ cross-linked alginic acid nanoparticles for solubilization of lipophilic natural colorants. J Agric Food Chem 57:7505–7512

Bradley EL, Castle L, Chaudhry Q (2011) Applications of nanomaterials in food packaging with a consideration of opportunities for developing countries. Trends Food Sci Technol 22:604–610

Brayner R, Ferrari-Iliou R, Brivois N, Djediat S, Benedetti MF, Fievet F (2006) Toxicological impact studies based on *Escherichia coli* bacteria in ultrafine ZnO nanoparticles colloidal medium. Nano Lett 6(4):866–870

Brody AL, Bugusu B, Han JH, Sand CK, McHugh TH (2008) Innovative food packaging solutions. J Food Sci 73:R107–R116

Brown DM, Stone V, Findlay P, MacNee W, Donaldson K (2000) Increased inflammation and intracellular calcium caused by ultrafine carbon black is independent of transition metals or other soluble components. Occup Environ Med 57:685–691

Chau CF, Wu SH, Yen GC (2007) The development of regulations for food nanotechnology. Trends Food Sci Technol 18:269–280

Chaudhry Q, Castle L (2011) Food applications of nanotechnologies: an overview of opportunities and challenges for developing countries. Trends Food Sci Technol 22:595–603

Chaudhry Q, Scotter M, Blackburn J, Ross B, Boxall A, Castle L, Aitken R, Watkins R (2008) Applications and implications of nanotechnologies for the food sector. Food Addit Contam Part A Chem Anal Control Expo Risk Assess 25:241–258

Chen H, Weiss J, Shahidi F (2006) Nanotechnology in nutraceuticals and functional foods. Food Technol 60:30–36

Cushen M, Kerry J, Morris M, Cruz-Romero M, Cummins E (2012) Nanotechnologies in the food industry – recent developments, risks and regulation. Trends Food Sci Technol 24:30–46

Das M, Saxena N, Dwivedi PD (2009) Emerging trends of nanoparticles application in food technology: safety paradigms. Nanotoxicology 3:10–18

European Food Safety Authority [EFSA] (2013) FAQ on nanotechnology. Available from http://www.efsa.europa.eu/en/faqs/faqnanotechnology.htm

FAO/WHO (2010) FAO/WHO expert meeting on the application of nanotechnologies in the food and agriculture sectors: potential food safety implications. Meeting report. Available from http://www.fao.org/docrep/012/i1434e/i1434e00.pdf

FDA (2011) Considering whether an FDA-regulated product involves the application of nanotechnology. Available from http://www.fda.gov/RegulatoryInformation/Guidances/ucm257698.htm

FDA (2013) Fact sheet: nanotechnology. Available from http://www.fda.gov/Food/GuidanceRegulation/GuidanceDocumentsRegulatoryInformation/IngredientsAdditivesGRASPackaging/ucm300914.htm

Garnett M, Kallinteri P (2006) Nanomedicines and nanotoxicology: some physiological principles. Occup Med 56:307–311

Geiser M, Rothen-Rutlshauser B, Knapp N, Schurch S, Kreyling W, Schulz H, Semmler M, Im H, Heyder J, Gehr P (2005) Ultrafine particles cross cellular membranes by non-phagocytic mechanisms in lungs and in cultured cells. Environ Health Perspect 113(11):1555–1560

Graveland-Bikker JF, de Kruif CG (2006) Unique milk protein based nanotubes: food and nanotechnology meet. Trends Food Sci Technol 17(5):196–203

Hoet PHM, Brüske-Hohlfeld I, Salata OV (2004) Nanoparticles-known and unknown health risks. J Nanobiotechnol 2:12

Hoppe PP, Krämer K, van den Berg H, Steenge G, van Vliet T (2003) Synthetic and tomato-based lycopene have identical bioavailability in humans. Eur J Nutr 42:272–278

Jani P, Halbert GW, Langridge J, Florence AT (1990) Nanoparticle uptake by the rat gastrointestinal mucosa: quantitation and particle size dependency. J Pharm Pharmacol 42:821–826

Kang S, Pinault M, Pfefferle LD, Elimelech M (2007) Single-walled carbon nanotubes exhibit strong antimicrobial activity. Langmuir 23:8670–8673

Kim H, Liu X, Kobayashi T, Kohyama T, Wen FQ, Romberger D, Conner H, Gilmour PS, Donaldson K, MacNee W, Rennard SI (2003) Ultrafine carbon black particles inhibit human lung fibroblast-mediated collagen gel contraction. Am J Respir Cell Mol Biol 28:111–121

Kreilgaard M (2002) Influence of microemulsions on cutaneous drug delivery. Adv Drug Deliv Rev 54:S77–S98

Lam CW, James JT, McCluskey R, Hunter RL (2004) Pulmonary toxicity of single-wall carbon nanotubes in mice 7 and 90 days after intratracheal instillation. Toxicol Sci 77:126–134

Maynard AD (2006) Nanotechnology: assessing the risks. Nano Today 1:22–33

Mozafari RM, Flanagan J, Matia-Merino L, Awati A, Omri A, Suntres EZ, Singh H (2006) Recent trends in the lipid-based nanoencapsulation of antioxidants and their role in foods. J Sci Food Agric 86:2038–2045

Mozafari MR, Johnson C, Hatziantoniou S, Demetzos C (2008) Nanoliposomes and their applications in food nanotechnology. J Liposome Res 18:309–327

Muller J, Huaux F, Moreau N, Misson P, Heilier JF, Delos M, Arras M, Fonseca A, Nagy JB, Lison D (2005) Respiratory toxicity of multi-wall carbon nanotubes. Toxicol Appl Pharmacol 207:221–231

Nel A, Xia T, Madler L, Li N (2006) Toxic potential of materials at the nanolevel. Science 311 (5761):622–627

Nemmar A, Hoet PH, Vanquickenborne B, Dinsdalem D, Thomeer M, Hoylaerts MF, Vanbilloen H, Mortelmans L, Nemery B (2002) Passage of inhaled particles into the blood circulation in humans. Circulation 105:411–414

Nugen SR, Baeumner AJ (2008) Trends and opportunities in food pathogen detection. Anal Bioanal Chem 391:451–454

Oberdorster G (2001) Pulmonary effects of inhaled ultrafine particles. Int Arch Occup Environ Health 74:1–8

Oberdörster G, Ferin J, Lehnert BE (1994) Correlation between particle size, in vivo particle persistence, and lung injury. Environ Health Perspect 102(Suppl 5):173–179

Oberdörster G, Oberdörster E, Oberdörster J (2005) Nanotoxicology: an emerging discipline evolving from studies of ultrafine particles. Environ Health Perspect 113:823–839

Reilly A (2010) Nanotechnologies: regulatory framework. In: International conference on food and agriculture applications of nanotechnologies, Sao Pedro, pp 111–115

Sanguansri P, Augustin MA (2006) Nanoscale materials development – a food industry perspective. Trends Food Sci Technol 17:547–556

Sekhon BS (2010) Food nanotechnology – an overview. Nanotechnol Sci Appl 3:1–15

Shegokar R, Müller RH (2010) Nanocrystals: industrially feasible multifunctional formulation technology for poorly soluble actives. Int J Pharm 399:129–139

Smolander M, Chaudhry Q (2010) Nanotechnologies in food packaging. In: Chaudhry Q, Castle L, Watkins R (eds) Nanotechnologies in food, vol 14, RSC nanoscience & nanotechnology. Royal Society of Chemistry, Cambridge, UK, pp 86e–101e, Chap. 6. ISBN 978-0-85404-169-5

Sorrentino A, Gorrasi G, Vittoria V (2007) Potential prospectives of bio-nanocomposites for food packaging applications. Trends Food Sci Technol 18:84–95

Srinivas PR, Philbert M, Vu TQ, Huang Q, Kokini JL, Saos E, Chen H, Peterson MC, Friedl KE, McDade-Ngutter C, Hubbard V, Starke-Reed P, Miller N, Betz JM, Dwyer J, Milner J, Ross SA (2010) Nanotechnology research: applications in nutritional sciences. J Nutr 140:119–124

Szentkuti L (1997) Light microscopical observations on luminally administered dyes, dextrans, nanospheres and microspheres in the pre-epithelial mucus gel layer of the rat distal colon. J Control Release 46:233–242

Thill A, Zeyons O, Spalla O, Chauvat F, Rose J, Auffan M, Flank AM (2006) Cytotoxicity of $CeO_2$ nanoparticles for *Escherichia coli*. Physico-chemical insight of the cytotoxicity mechanism. Environ Sci Technol 40(19):6151–6156

Valdés MG, González ACV, Calzón JAG, Díaz-García ME (2009) Analytical nanotechnology for food analysis. Microchim Acta 166:1–19
Weiss J, Takhistov P, McClements J (2006) Functional materials in food nanotechnology. J Food Sci 71:R107–R116
Yang W, Shen C, Ji Q, An H, Wang J, Liu Q et al (2009) Food storage material silver nanoparticles interfere with DNA replication fidelity and bind with DNA. Nanotechnology 20:085102