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Potential of nanotechnology in functional foods

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Abstract

Food nanotechnology is a relatively recent area which has opened up a whole universe of new applications in food industry. Some of these applications include; improved taste, flavor, color, texture and consistency of foodstuffs, increased absorption and bioavailability of nutraceuticals and health supplements, development of food antimicrobials, new food packaging materials with improved mechanical barrier and antimicrobial properties, nanosensors for traceability and monitoring the condition of food during transport and storage, encapsulation of food components or additives. Smart delivery of nutrients, bioseparation of proteins, rapid sampling of biological and chemical contaminants and nanoencapsulation of nutraceuticals are few more emerging areas of nanotechnology for food industry. Nanotechnology holds great promise to provide benefits not just within food products but also around food products. There is an urgent need for regulatory systems capable of managing any risks associated with nanofoods and the use of nanotechnology in food industry. In this review, applications of nanotechnology in functional food with special attention to related regulatory issues are discussed.

Key words: Functional Foods, Food Industry, Nanotechnology, Nano-food

Introduction

The term 'nano' is derived from the Greek word for dwarf (Sangamithra and Thirupathi, 2009). The term "Nanotechnology" was first used in 1974 by the late Norio Taniguchi and concepts were given by Richard Feynman in 1959 (Warad and Dutta, 2005). Nanoscience is defined as the study of phenomena and the manipulation of materials at the atomic, molecular and macromolecular scales, where the properties differ from those at a larger scale (Mannino and Scampicchio, 2007).

The National Nanotechnology Initiative (2006) has defined nanotechnology as the understanding and control of matter at dimensions of roughly 1 - 100 nm, where unique phenomena enable novel applications; encompassing nanoscale science, engineering and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale (Chen et al., 2006a). In 2006, Food and Drug Administration (FDA) defined nanomaterials as "particles with dimensions less than micrometer scale that exhibit unique properties" (Miller and Senjen, 2008).

Nanotechnology in agricultural and food industries was first addressed by a United States Department of Agriculture (USDA) roadmap published in September 2003 (Joseph and Morrison, 2006). A range of nanotechniques and materials are being developed in an attempt to assert greater control over food character traits, to enhance processing functionalities, such as flavour, texture, speed of processing, heat tolerance, shelf life, traceability, safety, the bioavailability of nutrients and cost effective food analysis major focus is on functional foods as they offer the ability to control and manipulate properties of substances close to molecular level (Chaudhry et al., 2008; Scrinis and Lyons, 2007; Weiss et al., 2006).

Nanotechnology in the food industry

The term "nanofood" describes the food which has been cultivated, produced, processed or packaged using nanotechnology techniques or tools, or to which manufactured nanomaterials have been added (Morris, 2007). Nanofood has, in fact, been part of food processing for centuries, since

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many food structures naturally exist at the nanoscale (Shekhon, 2010). The applications of nanotechnology for the food sector fall into the following main categories:

- Where nano-sized, nano-encapsulated or engineered nanoparticle additives have been used;
- Where food ingredients have been processed or formulated to form nanostructures;
- Where nanomaterials have been incorporated to develop improved, active, or intelligent materials for food packaging or in food contact materials or surfaces;
- Where nanotechnology-based devices and materials have been used, e.g. for nanofiltration, water treatment;
- Where nanosensors have been used for food safety and traceability and contaminant detection (Chaudhry et al., 2008; McCall, 2007).

Nanofood market

The worldwide sales of nanotechnology products in the food and beverage packaging sector increased from US$ 150 million in 2002 to US$ 860 million in 2004 and are expected to reach to US$ 20.4 billion by 2010 (Helmut Kaiser Consultancy, 2004). The consulting firm Cientifica, has estimated the then (2006) food applications of nanotechnologies at around $410 million (food processing US$100 million, food ingredients US$100 million and food packaging US$210 million). According to the report, the existing applications are mainly for improved food packaging, with some applications for delivery systems for nutraceuticals. The report estimated that by 2012 the overall market value would reach US$5.8 billion (food processing US$1303 million, food ingredients US$1475 million, food safety US$97 million and food packaging US$2.93 billion) (Cientifica, 2006).

More than 200 companies are actively involved in research and development (Asadi and Mousavi, 2006). USA is the leader followed by Japan and China (Helmut Kaiser Consultancy, 2004). There is a large potential for growth of the food sector in developing countries. Today, many of the world's leading food companies including H.J. Heinz, Nestlé, Hershey, Unilever, and Kraft are investing heavily in nanotechnology research and development (Joseph and Morrison, 2006; Kuzma and VerHage, 2006; Shelke, 2006; Miller and Senjen, 2008).

Kraft's global 'Nanotek Research Consortium' of 15 universities and national research centre, reflects a corporate strategy to lead developments for a nano food future (http://www. ifst.org/science_technology_resources/for_food_pr ofessionals/information_ statements / index/#). As of March 2006, over 200 ''nano'' consumer products are currently available, and about 59% and 9% of the products are categorized as ''Health and Fitness'' and ''Food and Beverage'' products, respectively (Chau et al., 2007).

Processes for nanomaterial production

The two approaches to attain nanomaterials are *top-down approach* and *bottom-up approach* (Table 1). The ''topdown'' approach involves physically machining materials to nanometre size range by employing processes such as grinding, milling, etching and lithography. For example, a high water-binding capacity wheat flour of fine size can be obtained by dry-milling technology. By contrast, self-assembly and self-organization are concepts derived from biology that have inspired a bottom-up food nanotechnology. Bottom-up techniques build or grow larger structures atom by atom or molecule by molecule. These techniques include chemical synthesis, self-assembly and positional assembly (Acosta, 2008; Sanguansri and Augustin, 2006; Sozer and Kokini, 2009; Meetoo, 2011).

Table 1. Range of sizes of nanomaterials in the food sector.

Structures	Diameter or length (nm)
DNA	12
Glucose	21–75
Liposome	30–10000
LDH	40–300
Amylopectin	44–200
Casein micelle	60–100
PLA nanosphere	100–300
Zein	200
Cubosome	500
Nanosensors	<1000

Owing to the greater surface area of nanoparticles per mass unit, they are expected to be more biologically active than larger sized particles of the same chemical composition. This offers several perspectives for functional food applications. Nanoparticles can, for instance, be used as bioactive compounds in functional foods (Sozer and Kokini, 2009).

Natural self-assembled nanostructures

Many natural foods contain nanoscale components and their properties are determined by their structure. These have been eaten safely for generations. In fact, some of most important nutrients of raw materials *i.e.,* proteins, starches and fats, undergo structural changes at the nanometer and micrometer scales during normal food processing (Morris and Parker, 2008). Milk proteins (for example, native beta-lactoglobulin, which is about 3.6 nm in length) can undergo denaturation (via pressure, heat, pH, *etc.*) and the denatured components reassemble to form larger structures, like fibrils or aggregates, which in turn can be assembled to form even larger gel networks (*e.g.,* yogurt). Self-assembled nanotubes from hydrolyzed milk protein α-lactalbumin, a potential new carrier for nanoencapsulation of nutrients, supplements, and pharmaceuticals, have been reported (Bugusu et al., 2009). Casein micelles may be useful as nanovehicles for entrapment, protection and delivery of sensitive hydrophobic nutraceuticals within other food products (Semo et al., 2007).

A cow's udder is an excellent example of a nano device synthesizing, assembling, and dispensing proteins and fat into an aqueous phase, where they later become building blocks for protein structures. Processes such as homogenization and fine milling causes microstructural changes in food. Homogenized milk has a nanostructure of 100 nm sized droplets in it. The dairy industry utilizes three basic micro sized and nanosized structures (casein micelles, fat globules, whey proteins) to build all sorts of emulsions (butter), foams (ice cream and whipped cream), complex liquids (milk), plastic solids (cheese), and gel networks (yogurt). In fact, dairy technology is not just a microtechnology but also a nanotechnology, and it has existed for a long time. Research into naturally occurring nanostructures in foods is mainly designed to improve the functional behavior of the food (Shekhon, 2010).

Nanoparticulate delivery systems

Nanoencapsulation

Nanoencapsulation is incorporation of ingredients in small vesicles or walled material with nano (or submicron) sizes (Surassmo et al., 2010). These nanomaterials offer several advantages such as, delivery vehicle for lipid soluble ingredients, protection from degradation during processing or in GIT, controlled site specific release, compatible with other food constituents, greater residence time and greater absorption (Chen et al., 2006a, b; Weiss et al., 2006). The protection of bioactive compounds, such as vitamins, antioxidants, proteins, and lipids as well as carbohydrates may be achieved using this technique for the production of functional foods with enhanced functionality and stability. Nanoencapsulation can make significant savings for formulators, as it can reduce the amount of active ingredients needed (Huang et al., 2009). Table 2 lists the products reported with such nanomaterials.

Nanoencapsulation of probiotics

According to FAO/World health organization (WHO) (2002), probiotics are defined as "live microorganisms which when administered in adequate amounts confer a health benefit on the host". They can be incorporated in fermented milk, yoghurts, cheese, puddings, fruit based drinks etc. Nanoencapsulation used to develop designer probiotic bacterial preparations that could be delivered to certain parts of the gastro-intestinal tract where they interact with specific receptors. These nanoencapsulated designer probiotic bacterial preparations may act as *de novo* vaccines, with the capability of modulating immune responses (Vidhyalakshmi et al., 2009).

Nanosized self-assembled liquid structures

Nanosized self-assembled liquid structures are used as vehicles for targeted nutraceuticals. The vehicles are expanded micelles in the size of <30 nm and used in "clear" beverages without phase separation. Potential applications include lycopene, beta-carotene, omega- 3 fatty acids, phytosterols, and isoflavones (Garti and Aserin, 2007).

Applications in food processing

Nanofrying

The US based Oilfresh Corporation has marketed a new nanoceramic product which reduces oil use in restaurants and fast food shops by half because of its large surface area (Joseph and Morrison, 2006; Pehanich, 2006).

Novel foods

A Hungarian company has developed an ice gel for soft drinks or ice-cream containing CO_2 bubbles of 1-10 nm in diameter for effervescence (http://files.nanobio-raise.org/ Downloads/ Nano technology-and-Food-fullweb.pdf). Nanotech spray is available in which Nanodroplets 87 nm are used to enhance the uptake of vitamin B_{12} and other supplements for use in foods (Bouwmeester, 2007). Kraft Foods and NanoteK consortium have plans to incorporate the electronic tongue (which is chemical change based biosensor) into foods to release accurately controlled amounts of the suitable molecules for the customized tailor-foods (Shelke, 2006; Sozer and Kokini, 2009).

Table 2. Nanoencapsulates in food products.

Nanoencapsulates	Products	References
Nanoemulsions - Oil in water emulsion, usually 50-500nm	β-Carotene; α-Tocopherol;Nanoemulsion based ice-cream (Nestle, Unilever)	Chu et al., 2007; Ribeiro et al., 2008; Tan et al., 2005; Yuan et al., 2008; Joseph and Morrison, 2006; Miller and Senjen, 2008
Biopolymeric Nanoparticles - Dense matrix network of sub-100nm in which active molecules are dispersed throughout	β- lactoglobulin; Nanoceuticals™ (RBC Life Sciences®); Nano Calcium/ Magnesium (Mag-I-Cal.com USA); nano-selenium-enriched Nanotea (Shenzhen Become Industry)	Bouwmeester, 2007; Chaudhry et al., 2008; Chen and Subirade, 2005: Sabliov and Astete, 2008; Shelke, 2006; Miller and Senjen, 2008; Zimet and Livney, 2009
Nanocapsules - Vesicles in which oil or liq. ingredients are confined within polymeric membrane of (20-100nm)	Nanocapsules of Capsium, oleoresin, eugenol, lysozymes, vitamins, phytosterols; "Tip top" up bread with nano fish oil (Nu-Mega), Kraft foods-personalized flavours and colours	Choi et al., 2009 a,b; Jafari et al., 2008; Joseph and Morrison, 2006; McCall, 2007; Semo et al., 2007; Shelke, 2006; Surassmo et al., 2010, Türk and Lietzow, 2004; Zhong et al., 2009
Nanospheres - Solid colloidal particles enclosed by polymer matrix with several phases in suspension	Omega 3 fatty acids, whey protein nanospheres; Citral flavour (Key Lime Formulations); Chocola Chocolate chewing gum with nanococoa (Olala)	Shelke, 2006; Subirade and Chen, 2008; Chen et al., 2006b
Nanoliposomes- Polymeric aggregates of lipid bilayers esp. phospholipids such as egg or soy	Lactoferrin, nisin, phosvitin, enzymes, vitamins, antioxidants, coenzyme Q10	Bouwmeester, 2007; Chen et al., 2006a; Liu and Park, 2010; Malheiros et al., 2010; Raman and Danino, 2008; Teixeira et al., 2008
Nanocochleates -Cigar shaped multilayered structure with spiral solid lipid bilayer	Bioral™ for nutrients (BioDelivery systems)	Chaudhry et al., 2008; Morris, 2007; Sangamithra and Thirupathi, 2009; Joseph and Morrison, 2006; Miller and Senjen, 2008
Nanoclusters	Slim shake chocolate, Nanoceuticals (RBC Life sciences); Nanococoa (Royal Body care)	Bouwmeester, 2007; Chaudhry et al., 2008; Morris, 2007; Shelke, 2006; Miller and Senjen, 2008.
Nanomicelles- Sub 100nm spherical particles formed spontaneously upon surfactant addition after Critical micelle conc. has reached	Limonene, carvacrol, lutein, eugenol, Omega 3 fatty acids, whey proteins, essential oils; Lycopene (BASF Germany), NutiNano™(Solgar, USA); Novosol (Aqanova®) for nutrients; Canola Activa Oil (Sheman Ind.)	Bouwmeester, 2007; Chaudhry et al., 2008; Chen et al., 2006a; Garti and Aserin, 2007; Gaysinsky et al., 2008; Joseph and Morrison, 2006; Losso, 2007; Zhang et al., 2009; Miller and Senjen, 2008;
Nanotube- 20 nm in diameter and several μm in length	α-lactoglobulin as gelling agent, delivery of nutrients and flavours	Bikker and Kruif, 2006; Ipsen and Otte, 2007
Nanofibers- 100nm fibers from polymer solutions	Vitamins, β-carotene, eugenol, antioxidants, flavors	Arecchi, 2009; Fernandez, 2009

Nanofiltration

Nano Filtration separating materials of less than 0.001 microns (10 angstroms) in size and rejects divalent and multivalent ions (Cuartas-Uribe et al., 2007; Sangamithra and Thirupathi, 2009). It is an alternative to Reverse Osmosis as it is cost effective (Sangamithra and Thirupathi, 2009). It has application in desalination, milk, whey and juice filtration, demineralization, colour removal, concentration of products, waste water treatment and water purification (Kaul, 2005; Doyle, 2006; Cuartas-Uribe et al., 2007; Duke et al., 2008; Tiwari et al., 2008; Diaz-Reinoso et al., 2009; Sangamithra and Thirupathi, 2009).

Food processing equipments

Nanotechnology-based translucent insulant coatings called Nansulate PT has been reported for dairy processing tanks and pipes for reduced costs and extended life (Pehanich, 2006; Baurah and Dutta, 2009).

Immobilization of enzymes

Nanoporous media, nanofibers, carbon nanotubes, magnetic nanoparticles are used for enzyme immobilization (Mao et al., 2006; Kim et al., 2008; Kosseva et al., 2009). Immobilization of lipase on nanofibers and magnetic nanoparticles for soybean oil hydrolysis have been reported (Li and Wu, 2009; Lee et al., 2009; Wang et al., 2009).

Application in food packaging

Nano packaging applications as Food Contact Materials (FCMs) are anticipated to grow from a $66 million business in 2003, to over $360 million by 2008 (Scrinis and Lyons, 2007). Applications for food contact materials (FCMs) using nanotechnology is as follow:

- FCMs incorporating nanomaterials to improve packaging properties (flexibility, gas barrier properties, temperature/moisture stability, light and flame resistant, transparency, mechanical stability).
- ‘‘Active’’ FCMs that incorporate nanoparticles with antimicrobial or oxygen scavenging properties.
- ‘‘Intelligent’’or “smart” food packaging incorporating nanosensors for sensing and signaling of microbial and biochemical changes, release of antimicrobials, antioxidants, enzymes, flavours and nutraceuticals to extend shelf-life
- Biodegradable polymer–nanomaterial composites by introduction of inorganic particles, such as clay, into the biopolymeric matrix and can also be controlled with surfactants that are used for the modification of layered silicate (Sozer and Kokini, 2009; Chaudhry et al, 2008; Miller and Sejnon, 2008; Joseph and Morrison, 2006; Doyle, 2006; Lopez- Rubio et al. 2006; Brody, 2007).

Improved packaging

A variety of nanoparticle reinforced polymers, also termed as ‘‘nanocomposites’’ have been developed, which typically contain up to 5% w/w nanoparticles with clay nanoparticle composites with improved barrier properties (80-90% reduction) for the manufacture of bottles for beer, edible oils and carbonated drinks and films (Chaudhry et al, 2008; Meech, 2007; Brody, 2007). Example of available nanoclay composites include Imperm® (from Nanocor® Inc.), Aegis® X (Honeywell), Durethan® KU2-2601 (Bayer AG), Plastic Technology, Miller Brewing Co. (USA), Hite Brewery Co. Nanoparticle composites include DuPont Light Stabilizer 210’, Durethan®, Bayer’shaving (Scrinis and Lyons, 2007; Chaudhry et al, 2008; Sozer and Kokini, 2009; Giner et al, 2009 Meech, 2007; Miller and Sejnon, 2008). United States Food and Drug Administration (USFDA) has approved the use of nanocomposite in contact with foods (Sozer and Kokini, 2009).

Active packaging

Nano silver, Nano magnesium oxide, nano copper oxide, nano titanium dioxide and carbon nanotubes are also predicted for future use in antimicrobial food packaging (Doyle et al, 2006, Miller and Sejnon, 2008; Chaudhry et al, 2008). Kodak company is developing antimicrobial packaging for food products that will be commercially available in 2005 and ‘active packaging,’ which absorbs oxygen (Asadi and Mousavi, 2006). Other companies include FresherLonger™ Miracle Food Storage Containers’’ and ‘‘Fresher Longer™ Plastic Storage Bags’’ from Sharper Image® USA, ‘‘Nano Silver Food Containers’’ from A-DO Korea, and ‘‘Nano Silver Baby Milk Bottle’’ from Baby Dream® Co. Ltd. (South Korea). Oxygen scavenging packaging using enzymes between poly ethylene films have also been developed (Lopez et al, 2006). An active packaging application could also be designed to stop microbial growth once the package is opened by the consumer and rewrapped with an active-film portion of the package (Brody, 2007). Zinc oxide quantum dots were utilized as a powder, bound in a polystyrene film (ZnO-PS), or suspended in a poly vinyl prolidone gel (ZnO-PVP) as antimicrobial packaging against *Listeria monocytogenes, Salmonella enteritidis, and Escherichia coli* O157:H7 (Sun et al, 2009).

Smart/ Intelligent packaging

BioMerieux have developed a multi-detection test – Food Expert ID for nano surveillance response to food scares. Nano-scale radio frequency identification tags (RFid) have been developed to track containers or individual food items (Burrah and Dutta, 2009) and are being used in retailing chains (Joseph and Morriosn, 2006; Asadi and Mousavi, 2006). The nanotech company pSiNutria are also developing nano-based tracking technologies, including an ingestible BioSilicon which could be placed in foods for monitoring purposes and pathogen detection, but could also be eaten by consumers (Scrinis and Lyons, 2007; Miller and Sejnon, 2008). US company Oxonica Inc has developed nano barcodes (20-500 nm in diameter and 0.04-15 mm in length) to be used for individual items or pellets, which must be read with a modified microscope for anti-counterfeiting purposes (Miller and Sejnon, 2008; Warad and Dutta, 2005). Engineered nanosensors are being developed by Kraft along with Rutgers University (U.S.) with in packages to change colour to warn the consumer if a food is beginning to spoil, or has been contaminated by pathogens using electronic 'noses' and 'tongues' to 'taste' or 'smell' scents and flavours (Joseph and Morrison, 2006, Asadi and Mousavi, 2006; Scrinis and Lyons, 2007; Sozer and Kokini, 2009). Nestlé, British Airways, MonoPrix Supermarkets are using chemical nanosensors that can detect colour change (Pehanich, 2006).

Edible nano coatings

A nanolaminate consists of 2 or more layers of material with nanometer dimensions that are physically or chemically bonded to each other (1-100 nm per layer, usually 5 nm) could be used to encapsulate various hydrophilic, amphiphilic, or lipophilic substances, active functional agents such as antimicrobials, antibrowning agents, antioxidants, enzymes, flavors, and colors with improved moisture and gas barrier properties and can be created entirely from food-grade ingredients (proteins, polysaccharides, lipids). These functional agents would increase the shelf life and quality of coated foods such as meats, cheese, fruit and vegetables, confectionery, bakery goods and fast food (Wiess et al, 2006). United States Company Sono-Tek Corp. announced in early 2007 that it has developed an edible antibacterial nano coating which can be applied directly to bakery goods; it is currently testing the process with its clients (Miller and Sejnon, 2008).

Nanosensors in food safety and analysis

A nanosensor is a device consisting of an electronic data processing part and a sensing layer or part, which can translate a signal such as light, or the presence of an organic substance or gas into an electronic signal structured at the nanometre scale (http://files.nanobio-raise.org/Downloads/Nanotechnology-and-Food-fullweb.pdf).

Array biosensors, Nanoparticle based sensors, Nanocantilevers, Nano-test-strips, Nanoparticles in solution; electronic noses etc. have been used as nanosensors to detect pathogens, toxins, chemicals and analysis in foods (Doyle, 2006; Bhattacharya et al., 2007; Baurah and Dutta, 2009; Naja et al., 2010; Sozer and Kokini, 2009; Tang et al., 2009; Valdes et al., 2009). EU-funded BioFinger project has developed portable biosensor Bio-Nano and MicroElectroMechanical Systems (BioMEMS) using nanocantilevers for detection of biological entities, chemicals and toxins (Joseph and Morrison, 2006).

Toxicology and safety aspect of nanoparticles

The nanomaterials incorporation into foods presents a whole new array of risks for the public, workers in the food industry and farmers because: (1) Are more chemically reactive than larger particles; (2) have greater access to our bodies than larger particles (3) Enhanced toxicity due to greater bioavailability (4) can compromise our immune system response and (5) may have longer term pathological effects (Hoet et al., 2004; Miller and Senjen, 2008).

They translocate to skin, brain, liver etc and cause oxidative damage in cells. Reports on nano-particle uptake by endothelial cells, pulmonary epithelium, intestinal epithelium, alveolar macrophages, other macrophages, nerve cells and other cells are available and may also be associated with rising levels of immune system dysfunction and inflammations of the gastrointestinal tract, including Crohn's disease (Chaudhry et al., 2008). They can translocate from lungs to blood, Central Nervous System (CNS) through nerve cells and have been implicated in Parkinson's and Alzheimer's disease (Chau et al., 2007; Miller and Sejnon, 2008). They can also cause oxidative damage to the cells (Chaudhry et al., 2008). Long term exposure can cause acute toxic response such as lesions in kidneys and liver, granulomas, cancers, clots etc. Nanoparticles can also be taken up by the broken or damaged skin or even by brain cells (Miller and Sejnon, 2008). Particles smaller than 70 nm can enter cell nuclei and even cause impairment of DNA replication and transcription (Chaudhry et al., 2008).

Regulations

The European Union regulations for food and food packaging have recommended that for the introduction of new nanotechnology, specific safety standards and testing procedures are required (Halliday, 2007). In the United States, nanofoods and most of the food packaging are regulated by the USFDA (Badgley et al., 2007), while in Australia, nanofood additives and ingredients are regulated by Food Standards Australia and New Zealand (FSANZ), under the Food Standards Code (Bowman and Hodge, 2006). In India food safety regulations are introduced but not adequate for the monitoring safety of nanoparticles.

Existing laws are inadequate to assess risks posed by nano based foods and packaging because: (1) Toxicity risks remain very poorly understood (because of their unique properties); (2) are not assessed as new chemicals according to many regulations (3) Current exposure and safety methods are not suitable for nanomaterials and (4) many safety assessments use confidential industry studies (Chaudhry et al., 2008; Miller and Senjen, 2008). Up to now, there is no international regulation of nanotechnology or nanoproducts.

Conclusion

The use of nanotechnology to manufacture of processed foods with enhanced processing, health and packaging functionalities - flavour, texture, shelf-life, transportability, reduced costs and nutritional traits will facilitate the expansion of the range, quality and quantity of processed foods, and to thereby meet the contemporary demands for both ‘health’ and ‘convenience’. It has enabled the development of food safety and food quality aspects. But in the end, regulatory considerations (including safety/toxicology and environmental impact), economics, and consumer acceptance of nanotechnology will ultimately dictate its success in food applications.

References

Acosta, E. 2008. Bioavailability of nanoparticles in nutrient and nutraceutical delivery. Curr. Opin. Coll. Interface Sci. 14(1):3-15.

Anon, Available: http://files.nanobio-raise.org/Downloads/Nanotechnology-and-Food-fullweb.pdf.

Anon, 2006. Nanotechnology. Available: http://www.ifst.org/science_technology_resources / for_ food_ professionals/ information_ statements/index/#

Anon, Nanotechnology and food. Available: http://files.nanobio-raise.org/Downloads/Nanotechnology-and-Food-fullweb.pdf.

Arecchi, A. 2009. 14th Workshop on the Developments in Italian Ph.D. Research on Food Science Technology and Biotechnology - University of Sassari Oristano, Sept.16–18, 2009. Electrospun nanofibrous membranes: novel materials for food technology Applications. Available:http://www.Consorziouno.it/consorziouno/export/sites/default/Workshop/Contributi/IIIAnno/Arecchi.pdf.

Asadi, G. and M. Mousavi. 2006. Application of Nanotechnology in Food Packaging. Available: http://iufost.edpsciences.org

Badgley, C., J. Moghtader, E. Quintero, E. Zakem, L. M. Chappel, K. Aviles-Vazquez, A. Salon and I. Perfecto. 2007. Organic agriculture and the global food supply. Renew Ag. Food Sys. 22(2):86-108.

Baurah, S. and J. Dutta. 2009. Nanotechnology applications in pollution sensing and degradation in agriculture: a review. Environ. Chem. Lett. 7:191–204.

Bhattacharya, S., J. Jang, L. Yang, D. Akinand R. Bashir. 2007. BioMEMS and nanotechnology-based approaches for rapid detection of biological entities. J. Rapid Methods Automation Microbiol. 15:1–32.

Bikker, J. F. G. and C. G. Kruif. 2006. Unique milk protein based nanotubes: Food and nanotechnology meet. Trends Food Sci. Technol. 17:196–203.

Bouwmeester, H., 2007. Health impact of nanotechnologies in food production. Available: http://www.rivm.nl/bibliotheek/digitaldepot/healthimpactnanotechnologies.pdf.

Bowman, D. and G. Hodge. 2006. Nanotechnology: Mapping the wild regulatory frontier. Futures 38:1060-1073.

Brody, A. L. 2007. Case studies on nanotechnologies for food packaging. Food Technol. 07:102-107.

Bugusu, B. C. Mejia, B. Magnuson, S. Tafazoli. 2009. Global regulatory food policies on nanotechnology. Food Technol. 63(5):24–29.

Chau, C. F., S. H. Wu and G. C. Yen. 2007. The development of regulations for food nanotechnology. Trends Food Sci. Technol. 18:269-280.

Chaudhry, Q., M. Scotter, J. Blackburn, B. Ross, A. Boxall, L. Castle, R. Aitken and R. Watkins. 2008. Applications and implications of nanotechnologies for the food sector. Food Additives Cont. 25(3):241–258.

Chen, H., J. Weiss and F. Shahidi. 2006a. Nanotechnology in nutraceuticals and functional foods. Food Technol. 03:30-36.

Chen, L. and M. Subriade. 2005. Chitosan/β-lactoglobulin core–shell nanoparticles as nutraceutical carriers. Biomaterials 26:6041–6053.

Chen, L., G. E. Remondetto and M. Subirade. 2006b. Food protein-based materials as nutraceutical delivery systems. Trends Food Sci. Technol. 17:272–283.

Choi, M. J., U. Ruktanonchai, A. Soottitantawat and S. G. Min. 2009a. Morphological characterization of encapsulated fish oil with β-cyclodextrin and polycapro-lactone. Food Research Int. 42:989–997.

Choi, M. J., U. Ruktanonchai, A. Soottitantawat and S. G. Min. 2009b. Physical and light oxidative properties of eugenol encapsulated by molecular inclusion and emulsion–diffusion method. Food Research Int. 42:148–156.

Chu, B. S., S. Ichikawa, S. Kanafusa and M. Nakajima. 2007. Preparation of protein-stabilized β-Carotene nanodispersions by emulsification – evaporation method. J. Am. Oil Chem. Soc. 84:1053–1062.

Cientifica Report. 2006. Nanotechnologies in the Food Industry, published August 2006. Available:www.cientifica.com/www/details.php?id=47. Accessed: 24 October 2010.

Cuartas-Uribe, B., M. I. A. Miranda, E. S. Costa and A. B. Pia, 2007. Comparison of the Behavior of Two Nanofiltration Membranes for Sweet Whey Demineralization. J. Dairy Sci. 90:1094–1101.

Díaz-Reinoso, B., A. Moure, H. Domínguez and J. C. Parajó. 2009. Ultra- and nanofiltration of aqueous extracts from distilled fermented grape pomace. J. Food Eng. 91:587–593.

Doyle, M. E. 2006. Nanotechnology: A brief literature review. Available: http://www.wisc.edu/fri/briefs/FRIBrief_Nanotech_Lit_Rev.pdf.

Duke, M. C., A. Lim, S. C. Luz and L. Nielsen. 2008. Lactic acid enrichment with inorganic nanofiltration and molecular sieving membranes by pervaporation. Food Bioprod. Process. 86:290–295.

Fernandez, A., D. Cavaa, M. J. Ocio and J. M. Lagaron. 2008. Perspectives for biocatalysts in food packaging. Trends Food Sci. Technol. 19:198-206.

Fernandez, A., S. T. Giner and J. M. Lagaron. 2009. Novel route to stabilization of bioactive antioxidants by encapsulation in electrospun fibers of zein prolamine. Food Hydrocoll. 23:1427–1432.

Garti, N. and A. Aserin. 2007. Understanding and Controlling the Microstructure of Complex Foods, In: M. D. Julian (Ed.), pp. 504–553. Nanoscale liquid self-assembled dispersions in foods and the delivery of functional ingredients, Woodhead Publishing Ltd., Cambridge, UK.

Gaysinsky, S., P. M. Davidson, D. J. McClements and J. Weiss. 2008. Formulation and characterization of phytophenol-carrying antimicrobial microemulsions. Food Biophys. 3:54–65.

Halliday, J. 2007. EU Parliament votes for tougher additives regulation. FoodNavigator.com 12.07.2007.

Helmut Kaiser Consultancy. 2004. Nanotechnology in food and food processing industry worldwide 2008-2010-2015 Report. Zurich, Switzerland.

Hoet, P. H. M., I. B. Hohlfeld and O. V. Salata. 2004. Nanoparticles – known and unknown health risks. J. Nanobiotech. 2:12.

Huang, Q. R., H. L. Yu. and Q. M. Ru. 2009. Bioavailability and delivery of nutraceuticals using nanotechnology. J Food Sci. Epub Online 2009 Dec 10.

Ipsen, R. and J. Otte. 2007. Self-assembly of partially hydrolysed α-lactalbumin. Biotechnol. Adv. 25:602–605.

Jafari, S. M., E. Assadpoor, B. Bhandari and Y. He. 2008. Nano-particle encapsulation of fish oil by spray drying. Food Research Int. 41:172–183.

Joseph, T. and M. Morrison. 2006. Nanotechnology in Agriculture Food: A Nanoforum report published in 2006. Available: www.nanoforum.org.

Kang, S., M. Pinault, L. D. Pfefferle and M. Elimelech. 2007. Single walled carbon nanotubes exhibit strong antimicrobial activity. Langmuir. 23(17):8670-8673.

Kaul, S. 2005. Nanofiltration. Available: http://tahan.com/charlie/nanosociety/course201/nanos/SK.pdf.

Kim, J., J. W. Grate. and P. Wang. 2008. Nanobiocatalysis and its potential applications. Trends Biotechnol. 26(11):639-646.

Kosseva, M. R., P. S. Panesar, G. Kaur and J. F. Kennedy. 2009. Use of immobilised biocatalysts in the processing of cheese whey. Int. J. Biol. Macromol. 45:437–447.

Kuzma, J. and P. Verhage. 2006. Nanotechnology in agriculture and food production - Anticipated applications, Available:

http://www.nanowerk.com/nanotechnology/reports / reportpdf/ report65.pdf.

Lee, D. G., K. M. Ponvel, M. Kim, S. Hwang, I. K. Ahn and C. H. Lee. 2009. Immobilization of lipase on hydrophobic nano-sized magnetite particles. J. Mol. Catal. B: Enzym. 57:62–66.

Li, F. S. and W. T. Wu. 2009. Lipase-immobilized electrospun PAN nanofibrous membranes for soybean oil hydrolysis. Biochem. Eng. J. 45:48–53.

Liu, N. and H. J. Park. 2010. Factors effect on the loading efficiency of Vitamin C loaded chitosan-coated nanoliposomes. Coll. Surf. B: Biointerfaces 76(1):16-19.

Lopez-Rubio, A., R. Gavara and J. M. Lagaron. 2006. Bioactive packaging: turning foods into healthier foods through biomaterials. Trends Food Sci. Technol. 17:567-575.

Losso, J. N. 2007. Development and delivery of anti-angiogenic functional food products: Opportunities and challenges. In: Anti-angiogenic functional and medical foods, Taylor and Francis Group, LLC. pp.673-697.

Malheiros, P. S., D. J. Daroit, N. P. Silveira and A. Brandelli. 2010. Effect of nanovesicle-encapsulated nisin on growth of *Listeria monocytogenes* in milk. Food Microbiol. 27(1):175–178.

Mannino, S. and M. Scampicchio. 2007. Nanotechnology and food quality control. Vet. Res. Commun. 31(1):149–151.

Mao, X., J. Huang, M. F. Leung, Z. Du, L. Ma, Z. Huang, P. Li and L. Gu. 2006. Novel core-shell nanoparticles and their application in high-capacity immobilization of enzymes. Appl. Biochem. Biotechnol. 135:229-239.

McCall, J. 2007. On some factors that affect the ‘feel’ of molecules. Thesis submitted in School of Applied Science, Cranfield University.

Meetoo, D. 2011. Nanotechnology and the food sector: From the farm to the table. Emirates J. Food Agric. 23(5):387-407.

Miller, G. and R. Senjen. 2008. Out of the laboratory and on to our plates - Nanotechnology in food and agriculture. Available:http://www.foeeurope.org/activities/nanotechnology/Documents/Nano_food_report. Pdf.

Morris, V. 2007. Nanotechnology and food. Available: http://www.iufost.org/reports_resources/bulletins/documents/IUF.SIB. Nanotechnology.pdf

Morris, V. J. and R. Parker. 2008. Natural and designed self-assembled nanostructures in foods. The World of Food Science: Food Nanotechnology 4. Available: http://www.worldfoodscience.org/cms/?pid=1004050.

Naja, G., P. Bouvrette, J. Champagne, R. Brousseau and J. H. T. Luong. 2010. Activation of nanoparticles by biosorption for *E coli* -detection in milk and apple juice. Appl. Biochem. Biotechnol. 162(2):460-475.

Pehanich, M. 2006. Small gains in processing and packaging. Food Process. 11: 46-48

Raman, O. and D. Danino. 2008. Lipid self-assembled particles for the delivery of nutraceuticals. In: Delivery and controlled release of bioactives in foods and nutraceuticals, Woodhead Publishing Limited. pp- 207-233.

Ribeiro, H. S., B. S. Chu, S. Ichikawa and M. Nakajima. 2008. Preparation of nanodispersions containing β-carotene by solvent displacement method. Food Hydrocoll. 22:12–17.

Sabliov, C. M. and C. E. Astete. 2008. Encapsulation and controlled release of antioxidants and vitamins. In: Delivery and controlled release of bioactives in foods and nutraceuticals, Woodhead Publishing Limited. pp-297-330.

Sangamithra, A. and V. Thirupathi. 2009. Nanotechnology in food. Available: http://www.technopreneur.net/informationdesk/sciencetechmagazine/2009/jan09/nanotechnology.pdf.

Sanguansri, P. and M. A. Augustin. 2006. Nanoscale materials development - a food industry perspective. Trends Food Sci. Technol. 17:547-556.

Sanvicens, N. and M. P. Marco. 2008. Multifunctional nanoparticles – properties and prospects for their use in human medicine. Trends Biotechnol. 26(8):425-433.

Scrinis, G. and K. Lyons. 2007. The emerging nanocorporate paradigm: nanotechnology and the transformation of nature, food and agri-food systems. Int. J. Sociol. Food Agri. 15(2):22-44.

Semo, E., E. Kesselman, D. Danino and Y. D. Livney. 2007. Casein micelle as a natural nano-capsular vehicle for nutraceuticals. Food Hydrocoll. 21:936–942.

Shelke, K. 2006. Tiny, invisible ingredients, Available: http://www.foodprocessing.com/articles/2006/227.html.

Shekhon, B. S. 2010. Food nanotechnology – an overview. Nanotech. Sci. Appl. 3:1–15.

Sozer, N. and J. L. Kokini. 2009. Nanotechnology and its applications in the food sector. Trends Biotechnol. 27(2):82-89.

Subirade, M. and L. Chen. 2008. Food-protein-derived materials and their use as carriers and delivery systems for active food components. In: Delivery and controlled release of bioactives in foods and nutraceuticals, Woodhead Publishing Limited. pp- 251-278.

Sun, D., T. Jin, J. Y. Su, H. Zhang and H. J. Sue. 2009. Antimicrobial efficacy of Zinc Oxide Quantum Dots against Listeria monocytogenes, Salmonella enteritidis, and Escherichia coli O157:H7. J. Food Sci. 74(1):M46-M52.

Surassmo, S., S. G. Min, P. Bejrapha and M. J. Choi. 2010. Effects of surfactants on the physical properties of capsicum-oleoresin-loaded nanocapsules formulated through the emulsion-diffusion method. Food Research Int. 43(1):8-17.

Tan, C. P. and M. Nakajima. 2005. β-Carotene nanodispersions: preparation, characterization and stability evaluation. Food Chem. 92:661–671.

Tang, D., J. C. Sauceda, Z. Lin, S. Ott, E. Basova, I. Goryacheva, S. Biselli, J. Lin, R. Niessner and D. Knopp. 2009. Magnetic nanogold microspheres-based lateral-flow immunodipstick for rapid detection of aflatoxin B2 in food. Biosensors Bioelectron. 25:514–518.

Teixeira, M. L., J. Santos, N. P. Silveira and A. Brandelli. 2008. Phospholipid nanovesicles containing a bacteriocin-like substance for control of Listeria monocytogenes. Innov. Food Sci. Emerg. Technol. 9:49–53.

Tiwari, D. K., J. Behari and P. Sen. 2008. Application of nanoparticles in waste water treatment. World Appl. Sci. J. 3(3):417-433.

Türk, M. and R. Lietzow. 2004. Stabilized nanoparticles of phytosterol by rapid expansion from supercritical solution into aqueous solution. AAPS PharmSciTech. 5(4):1-10.

Valdés, M. G., A. C. V. González, J. A. G. Calzón and M. E. D. García. 2009. Analytical nanotechnology for food analysis. Microchim. Acta.166:1–19.

Vidhyalakshmi, R., R. Bhakyaraj and R. S. Subhasree. 2009. Encapsulation "The future of probiotics" – A review. Adv. Biol. Res. 3(3-4):96-103.

Wang, W., L. Zhang, S. Tong, X. Li and W. Song. 2009. Three-dimensional network films of electrospun copper oxide nanofibers for glucose determination. Biosens. Bioelectron. 25(4):708–714.

Warad, H. C. and J. Dutta. 2005. Nanotechnology for agriculture and food systems – a view. Available: http://www.nano.ait.ac.th/Download/AIT%20Papers/2005/Nanotechnol ogy %20 For%20Agriculture %20And%20 Food% 20Systems%20_%20A%20View.pdf.

Weiss, J., P. Takhistov and D. J. Mcclements. 2006. Functional materials in food nanotechnology. J. Food Sci. 71(9):R107-R116.

Yuan, Y., Y. Gao, J. Zhao and L. Mao. 2008. Characterization and stability evaluation of β-carotene nanoemulsions prepared by high pressure homogenization under various emulsifying conditions. Food Research Int. 41:61–68.

Zhang, S., H. Zhang, Q. Wang, P. He and Y. Fang. 2008. Determination of carbohydrates by capillary zone electrophoresis with amperometric detection at a nano-nickel oxide modified carbon paste electrode. Food Chem. 106:830–835.

Zhong, Q., M. Jin, P. M. Davidson and S. Zivanovic. 2009. Sustained release of lysozyme from zein microcapsules produced by a supercritical anti-solvent process. Food Chem. 115:697–700.

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