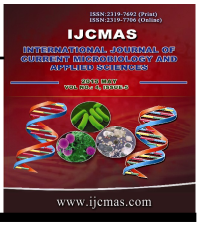

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Review Article

Nanotechnology in Food Industry; Advances in Food processing, Packaging and Food Safety

Mahmoud M. Berekaa*

Environmental Health Department, College of Applied Medical Sciences, University of Dammam, Dammam 31441, Saudi Arabia

**Corresponding author*

ABSTRACT

Keywords

Nanoparticles, Nanocapsules, Nanosensors, Food packaging, Food safety, Food processing

This review focuses on tremendous benefits of nanotechnology in food industry in terms of food processing, packaging, safety and quality control. Nanotechnology can modify permeability of packaging material, increasing barrier properties, improving mechanical and heat-resistance, developing active antimicrobial surfaces, and creates nano-biodegradable packaging materials. Nanotechnology has prospective revolution in food industry by design of nutrient delivery system to produce nano-formulated agrochemicals, enrich nutritional values and generation of novel products through bioactive encapsulation. It has been used in innovative development of biosensors for detection of pathogens and chemical contaminants. This new technology also raises a serious concern about toxicological aspects of nanoparticles in food, with emphasis on the risk assessment and safety issues. Also, it reflects the urgent need for regulatory framework capable of managing any risks associated with implementation of nanoparticles in food technology.

Introduction

Nanotechnology is emerging as a rapidly growing field with its wide application in science and technology for manufacturing of new materials at nanoscale level (Albrecht *et al.*, 2006). This technology gained a tremendous impetus due to its capability of reformulating metals into new nanosized particles, with dimension less than 100 nm in size. Due to nanoparticle size, their physio-chemical properties drastically changes leading to broad spectrum of new applications.

In recently years, huge advances in nanotechnology open up a new era in industrial technology. Majority of nanoparticles incorporated into products related to several fields (Benn and Westerhoff, 2008; Heinlaan *et al.*, 2008; Li *et al.*, 2008; Wokovich *et al.*, 2009; Marambio-Jones and Hoek, 2010; Antonio *et al.,* 2014). Nanoparticles have been used in disinfection of textile fabrics, water disinfection, medicine, and food packaging (Hajipour *et al.,* 2012; Seil and Webster, 2012: Mihindukulasuriya and Lim, 2014). Due to their high surface area to volume ratio and the unique chemical and physical properties, nanoscale materials have emerged up as novel antimicrobial agents (Morones *et al.,* 2005; Kim *et al.,* 2007).

As an example, conventional TiO_2 has been applied in several applications due to its biocidal and antiproliferative properties, especially in presence of UV (Blake *et al.,* 1999). The use of silver nanoparticles as a new generation of antimicrobials was extensively discussed (Rai *et al.,* 2009; Duncan, 2011). Duran *et al.* (2007) reported that ionic or metallic silver as well as silver nanoparticles can be used in medicine, steel coating, textile fabrics, water treatment, sunscreen lotions and others.

Recently, innovative nanotechnology has revolutionized the food industry (Sanguansri and Augustin, 2006; Weiss *et al.,* 2006; Chaudhry *et al.,* 2008; Silvestre *et al.,* 2011; Cushen *et al.,* 2012; Rossi *et al.,* 2014; Thangave and Thiruvengadam, 2014).There is progressive improvement in use of nanoparticles in food industry especially on food processing, packaging, storage and development of innovative products. Nanoparticles aimed at enhancing bioavailability of nano-sized nutraceuticals and health supplements, improving taste and flavor, consistency, stability and texture of food products (Chaudhry *et al.,* 2008; Chaudhry *et al.,* 2010; Momin *et al.,* 2013). Due to antimicrobial characteristics of nanoparticles it can be incorporated into the food packaging materials to increase shelf life and keep it safe for human consumption. It is predicted that the invasion of the food production market with nanoparticles will be significantly increased in the near future (Heinlaan *et al.,* 2008). Moreover, the use of encapsulated nanoparticles enable the development of nano-formulated agrochemicals such as pesticides, fertilizers, biosides, veterinary medicine, additives, antimicrobials and detoxifying compounds. In human food processing, nanocapsules have been used as nano-sized ingredients, additives, nutritional supplements, and in functional foods (Momin *et al.,* 2013). Cushen *et al.,* (2012) reported that nanoencapsulation of food ingredients and additives have been carried out to provide protective barriers, flavor and taste masking, controlled release, and better dispensability for water-insoluble food ingredients and additives. There is developing public concern regarding the toxicity and adverse effect of nanoparticles on human health and environment. Therefore, establishment of regulatory system capable of managing risks associated with the use of nanoparticles is recommended.

This review provides a comprehensive analysis of current developments in nanoparticles technology applied to food industry starting from food processing and packaging to food safety and quality control. With emphasis on toxicity and health concerns due to the incorporation of nanoparticles in food, with brief overview on the regulatory outlook.

Nanotechnology in food processing and packaging

Nanotechnology in food processing

During food processing, nanoparticles have been applied to improve nutritional quality, flow properties, flavor, color and stability or to increase shelf life. Indeed, nanotechnology might help in development of healthier food with lower fat, sugar and salts to overcome many food-related diseases. Recently, bulk amounts of SiO_2 and TiO_2 oxides have been permitted as food additives (E551 and E171, respectively) (EFSA, 2000). Effective olive oil hydrolysis by the use of covalent immobilization of porcine triacylglycerol lipase onto functionalized nanoscale SiO2 with reactive aldehyde group for better reuse, adaptation and stability have been reported (Bai *et al.*, 2006). Several nano- and micro-structured assemblies of nanoparticles have been designed for encapsulation of food ingredients, additives, nutritional supplements as well as functional foods (Augustin and Hemar, 2009).

Nano-sized additives and nutraceuticals

The potential of nanotechnology in functional food, design of nutritional supplements and nutraceuticals containing nanosized ingredients and additives such as; vitamins, antimicrobials, antioxidants, and preservatives are currently available for enhanced taste, absorption and bioavailability (Momin *et al.*, 2013). Some nutraceuticals incorporated in the carriers include lycopene, beta-carotenes and phytosterols are used in healthy foods to prevent the accumulation of cholesterol (Mozafari *et al.*, 2006).

Nanoencapsulation

The design of nanostructured assemblies for delivery of food additives recently reviewed (Augustin and Hemar, 2009). Nano-sized carrier systems or nanocapsules, in the form of liposomes, micelles, or protein based carriers have been used as nano-food additives, nutritional supplements, mask the undesirable taste, enhance bioavailability, and allow for better dispersion of insoluble additives without need for surfactants or emulsifiers (Morris *et al.*, 2011; Cushen *et al.*, 2012; Duran and Marcato, 2013). During nanoencapsulation the food additive substances are enclosed in nanocomposite polymer e.g. Octenyl succinic anhydride-ε-polylysine for controlled release (Yu *et al.*, 2009; Sekhon, 2010). Anti-cancer activity of curcumin was enhanced by encapsulation in hydrophobically modified starch (Yu and Huang, 2010). Furthermore, the use of lipid-based nanoencapsulation e.g. nanoliposomes, nanocochleates, and archaeosomes as nano-delivery system for nutraceuticals, enzymes, food additives, and anitmicrobials was reported (Mozafari *et al.*, 2006; Mozafari *et al.*, 2008). Nanoencapsulation of probiotics to be targeted to specific region in GI tract has been achieved (Vidhyalakshmi *et al.*, 2009).

Inorganic nano-sized additives and composites such as; silver, iron, calcium, magnesium, selenium and silica have been used as preservative and additives to improve taste and flavours. Moreover, silica gel micro-spheres mixed with silica thio-sulfate are used for long lasting antibacterial activity (Gupta and Silver, 1998). An example of nano-sized particles is the addition of food-grade polypeptide, ε-Polylysine as antioxidant to protect oil from oxidation. These Polylysine nanoparticles are much smaller than phytoglycogenoctenyl succinate nanoparticles, allowing them to fill in the gaps between phytoglycogenoctenyl succinate nanoparticles (Scheffler *et al.*, 2010). Vargas *et al.* (2008) described the design of a nanocoating to be used as carrier of functional ingredients during nanoencapsulation process. Edible nanoparticle films based on chitosan obtained by incorporating nanoparticles made from montmorillonites, nanosilver or silver zeolite (Rhim *et al.*, 2006).

On the other hand, there is growing interest for the use of encapsulated nanomaterials in agriculture for production of nano-formulated agrochemical such as; pesticides, fertilizers, biosides and in veterinary medicine. These nanocapsules proved to be more efficient, durable and help in controlled release of active ingredient. In animal feeds nanocapsules can be used designed to incorporate nanoadditives, antimicrobials and detoxifying compounds e.g. mycotoxin-binding. The use of nanosensors for Detection of animal pathogens is aspect for use of nanoparticles in agriculture. Recently, nanocapsules and nanoemulsions have been used in production of nanopesticide e.g. products containing pristine engineered nanoparticles, such as metals, metal oxides, and nanoclays (Kahand Hofmann, 2014; Kookana *et al.*, 2014).

Silver zeolite

Another important application of silver nanoparticles is its use in the form of Silver zeolite. Silver zeolite is made by complexing alkaline earth metal with crystal aluminosilicate, which is partially replaced by silver ions using ion exchange method. In fact, the antimicrobial activity of silver zeolites is mainly due to the ability of silver to produce ROS that is responsible for cell death (Inoue *et al.*, 2002). Silver zeolite coated ceramics are used as antimicrobial agent in many products e.g. food preservation, disinfection of medical products and decontamination of materials (Kawahara *et al.*, 2000; Matsumura *et al.*, 2003).In Comparison with zeolite-based material, silver-based nanocomposite showed sustained antimicrobial activity and thus better suited for long term food packaging (Egger *et al.*, 2009).

Nanotechnology in food packaging

The crucial role of nanotechnology in food packaging process is considered as the largest commercial application in food sector (Chaudhry *et al.*, 2010). In recent years, there is more concern about research and innovation in food packaging materials ranging from films, carbon nanotubes, to waxy nano-coatings for some foods. The use of nanoparticles might help in production of new food packaging materials with improved mechanical, barrier and antimicrobial properties to increase shelf life (Chaudhry *et al.*, 2008; Mihindukulasuriya and Lim, 2014). Beside antimicrobial characteristics, nanoparticles can be used as vehicle to deliver antioxidants, enzymes, flavors, anti-browning agents and other materials to extend shelf life, even after opening (Cha and Chinnan, 2004; LaCoste*et al.*, 2005; Weiss *et al.*, 2006). Inorganic nanomaterials of some metals and metal oxides such as; silver, iron, titanium dioxide, zinc oxides, magnesium oxide as well as silicon dioxide and carbon nanoparticles have been used as antimicrobial agents in food packaging and in some cases as food supplement (Sekhon, 2010). Interestingly, TiO_2 is widely used as a disinfecting agent as it generates highly reactive oxygen species (ROS) that are toxic to pathogenic microorganisms. Antimicrobial activity of silver nanoparticles against *E. coli* and *Bacillus cereus* spores is greatly enhanced if combined with titanium dioxide and carbon nanotubes, respectively (Krishna *et al.*, 2005). Silver-doped TiO_2 nanoparticles also inactivated *B. cereus* spores on aluminum and polyester surfaces (Vohra *et al.*, 2005) and destroyed airborne bacteria and molds when incorporated into air filters (Vohra *et al.*, 2006). Stabilization of silver nanoparticles with SDS or PVP increases antimicrobial activity against *E. coli* and *Staphylococcus aureus* 35. Therefore, surfaces of refrigerators and storage containers are coated with silver nanoparticles to prevent growth of foodborne pathogens and food spoilage bacteria (Cho *et al.*, 2005).

Effect of UV activated TiO_2 nanoparticles against some foodborne pathogens namely; *Salmonella choleraesuis*, *Vibrio parahaemolyticus*, and *L. monocytogenes* have been reported (Kim *et al.*, 2003). Ultrasonic dispersal of TiO2 nanoparticles throughout EVOH films and its photo-activated biocidal properties against nine food poisoning microorganisms have been reported by Cerrada *et al.* (2008). Other food packaging nanoparticles with antimicrobial activity including; MgO (Stoimenov *et al.*, 2002), Cu_2O (Yoon *et al.*, 2007; Cioffi *et al.*, 2005), ZnO (Emamifar *et al.*, 2011), and chitosan (Qi *et al.*, 2004; Tan *et al.*, 2013), as well as carbon nanotubes (Kang *et al.*, 2007; Kang *et al.*, 2009) have been reported. Starch-based colloidal coating filled with antimicrobial nanoparticles enabled protection and food packaging (Boumans, 2003). Antimicrobial activity of silver nanoclay was greatly enhanced after replacement of sodium ions of montmorillonitenanoclays with silver ions when dispersed in poly(e-caprolactone) (Incoronato *et al.*, 2011) or poly(lactic acid). Recently, Gu *et al.* (2003) discovered that covalently attached vancomycin molecules to gold nanoparticles showed more potency against vancomycin-resistant bacteria. Functionalized lysozyme-coated polystyrene nanoparticles with selective antibodies and exhibited bactericidal action against *L. monocytogenes* (Yang *et al.*, 2007). Bi *et al.* (2011) revealed that phytoglycogen nanoparticles showed enhanced antimicrobial activity against *L. monocytogenes* when “nisin” was used.

Nanocomposites

Among the most prevailing application of nanoparticles in food industry is the development of nanocomposites. Production of nanocomposite material to be used for packaging and material coating was reported (Pinto *et al.*, 2013; Mihindukulasuriya and Lim, 2014). Duncan (2011) reviewed the design of several inert nanoscale fillers in a polymer matrix such as; clay and silicate nanoplatelets, silica (SiO_2) nanoparticles, carbon nanotubes, graphene, starch nanocrystals, cellulose-based nanofibers or nanowhiskers, chitin or chitosan nanoparticles and other inorganics. Incorporation of those materials into the polymer matrix renders it lighter, stronger, fire resistance, better thermal properties, less permeable to gases. Development of nanocomposites (up to 5% w/w nanoparticles) has been reported (Llorens *et al.*, 2012). Incorporation of silver nanoparticles to the polymer matrix made the nanocomposites more attractive for use in packaging (Duncan, 2011). Polymer-silicate based nanocomposites have been developed for better barrier quality, physical strength and thermal stability (Holley, 2005; Brody, 2006; Doyle, 2006). Arora& Padua (2010) studied the possible production of nano-sized fillers namely; montmorillonite, kaolinite clays, and graphite nanoplates for enhanced permeability of the food packaging materials. The use of carbon nanotubes in packaging to pump out carbon dioxide or absorb undesirable flavors is being developed (Sinha *et al.*, 2006).The use of nanoclay in design of nanocomposite (bentonite) during manufacture of bottles and other food packaging materials leads to better improvement in gas barrier properties, prevent oxygen and moisture from penetration, drink destabilisation and spoilage of food materials. Lagarón *et al.* (2005) reported that clay nanoparticles incorporated into an ethylene-vinyl alcohol copolymer as well as polylactic acid biopolymer have been found to improve the oxygen barrier properties and extend shelf life of food products. Organically-modified nanoclays have been used with polymer matrix confer mechanical strength and act as barrier against gas, volatile compounds or moisture (Chaudhry *et al.*, 2008).

Interestingly, biopolymer-based nanocomposites may even offer environmental advantages over conventional plastics. Recently, Othman (2014) reviewed the different types of nano-sized fillers and biopolymers that could be used to form biocomposite materials for food packaging purposes. Goyaland Goyal (2012) discussed the possible design of biodegradable nanocomposite using starch, polylactic acid (PLA) or polyhydroxybutyrate (PHB) biopolymers. Large number of biopolymer have been used in design of nanoclay-based nanocomposites namely; polyamides (PA), nylons, polyolefins, polystyrene (PS), ethylene vinylacetate (EVA) copolymer, epoxy resins, polyurethane, polyimides and polyethylene terephthalate (PET). Ray *et al.* (2002) reported that; when nanofilleris dispersed within the bio-compatible polymer PLA, the PLA bionanocomposite actually has a faster rate of biodegradation than PLA containing no such additives.

Nanotechnology and food safety

Nanosensors and nanosieves

The use of nanoparticles to develop nanosensors for detection of food contaminant and pathogens in food system is another potential use of nanotechnology. Indeed, tailor-made nanosensors for food analysis, flavours or colours, drinking water and clinical diagnostics have been developed (Li and Sheng, 2014). In fact, nanoparticles can be incorporated as nanostructured transducer of the biosensor devices (Vo-Dinh *et al.*, 2001). Nakamura and Karube (2003) have recently reviewed research in biosensors. Nanosensors incorporated into the food packaging materials might help in track of any physical, chemical or even biological modification during food processing phase. Smart packaging with specialized nanosensors and nano-devices have been designed to detect toxins, food pathogens and chemicals (Cheng *et al.*, 2008; Dingman, 2008; Lerner *et al.*, 2011; Yang *et al.*, 2011). Recently, Mihindukulasuriya and Lim (2014) reported the innovative application of nanotechnology in design of smart or intelligent packaging to enhance communication aspect of package. This smart packaging might increase efficiency of information transfer during distribution. The response generated due to changes related with internal or external environmental factor, will be recorded through specific sensor.

Recently, nanotechnology allowed for the design of nanosensors for identification of foodborne pathogens or toxins (Doyle *et al.*, 2006). Example; immunosensing of *Staphylococcus* sp. enterotoxin B using poly(dimethylsiloxane) (PDMS) chips with reinforced, supported, fluid bilayer membranes(r-SBMs) and specific antibodies to the toxin(Dong *et al.*, 2006). (Rivas *et al.*, 2006) developed universal G-liposomal nanovesicles based immune-magnetic bead sandwich assay to detect *E. coli* O157:H7, *Salmonella* sp., and *Listeria monocytogenes*in food. Other pathogenic microorganisms were detected with specific type of immunosorbent assay using universal protein G-liposomalnanovesicles (Chen and Dust, 2006). Furthermore, nanoparticles have been used as nanosieves to filter out bacteria. In agriculture, nanoparticles used as smart nanosensors for early warning of changing conditions that are able to respond to different conditions.

On the other hand, detection of bacterial toxins using nanoparticle technology was recently reported (Zhu *et al.*, 2014). Several biosensors have been designed for detection of most common food pathogens e.g. *Listeria monocytogenes*, *E. coli* and *Salmonella* sp. as well as mycotoxins in food (Duran and Marcato, 2013). Application of nanoparticles for detection of foodborne pathogens and their toxins was reported (Burris and Stewart, 2012). Furthermore, aflatoxins produced by *Aspergillus flavus* and *A. parasiticus* that contaminate food products could be detected by the use of magnetic nanoglodimmuno sensor (Tang, 2009).

Toxicological aspects of nanoparticles in food

Despite the tremendous benefits of nanoparticles in food industry, there is great public concern regarding toxicity and environmental effect. The key aspects concerning the bioavailability, fate, behavior, disposition and toxicity of nanoparticles in environment was discussed by Klaine *et al.* (2008). Direct exposure of consumers to nanoparticles applied in food industry poses a serious problem to human health. As long as the nanoparticles remain bound in the food packaging materials, exposure is limited or very low. However, migration of nanoparticles incorporated in food material to human is high risk.Health impact and safety regarding the use of nanoparticles was reported by Teow *et al.* (2011). The discussed the portals of nanoparticles, absorption, and distribution on human body, with emphasis on cytotoxicity as well as genotoxicity. Understanding the behavior and mechanism of action of nanoparticles in biological systems, for the development of safe nanotechnology was discussed by Stark (2011). Recently, it is reported that TiO_2 nanoparticles capable of inducing "tumor-like" changes in exposed human cells (Sanders *et al.*, 2012; Valdiglesias *et al.*, 2013; Botelho *et al.*, 2014). Toxicity assessment of metal-based nanoparticles was reviewed by Schrand *et al.* (2010). They revealed that as the particle size decrease the toxicity level increase. Modern techniques revealed that nanoparticles characterized by higher reactivity and greater ability to cross membrane barriers and capillaries, therefore can lead to different toxico kinetic and toxico dynamic properties. Some nanoparticles interact with protein and enzymes leading to induction of oxidative stress and generation of ROS, thus destruction of mitochondria and causing apoptosis following the administration of nanoparticles (Hajipour *et al.*, 2012). Unfortunately, there are limited human studies on potential toxicity of nanoparticles, although preliminary studies on animal have shown potential toxicity for liver, kidneys, and immune system. Therefore, risk assessment studies to show the adverse effect of nanoparticles on human health should be critically investigated.

Regulations

Despite the tremendous benefits of nanoparticles in food industry, there is great public concern regarding toxicity and environmental effect. Due to health implications of nanoparticles that enter body, assessment of potential risks to human health is urgently needed. Halliday (2007) mentioned that the European Union regulations for food and food packaging have recommended specific risk assessment and safety standards should be met before introduction of nano-food to market. In United States, nanofoods and most of the food packaging are regulated by the USFDA (Badgley *et al.*, 2007). While in Australia, nano-food additives and ingredients are regulated by Food Standards Australia and New Zealand (FSANZ), under the Food Standards Code (Bowman and Hodge, 2006).The raising regulatory issues enforced many countries to establish regulatory systems capable of managing any risks associated with nanofood (Cushen *et al.*, 2012; Tinkle *et al.*, 2014).

Recently, EU regulations established that any food ingredient result from application of nanotechnologies must undergo safety assessment before being authorized for use (Cubadda *et al.*, 2013). And the new nano-food or food ingredients are covered by the Novel Food regulation- implicitly in the current Regulation (EC) 258/97. Furthermore, authorized nano-food additives before 2009, and food packaging materials are subject to a re-evaluation programme by the EFSA. In many other countries, incomplete food safety regulations are introduced due to poor information about exposure, availability and toxicity to human. In fact there is urgent need for international regulation system for use of nanoparticles.

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