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A critical review on potential role of nanotechnology in food safety

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Abstract: Food safety is a great concerning issue around the world. Ensuring a sustainable supply of nutrient-dense and safe food is a grand challenge. This review assesses applications of nano-materials in food packaging, processing and safety issues. Nanotechnology has potential applications in all aspects of food sectors including food processing, food packaging, food monitoring, production of functional foods, development of foods capable of modifying their colour, flavour or nutritional properties according to a person's dietary needs as well as production of stronger flavourings, colourings and nutritional food additives. Moreover, lowering the costs of food additive ingredients and increasing the shelf life of food products could be achieved using this technology. Nano-materials particularly nanoparticles due to their mechanical, optical, catalytic, and antimicrobial properties could play a major role in food packaging. Nano food processing and products can change the color, flavor, or sensory characteristics; they also change the nutritional functionality, removes chemicals or pathogens from food. Nanobarcodes are used for safety labeling and monitor distribution of food products. This review summarizes the potential of nanoparticles for their uses in the food industry in order to provide consumers a safe and contamination free food and to ensure the consumer acceptability of the food with enhanced functional properties.
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Introduction

Food safety is one of the most concerned problems of consumers. From land to table, food ingredients need to be regulated and preserved. The main factors affecting food safety include microbial contamination, oxygen deterioration reaction, etc. Food packaging and safety detection are indispensable components of the food supply chain (Kalpana et al. 2019). In order to meet the needs of consumers for safer and better food, more accurate detection sensors and packaging with high barrier performance, antibacterial and biodegradable are needed. Food security is a broader concept than food safety, food security is built mainly on three pillars: (1). adequacy of food production, which is sufficient for the global human population; (2). sufficient resources to purchase or obtain the available food; (3). sufficient food nutrition, as well as proper food hygiene (Von Braun 2010). In recent decades, (bio)nanotechnology has become increasingly important as an appealing technology for the food industry. Nanotechnology has underpinned vital progress in current research and has immensely promoted the food production chain. Nanotechnology is a discipline composed of several fields of technology, and serves as a tool for creating, studying phenomena, or manipulating matter in nanoscale dimensions (Luttge et al. 2011). Development of novel nanomaterials makes possible to improve food quality and safety, crop growth, and monitoring environmental conditions (He et al. 2019). The obtained materials have unique properties such as high surface-to-volume ratio and their other physiochemical properties such as color, solubility, strength, diffusivity, toxicity, magnetic, optical, thermodynamic properties, etc. are improved (Singh et al. 2017). Therefore, new studies are focused on developing novel methods, techniques, and procedures for the purpose of processing, packaging, functionalization, and quality control implementation of food, and also the for nutraceutical products delivery system (Dasgupta et al. 2015). Recently, the demand for nanoparticle-based materials for the different applications e.g., food industry has increased, especially in the EU. The European nanomaterials market generated more than $2.5 million in 2015 and is expected to reach around $9 million in revenue by 2022. Many of these materials contain essential elements, some of them non-toxic that can be stable at high pressures and temperatures (Mohamadian et al. 2019; Samadi et al. 2018). Nanotechnology is one such known to possess extensive uses in food processing. Nanoparticles are often used as food additives to protect the food from contamination thereby enhancing the lifespan. Nanomaterials and nanoscale food additives in forms of preservatives, antimicrobial sensors, flavoring agent, packaging substances, encapsulated food components, and so forth are used to influence nutrient composition and improve product shelf life, texture, flavor, and so on (Bajpai et al. 2012). Nanotechnology offers multiplier opportunities for the development of inventive products and expansion of applications in food systems such as bioactives, nutraceuticals, functional foods, pharma foods, and so on (Samal and Biotechnology 2017). It can even be used to detect food pathogens acting as food quality and safety indicators (Benvenuto et al. 2014). In food processing, nanoencapsulation of food (nano-sized) ingredients, nutritional supplements (e.g., proteins and antioxidants), and additives (e.g., flavor and color) forms nanocapsules that can be incorporated in functional foods. This provides odd taste and off-flavor masking, protective barriers, controlled release, enhanced bioavailability of many vitamins and their precursors, and better delivery and dispensability for water-insoluble ingredients (solubilized by a nanoparticle formulation) (Berekaa 2015; Prakash et al. 2013).

Nanotechnology in food Packaging

Nanomaterials particularly nanoparticles are increasingly used to improve antimicrobial function, mechanical and barrier properties of food package materials, thereby extending the shelf life and maintaining freshness of packaged foods (Adeyeye and Ashaolu 2021). Because nano-materials have varying properties, they are widely used in food packaging (Rovera et al. 2020). It involves incorporating nano-materials into the packaging polymers to enhance their gas barrier properties, temperature and humidity resistance. In fish and fish product packaging, nano-materials are used as antimicrobials and to enhance barrier function. This extends the storage life of packaged food products (Anirudhan et al. 2018). The properties of polymer composites make them attractive as packaging materials; their properties depend on the type of nanoparticles that incorporate their size and shape, their concentration and their interactions with the polymer matrix (Kango et al. 2013). Nanoscale matrix is small enough to fill gaps in common polymers to meet different commercial needs. Nanoparticles also have large surface area, which can enhance the reaction efficiency of active substance and increase the uniformity of material. Due to compact structure of nanoparticles, they can be used to develop high barrier materials (Wang et al. 2020). A desirable packaging material must have gas and moisture permeability combined with strength and biodegradability (Couch et al., 2016). Nano-based "smart" and "active" food packagings confer several advantages over conventional packaging methods from providing better packaging material with improved mechanical strength, barrier properties, antimicrobial films to nanosensing for pathogen detection and alerting consumers to the safety status of food. Application of nanocomposites as an active material for packaging and material coating can also be used to improve food packaging (Pinto et al., 2013). Many researchers were interested in studying the antimicrobial properties of organic compounds like essential oils, organic acids, and bacteriocins (Gálvez et al., 2007; Schirmer et al., 2009) and their use in polymeric matrices as antimicrobial packaging. The application of nanoparticles is not limited to antimicrobial food packaging but nanocomposite and nanolaminates have been actively used in food packaging to provide a barrier from extreme thermal and mechanical shock extending food shelf-life. In this way, the incorporation of nanoparticles into packaging materials offers quality food with longer shelf-life. The purpose of creating polymer composites is to have more mechanical and thermostable packing materials. Many inorganic or organic fillers are being used in order to achieve improved polymer composites. The incorporation of nanoparticles in polymers has allowed developing more resist packaging material with cost effectiveness (Sorrentino et al., 2007). Use of inert nanoscale fillers such as clay and silicate nanoplatelets, silica (SiO_2) nanoparticles, chitin or chitosan into the polymer matrix renders it lighter, stronger, fire resistance, and better thermal properties (Duncan, 2011; Othman, 2014). Antimicrobial nanocomposite films which are prepared by impregnating the fillers (having at least one dimension in the nanometric range or nanoparticles) into the polymers offer two-way benefit because of their structural integrity and barrier properties (Rhim and Ng, 2007). The significant purpose of nano-packaging is to set longer shelf life by improving the barrier function of food packaging to reduce gas and moisture exchange and UV light exposure. By 2003, over 90% of nano-packaging was based on nanocomposites, in which nanomaterials were used to improve the barrier function of plastic wrapping for foods, and plastic bottles for beer, soft drinks and juices. Nano-packaging can also be designed to release antimicrobials, antioxidants, enzymes, flavours and nutraceuticals to extend shelf life. Biodegradable materials are mainly preferred for the development and manufacturing of food packaging in order to decrease environmental pollution (Chellaram et al. 2014). In recent years, the coating of natural polymer or a biopolymer on the surface of the food has gained much attention and has shown promising results in preserving produce (Luo et al. 2020). Food preservation is the process of treating and handling food to reduce spoilage and prevent the loss of food quality and nutrition value by microorganisms.

Nanotechnology in food Processing

Food processing is when nanoparticles are utilized in order to improve nutritional quality, flavour, colour and/ or to which increases serviceable life expectancy of the edible items. Increasing the life of the shelf and the different kinds of consumable and edible materials helps decrease the level of ruination of food that happens because of microbial contamination (Pradhan et al. 2015). Nanotechnology has many functional applications in food processing, including nanoencapsulation of flavours and aromas, and nanoemulsions to improve flavours, aromas, textures and consistency (Chaudhry et al. 2017). Such applications may result in products with improved health attributes without compromising on sensory characteristics, e.g. low fat mayonnaise which is as creamy and flavoursome as conventional alternatives (Sekhon and applications 2010), or they may more simply mask undesirable odours and flavours from healthy ingredients such as fish oils (Handford et al. 2014). Nanotech could also potentially contribute to the advancement of more beneficial nourishment with lower fat, sugar and salts that could thus defeat numerous food related ailments (Morris et al. 2011). Nanotechnology increasing the shelf-life of different kinds of food materials and also help brought down the extent of wastage of food due to microbial infestation (Pradhan et al., 2015). Nowadays nanocarriers are being utilized as delivery systems to carry food additives in food products without disturbing their basic morphology. Particle size may directly affect the delivery of any bioactive compound to various sites within the body as it was noticed that in some cell lines, only submicron nanoparticles can be absorbed efficiently but not the larger size micro-particles (Ezhilarasi et al., 2013). An ideal delivery system is supposed to have following properties: (i) able to deliver the active compound precisely at the target place (ii) ensure availability at a target time and specific rate, and (iii) efficient to maintain active compounds at suitable levels for long periods of time (in storage condition). Nanotechnology being applied in the formation of encapsulation, emulsions, biopolymer matrices, simple solutions, and association colloids offers efficient delivery systems with all the above-mentioned qualities. Nano polymers are trying to replace conventional materials in food packaging. Nanosensors can be used to prove the presence of contaminants, mycotoxins, and microorganisms in food (Bratovčić, 2015).

Most commercially available PCNC products are marketed toward a very specific application, including several in the food and beverage industry. PCNC packaging materials have, for example, become popular with beverage manufacturers, such as Miller Brewing Company (Lagaron et al. 2010), which has used them to manufacture plastic bottles possessing both high barriers to oxygen and carbon dioxide migration. Other interested parties in PCNC technology include the US Army Natick Soldier Research, Development and Engineering Center (NSRDEC), which has invested considerable time and money researching the potential use of PNC plastics to package meals ready to eat (MREs) for soldiers; in addition to currently creating an enormous amount of waste, MREs have incredibly stringent shelf-life and robustness requirements which PCNC-based packages may be uniquely able to satisfy. Processed foods are usually less susceptible to early spoilage than fresh foods and are better suited for long distance transportation from the source to the consumer. All these are made more effective by the incorporation of the nanotechnology nowadays .Nano capsules delivery systems plays an important role in processing sector and the functional property are maintained by encapsulating simple solutions, colloids, emulsions, biopolymers and others into foods (Abbas et al. 2009). Nano sized self assembled structural lipids serves as a liquid carrier of healthy components that are insoluble in water and fats called as nanodrops. They are used to inhibit transportation of cholesterol from the digestive system into the bloodstream (Dingman 2008). The application of nanotechnology in food processing can be broadly classified as “direct” and “indirect” usage. Direct applications mean direct incorporation of nanosized substances in the food matrix along with the declaration as such. The direct applications mostly include mixing of fragrances, coloring agents, nanopreservatives, antioxidants, and bioactive compounds such as vitamins, fatty acids, polyphenols, and so on. Indirect application comprises the usage of nanosized substances in the packaging material (McClements et al., 2012), nanosensors, and catalysts in hydrogenation of fats (Barbosa-Canovas et al. 2009; Stanković et al. 2009). The foods in which nanostructures are indirectly applied subsequently come in direct application to the food such as fats and oils hydrogenated with nanostructured catalysts finally find their way in the direct application of foods (Yam et al., 2005).

Nanotechnology in food safety

Food safety is a growing public health concern of global significance. Foodborne microbial diseases account for about 20 million cases annually in the world. The primary objective of food safety is to assure that food will not cause any harm to the consumer when it is prepared and/eaten (Pal 2017). It is important that all foods must be protected from physical, chemical, and biological contamination through processing, handling, and distribution (Wesley et al. 2014). Food is susceptible to microbial contamination causing foodborne diseases, which is a widespread societal concern and priority (Kennedy 2008). Early detection of contaminated food can prevent more food from being affected. The traditional methods for detecting food microorganism, such as manual identification of microorganism culture by experiment, are tedious and relatively slow (Papadakis et al. 2018). Therefore, sensors based on nanotechnology have been developed for rapid and accurate detection of microorganism. For example, Singh et al. invented a microfluidic-based nanobiosensor, which is quite sensitive and efficient compared with the previous technology. The main principle of this technology is using covalent binding of quantum dot nanoparticles and anti-Salmonella polyclonal antibodies to specifically detect *Salmonella (Singh et al. 2018)*. Using microfluidic chips, as well as super paramagnetic particles can achieve cell separation and enrichment from complex food systems in short time with high sensitivity (Weng et al. 2021). Foodborne pathogens and toxins can cause foodborne illnesses and present serious risks to human health (Bajpai et al. 2018). Meanwhile, data from the Foodborne Disease Outbreak Surveillance System (FDOSS) received for the period 2009–2015 revealed that 5760 foodborne disease outbreaks were recorded and resulted in 100,039 illnesses, 5699 hospitalizations, and 145 deaths in all 50 states (Dewey-Mattia et al. 2018). With regard to food safety, nanotechnology offers various tools and techniques that can solve food safety issues, including microbial and toxin detection, shelf life extension, and improvements in food packaging (Kumar et al. 2021). Nanotechnology detecting techniques also significantly reduce the time required for incubation and measurements and offer a high level of sensitivity and accuracy. For example, one study reported that it only took a 45 min incubation period to isolate 88% of *E. coli* in a sample using nanosized magnetic iron oxide particles with sugar molecules (Duncan and science 2011). With regard to the antimicrobial characteristics of nanoparticles, it was found that combining two or more nanoparticle materials provided a synergistic effect resulting in a more effective antimicrobial than a single nanoparticle (Nile et al. 2020). For instance, combining sliver nanoparticles with titanium dioxide and carbon nanotubes was found to be twice as effective against *E. coli* and *Bacillus cereus* spores (Krishna et al. 2005). Detection of *Listeria monocytogenes* in milk powder and lettuce using NMR has recently been reported (Zhao et al. 2017). *L. monocytogenes* is a foodborne pathogen usually found in raw and processed foods. The specific binding between *L. monocytogenes* and antibody-modified MNPs resulted in clustering of MNPs. The aggregation of bound MNPs changed T2 relaxation time, which was measured using a MRSw based assay. The detection limit of this assay was as low as 3 CFU/mL and the assay requires less than an hour to complete the test. The same authors also reported the detection of *Cronobacter sakazakii,* a bacterium that causes rare but fatal foodborne infection in infants by contaminated powdered infant formula, using the same method and achieved a detection limit of 1.1 CFU/mL in less than 2 h (Zhao et al. 2013). The nanosensor works as an indicator that responds to changes in environmental conditions such as humidity or temperature in storage rooms, microbial contamination, or products degradation (Bouwmeester et al., 2009). Various nanostructures like thin films, nanorods, nanoparticles and nanofibers have been examined to their possible applications in biosensors (Jianrong et al., 2004). Thin film-based optical immunosensors for detection of microbial substances or cells have led to the rapid and highly sensitive detection systems. In these immunosensors, specific antibodies, antigens, or protein molecules are immobilized on thin nano-films or sensor chips which emit signals on detection of target molecules (Subramanian, 2006). A dimethylsiloxane microfluidic immunosensor integrated with specific antibody immobilized on an alumina nanoporous membrane was developed for rapid detection of foodborne pathogens *Escherichia coli* O157:H7 and *Staphylococcus aureus* with electrochemical impedance spectrum (Tan et al., 2011). Nanotechnology can also assist in the detection of pesticides (Liu et al., 2008), pathogens (Inbaraj and Chen, 2015), and toxins (Palchetti and Mascini, 2008) serving in the food quality tracking–tracing–monitoring chain.

Biosensors based on carbon nanotubes also gained much attention due to their rapid detection, simplicity and cost effectiveness and have also been successfully applied for the detection of microorganisms, toxins, and other degraded products in food and beverages (Nachay, 2007). Toxin antibodies attached to these nanotubes causes a detectable change in conductivity when bound to waterborne toxins and therefore are used to detect waterborne toxins (Wang et al., 2009). Further, the use of electronic tongue or nose which is consists of the array of nanosensors monitor the food condition by giving signals on aroma or gases released by food items (Garcia et al., 2006). The quartz crystal microbalance (QCM)-based electric nose can detect the interaction between various odorants and chemicals that have been coated on the crystal surface of the QCM. Many studies on small molecule detection have used quartz crystal surfaces that have been modified with different functional groups or biological molecules, such as amines, enzymes, lipids, and various polymers (Kanazawa and Cho, 2009).

Conclusions:

Based on the discussion above, it is evident that nanotechnology provides substantial hope for the development of enhanced food security and safety. Food safety is closely related to human health. Products of nanotechnology can be more acceptable to the consumers. Developers need to consider the security of nano-applications in all aspects, which will require more systematic laboratory and field tests to determine the responses initiated by nanomaterials. It is necessary to improve the public perception and clear understanding of nanotechnology.

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