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Application of nanotechnology in food and feed: A review

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Abstract
Nanotechnology has become a buzz word among the scientific community in recent years. Nanotechnology exhibits great potential for exploitation in the food industry. It is an enabling technology that has the potential to revolutionize the food industry. Nanotechnology is having an impact on several aspects of food science, from how food is grown to how it is packaged. The prediction is that nanotechnology will transform the entire food and feed industry, changing the way food is produced, processed, packaged, transported, and consumed. This review paper deals with the potential application of nanotechnology in food and feed industry.

Keywords: Nanotechnology, food, feed, nutraceutical

Introduction

Nano-technology is the intentional control of matter (including food and feed) at very small dimensions ranging from 1 nanometre (nm) to 100 nm, and a nanoparticle is a particle of matter in this size range (Duncan, 2011) [12]. The word "nano" refers to a millionth of a millimetre. To put this into context, a human hair is about 80,000 nm wide. At these very small dimensions, the matter in food can behave in different, and potentially beneficial ways that can be used by industry to create new or improve existing food and feed, and processing operations.

The National Nanotechnology Initiative (NNI, 2006) [23] of United States defines nanotechnology as "the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications." Their extremely small size and high surface area are associated with their greater strength, stability and chemical and biological activities. Therefore, nanotechnology enables development of novel materials with a wide range of potential applications. Nano-materials are used in a variety of consumer, medical, commercial and industrial products. Within the food and animal feed sectors there are a number of applications where nano-properties can be utilized in a beneficial way. To date, however, only a small percentage of applications are in the food arena, mainly concerned with food and nutritional supplements and packaging.

Recent research has begun to address the potential applications of nanotechnology for functional foods and nutraceuticals by applying the new concepts and engineering approaches involved in nano-materials to target the delivery of bioactive compounds and micronutrients. Nano-materials allow better encapsulation and release efficiency of the active food ingredients compared to traditional encapsulating agents, and the development of nano-emulsions, liposomes, micelles and biopolymer complexes have led to improved properties for bioactive compounds protection, controlled delivery systems, food matrix integration, and masking undesired flavors.

The rapid development of nanotechnology has been facilitating the transformations of traditional food and agriculture sectors, particularly the invention of smart and active packaging, nano-sensors, nano-pesticides and nano-fertilizers. Numerous novel nano-materials have been developed for improving food quality and safety, crop growth, and monitoring environmental conditions (Xiaojia *et al.*, 2019) [32].

Nanotechnology also has the potential to improve food processes that use enzymes to confer nutrition and health benefits. For example, enzymes are often added to food to hydrolyze anti-nutritive components and hence increase the bio-availability of essential nutrients such as minerals and vitamins.

To make these enzymes highly active, long lived and cost-effective, nano-materials can be used to provide superior enzyme-support systems due to their large surface-to-volume ratios compared to traditional macro scale support materials.

The main food application areas considered potential to benefit from nanotechnology are

- Agriculture nanotechnology for increased food and feed production
- Food processing
- Application of nanotechnology in food packaging
- Food supplements
- Nanotechnology in food microbiology
- Animal nano-feed applications

a. Agriculture nanotechnology for increased food and feed production

Nanotechnology provides new agrochemical agents and new delivery mechanisms to improve crop productivity, and it promises to reduce pesticide use. Nanotechnology can boost agricultural production, and its applications include: 1) nano formulations of agrochemicals for applying pesticides and fertilizers for crop improvement; 2) the application of nano sensors/nano biosensors in crop protection for the identification of diseases and residues of agrochemicals; 3) nano devices for the genetic manipulation of plants; 4) plant disease diagnostics; 5) animal health, animal breeding, poultry production; and 6) postharvest management. Precision farming techniques could be used to further improve crop yields but not damage soil and water, reduce nitrogen loss due to leaching and emissions, as well as enhance nutrients long-term incorporation by soil microorganisms. Nanotechnology uses include nanoparticle-mediated gene or DNA transfer in plants for the development of insect-resistant varieties, food processing and storage; nano-feed additives, and increased product shelf life (Bhupinder, 2014) [2].

b. Food Processing

Food processing is conversion of raw ingredients into food and its other forms by making it marketable and with long shelf life. Processing includes toxin removal, prevention from pathogens, preservation, improving the consistency of foods for better marketing and distribution. 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. Food undergoes a variety of postharvest and processing-induced modifications that affect its biological and biochemical makeup, so nanotechnology developments in the fields of biology and biochemistry could eventually also influence the food industry. Ideally, systems with structural features in the nano-meter length range could affect aspects from food safety to molecular synthesis (Chen *et al*., 2006) [8]. The nanostructured food ingredients are being developed with the claims that they offer improved taste, texture, and consistency.

Nano capsules delivery system plays an important role in processing sector and the functional property are maintained by encapsulating simple solutions, colloids, emulsions, biopolymers and others into foods. Nano sized self-assembled structural lipids serve as liquid carrier of healthy components that are insoluble in water and fats such are regarded as nano-drops. Nanotechnology increases the shelf life of different kinds of food materials and also helps to bring down the extent of wastage of food due to microbial infestation. Food processing methods that involve the nano-materials in their contents include incorporation of nutraceuticals, gelation and viscosifying agents, nutrient delivery, mineral and vitamin fortification and nano-encapsulation of flavors (Pradhan *et al*., 2015) [25].

Nutraceuticals

Nutraceutical compounds such as bioactive proteins are used in functional foods to impart a health benefit to consumers in addition to the nutrition that the food itself offers. The prospect of the production of nutraceuticals at the nano-scale, which will have increased stability throughout the processing chain, will be of significant interest to food processors trying to maximize nutrient content and hence will ultimately be of benefit to consumers. Nanotechnology has shown great potential for improving the effectiveness and efficiency of delivery of nutraceuticals and bioactive compounds in functional foods to improve human health. It can enhance solubility, facilitate controlled release, improve bioavailability, and protect the stability of micronutrients and bioactive compounds during processing, storage, and distribution. It can also lead to the development of new flavor delivery systems to improve food quality and functionality. Controlled release may eventually lead to in-situ flavor and color modification of products (Chen *et al.,* 2006) [9].

No-encapsulation

Nano-encapsulations has several benefits as it masks odors or tastes, control interactions of active ingredients with the food matrix, control the release of the active agents, ensure availability at a target time and specific rate, and protect them from moisture, heat, chemical, or biological degradation during processing, storage and utilization and also exhibit compatibility with other compounds in the system. Nano-capsules are prepared basically in six ways named as nano-precipitation, emulsion-diffusion, double emulsification, emulsion coacervation, polymer coating and layer-by-layer (Maynard *et al.,* 2006) [19].

Nano-emulsions

Nano-emulsions are emulsions which are thermodynamically stable compared to conventional emulsions under a range of different conditions. This is due to their small size (typically 50 to 500nm compared to 1200nm) and mono dispersivity. They can be diluted with water without changing the droplet size distribution. The type of surfactant used to formulate a nano-emulsion is critical to the stability of the final emulsion. Preparations of nano-emulsions can be used to encapsulate functional food components at oil/water interfaces, or throughout the continuous phase of the system (Weiss *et al.*, 2006) [8, 9].

Nano-emulsions can protect flavor compounds from manufacturing conditions and throughout the beverage's shelf-life. It is claimed that nano-emulsions can capture the flavor and protect it from temperature, oxidation, enzymatic reactions and hydrolysis and are thermodynamically stable at a wide range of pH values. These enable the addition of nano-emulsified bio actives and flavors to a beverage without a change in product appearance. Nano-emulsions are effective against a variety of food pathogens.

c. Application of nanotechnology in food packaging

The purpose of food packaging is to increase food shelf life by avoiding spoilage, bacterial contamination or the loss of food nutrient. Nanotechnology offers higher hopes in food packaging by promising longer shelf life, safer packaging, better traceability of food products and healthier food (Brody, 2003) [5]. In recent years, there is more concern about research and innovation in food packaging materials ranging from films, carbon nano tubes, to waxy nano-coatings for some foods. The use of nano particles might help in production of new food packaging materials with improved mechanical barrier and antimicrobial properties to increase shelf life (Chaudhary *et al*., 2008; Mihindukulasuriya and Lim, 2014) [6, 20]. A variety of nano-materials such as silver nanoparticle, titanium nitride nanoparticle, and nano titanium dioxide, nano-zinc oxide, and nano-clay are introduced as functional additives to food packaging. Nanotechnology enabled food packaging can be divided into three main categories (Duncan, 2011 and Silvestre *et al*., 2011) [12, 28].

i. Improved packaging

The use of nanoparticles in the polymer chain improves the packaging properties of polymer such as gas barrier properties, polymer flexibility as well as temperature and humidity resistance.

ii. Active packaging

The use of nano-materials in packaging allows packages to interact with food and the environment and also play a dynamic role in food preservation. Several nano-materials like nano-copper oxide, Nano silver, nano-titanium dioxide, nano-magnesium oxide and carbon nanotubes can provide antimicrobial properties. Presently, the use of silver nanoparticles as antibacterial agents in food packaging is increasing (Duncan, 2011) [12].

iii. Intelligent/smart packaging

The use of nano-devices in the polymer matrix can monitor the condition of packaged food. This packaging is designed for sensing biochemical or microbial changes in the food. It can detect specific pathogen developing in the food or specific gases from food spoiling. Some smart packaging has been developed to be used as a tracking device for food safety or to avoid counterfeit (Duncan, 2011; Silvestre *et al*., 2011 and Samal, 2017) [12, 28, 27]. Or alternatively, smart packaging could release a dose of additional nutrients to those which it identifies as having special dietary needs, for example calcium molecules to people suffering from osteoporosis (Miller, 2008) [21].

iv. Packaging of the Nonedible thin film

Nano bio-technology can be used for the improvement of the plastic substance barrier, incorporation of bioactive, sensing and signaling of relevant information about the food; for the alteration of the pervasion action of foils, growing barrier characters (thermal, mechanical, microbial and chemical); enhancing heat-resistance and mechanical characters (Durán, and Marcato, 2013) [13].

v. Antimicrobial Packaging

The barriers include natural nanoparticle to control microbial growth which leads to pathogens or spoiling. Silver nanoparticles are used in all forms including bio textiles, electrical appliances, refrigerators and kitchen wares. These nanoparticles show needed action in bulk form, and its ions have the ability to inhibit wide range of biological processes in bacteria. Zinc oxide's antibacterial nature increases with decreasing particle size, it can be stimulated by visible light, and they are incorporated in number of polymers including polypropylene. *E. coli* contamination can be controlled using titanium dioxide as a coating in packing material. It is also combined with silver to improve disinfection process. Chiston, a biopolymer derived from chitin recently reported to have antimicrobial properties additional to material for encapsulation. Antimicrobial packaging would be highly healthy and consumer friendly products (Pal, 2017) [24].

A recent paper in Trends in Food Science & Technology provides a summary of the kind of applications industry and universities are working on ("Food applications of nanotechnologies: An overview of opportunities and challenges for developing countries").

Table 1: Food applications of nanotechnologies: An overview of opportunities and challenges for developing countries

Application	Status
Processed nanostructured or -textured food (e.g. less use of fat and emulsifiers, better taste	A number of nanostructured food ingredients and additives understood to be in the R&D pipeline; eg. mayonnaise
Nano-carrier systems for delivery of nutrients and supplements in the form of liposomes or biopolymer-based nano-encapsulated substances	A number are commercially available in some countries and over the internet Eg. Encapsulation of proteins
Organic nano-sized additives for food, supplements and animal feed	Materials range from colors, preservatives, flavorings to supplements and antimicrobials
Inorganic nano-sized additives for food, health food, and animal feed	A range of inorganic additives (silver, iron, silica, titanium dioxide, selenium, platinum, calcium, magnesium) is available for supplements, nutraceuticals, and food and feed applications
Food packaging applications eg. plastic polymers containing or coated with nano-materials for improved mechanical or functional properties	This area makes up the largest share of the current/short-term market for nanotech applications in the food sector
Nano-coatings on food contact surfaces for barrier or antimicrobial properties	A number of nanomaterial-based coatings are available for food preparation surfaces and for coating food preparation machinery
Surface-functionalized nano-materials	Main uses are currently in food packaging; possible uses emerging in animal feed
Water decontamination	Nano iron is already available in industrial-scale quantities. A number of companies thought to be using the technology in developing countries
Animal feed applications	Nano-sized additives specifically developed or are under development for feed include nano-materials that can bind and remove toxins or pathogens

d. Food supplements

Nano-sized powders are used for increasing absorption of nutrients, nano-co-chelates are considered as effective tool for nutrient delivery to cells without affecting color and taste of food products. Supplementary aspect mainly involves encapsulation techniques where the needed probiotics, and other products are targeted into the human system with the help of iron and zinc nano structured capsules. Thus, nanotechnology in food supplements is very effective than common supplements because they react more effectively with human cells due to their size.

Cholecalciferol (Vitamin D3) mini tablets and an optimized bile salt/lipase alginate-glycerin film provided unique oral components for inclusion in a bioactive association platform (BAP) capsule designed to deliver the active nutraceutical ingredient from the formulation framework resulting in the enhanced *in vitro* and *in vivo* performance of cholecalciferol. The *in vivo* experiment showed that cholecalciferol bioavailability from the BAP was 3.2-fold greater than that of the conventional product, and improved and maintained serum levels of 25-hydroxyvitamin D3 were observed as well, suggesting that BAP could be considered as an ideal oral vehicle for enhanced delivery of cholecalciferol (Braithwaite, *et al*,2016) [4].

Ca alginate NPs (200–500 nm in diameter) loaded with collagen peptide chelated Ca with the average diameter of approximately 150 nm and the Ca content of up to 130.4 g/kg notably enhanced Ca absorption and significantly increased femur bone mineral density and femur Ca content in rats, suggesting that they could prevent Ca deficiency and could be used as a new Ca supplement in the food industry (Guo *et al.*, 2015) [16].

e. Nanotechnology in food microbiology

Food microbiologists are interested in safety and quality assurance programs to produce safe and high-quality food products which have zero defects and free of pathogens. The main applications of nanotechnology in food safety programs are antimicrobial effect of nanoparticles and nanosensors for detection of pathogens and contaminating microorganisms (Nasr., 2015) [22].

The application of nanotechnology on the detection of pathogenic organisms in food and the development of nano-sensors for food safety is also studied at the Bio-analytical Microsystems and Biosensors Laboratory at Cornell University. The focus of the research performed at Cornell University is on the development of rapid and portable biosensors for the detection of pathogens in the environment, food and for clinical diagnostics. The bio-analytical microsystems use the same biological principles as were used in the simple biosensors, i.e. RNA recognition via DNA/RNA hybridization and liposome amplification. The bio-analytical microsystems that are studied focus on the very rapid detection of pathogens in routine drinking water testing, food analysis, environmental water testing and in clinical diagnostics (Shefer, 2005) [29]. Nano-sensors that are being developed by researchers at both Purdue and Clemson universities use nanoparticles, which can either be tailor-made to fluoresce different colors or, alternatively, be manufactured out of magnetic materials.

Nano capsulation improves the rate of inhibition compared with conventional delivery and retains the antimicrobial efficacy for a longer time. Moreover, Chopra *et al.* (2014) [10] evaluated the antibacterial activity of Nisin loaded chitosan/carageenan nano capsules, results indicated that encapsulated nano capsules showed better antibacterial effect on microbe's (*Micrococcus luteus*, Pseudomonas aeruginosa, Salmonella enteric, and *Enterobactor aerogenes*) *in vitro* as well as in tomato juice for prolonged periods (6 months) as compared to the components evaluated separately.

f. Animal nano-feed applications

With rapid development of modern animal farming and ever-growing awareness of consumers, meat quality must be on constant rise, both in terms of its nutritious and organoleptic properties. Because of that fact, animal farming industry is searching for new ways to improve the overall quality of the meat and resources resulting from its processing, and one of the recently developed ways, bio fortification with utilization of nanotechnology, shows great potential in doing so. Current research in the field is mainly focusing on feed enrichment with nano-sized particles and its effects on properties of meat (Konkol and Wojnarowski., 2018) [18].

Eggs are very much appreciated by consumers due to their relatively low price, taste, and high nutritional value. Due to the popularity of this product, consumers often pay attention to its size, freshness, appearance, cholesterol content, fatty acid profile, as well as the content of minerals. In addition, food production, which will be characterized by a higher content of biologically active ingredients, and better quality becomes more and more important due to the growing consumer awareness and common shortages. A good solution to the problem may be enriching food at the level of animal husbandry, using feed additives in which biologically active ingredients, such as micro- and Macro elements, will be characterized by better bioavailability (Słupczynska., 2014) [29]. Such a solution may be nanominerals used in animal nutrition. Attempts to improve the composition and quality of eggs using nanominerals have already been carried out several times (Konkol and Wojnarowski., 2018) [18]. Ahmadi *et al*. 2018 [1]., conducted an experiment in which nano-selenium was added to the feed provided ad libitum to 180 Ross and 308 chicks that were divided into 6 groups with 10 birds each and 3 replicates of group. Supplementation has significantly improved weight gain and feed conversion rate during the entire experiment. Breast and drumsticks percentages were significantly higher in chicks with nano-selenium supplementation than in the control group.

Improving the feeding efficiency and nutrition of animals, minimizing losses from animal diseases, and turning animal by-products and wastes with environmental concerns into value-added products are among applications of nanotechnology in animal husbandry. Nano-feed (a food supplement for animals) encourages the activation of the animal's own self-healing forces, equal to improved resistance against diseases (Chen, 2011) [7]. Nano-feed also acts as an antioxidant to maintain healthy cell activity and overall animal health. Benefits can be seen in the reduction of antibiotics needed, improved bone growth, improved phosphate utilization, and reduction in mortality rates. Rajendran *et al.* (2013) [26]. used nano-zinc in feeding dairy cows. Their research has shown that the use of this nanomineral reduces the number of somatic cells in cow's milk with subclinical mastitis. In the course of these studies, it was also found that the use of nano-zinc in feeding dairy cows improves milk production compared with conventional sources of zinc. Considering the many positive effects that nanominerals have had on the composition and quality of other animal products, such as eggs and meat, research into the possibility of improving the quality of milk using these materials should also be carried out.

The future of nanotechnology
There are many perceived as well as actual benefits from the use of nanotechnology; however, there is a lack of awareness about the technology. Although it is difficult to assess how consumers will react to current and future applications of nanotechnology, there is no doubt that consumer acceptance will be critical if it is to be used widely in the future. There is therefore a need to inform consumers of the potential benefits and safety considerations to increase their understanding. This may help to avoid unnecessary alarm stemming from unfamiliarity with the technology (Food Safety Authority of Ireland (2010) [15] and European Food Safety Authority (EFSA) (2011) [14]. As developments in nanotechnology continue to emerge, its applicability to the food industry is sure to increase. The success of these advancements will be dependent on consumer acceptance and the exploration of regulatory issues. Food producers and manufacturers could make great strides in food safety by using nanotechnology.

Conclusion
The data available on nano science substantiates the different applications of nano particles in agricultural science for improved productivity, livability and biological activities of animals. Also, quality, processing, packaging and commercialization of food and feed. Besides a lot of advantages of nanotechnology to the food industry, safety issues associated with the nanomaterial cannot be neglected. Many researchers have discussed safety concerns associated with nanomaterial giving emphasis on the possibility of nanoparticles migrate from the packaging material into the food and their impact on consumer’s health as well as animals health.
Ultimately, understanding the mechanism of targeted delivery will provide a foundation that will enable food and feed manufacturers to design smart food systems capable of ensuring the optimal health of each individual citizen.

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