CHAPTER

16

Nanoparticle applications in sustainable agriculture, poultry, and food: trends and perspective

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16.1 Introduction

Nanotechnology has been a new frontier integrated vastly in diverse fields for a myriad applications during the past decade. The multidomain applications could be attributed to the unique features of nanoparticles (NPs) viz., small size (1−100 nm), surface area, reactivity, physical strength, magnetic property, electrical, and optical characteristics [1−3]. These properties have been helpful in exploring a wide range of possibilities in the fields of medicine, food industry, textiles, etc. NPs synthesis can be achieved through chemical, physical, and biological methods. But chemical and physical synthesized NPs could result in toxicity due to chemicals involved in preparation methods limiting their applications in agriculture, food, and health aspects [4,5]. However, the biological synthesis has been reported to be less toxicity along with polydispersity, better stability, environmentally friendly, and cost-effective [5]. The nano-based engineered particles have been key driving forces in both food and agriculture sectors. Fig. 16.1 summarizes the main applications of nanomaterials in food and agriculture sectors.

The agriculture applications include biosensors, plant growth regulators, plant growth promotion, nano-sized nutrients, bio-nanocomposites, nano-coated fertilizers, nano-biopesticide,

Nanotoxicity
DOI: https://doi.org/10.1016/B978-0-12-819943-5.00016-6

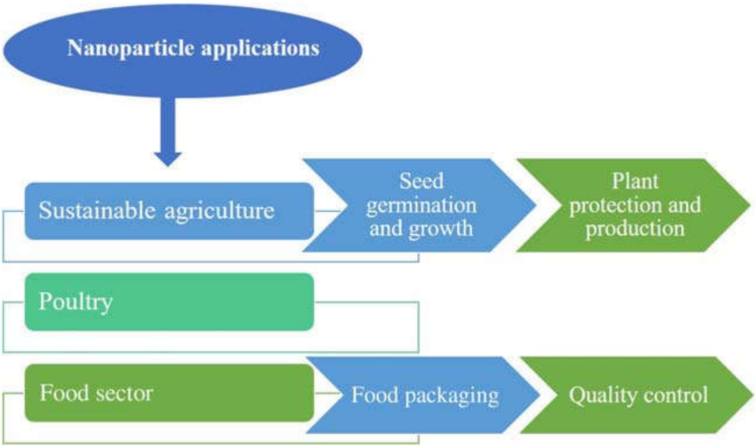

FIGURE 16.1 Main applications of nanoparticles (NPs) in food and agriculture sectors.

nano-insecticides, nutrient management, and protection against phytopathogens. In food sector for both poultry and agriculture produce nano-applications could be employed in food processing, packing industry, dairy industry, transportation and quality control [6]. The research and development of nano-based technology for both agriculture, poultry, and food has been extensively focused since the last decade. The reports have shown positive output regarding sustainability along with improved productivity.

Even though the potential of the NPs in their applications, commercialization has been marginal and has been unable to meet major market share. The main reason could be associated with a lack of interest from big industries. The R&D has been mainly focused by academia and new start-ups which are usually small enterprises [7]. This chapter highlights the applications of nanomaterial agriculture, poultry, and food, also possible risk associated, policies, and regulatory consensus.

16.2 Nanoparticle applications in agriculture

Agricultural commodities play a crucial role by providing various materials such as textiles, feedstock including food and feed. Technological advancement is required to meet the expectation of global needs from agriculture. The integration of nano-based technologies in agriculture has been the potential for enhancing productivity, economical sustainability, and ecofriendly. Several kinds of NP applications in agriculture are shown in Fig. 16.2.

16.2.1 Seed germination and growth

The seed germination refers to the process of formation of seed into a seedling. Seedling is the result of reactivation metabolic activities from its dormancy. The dormant seeds would

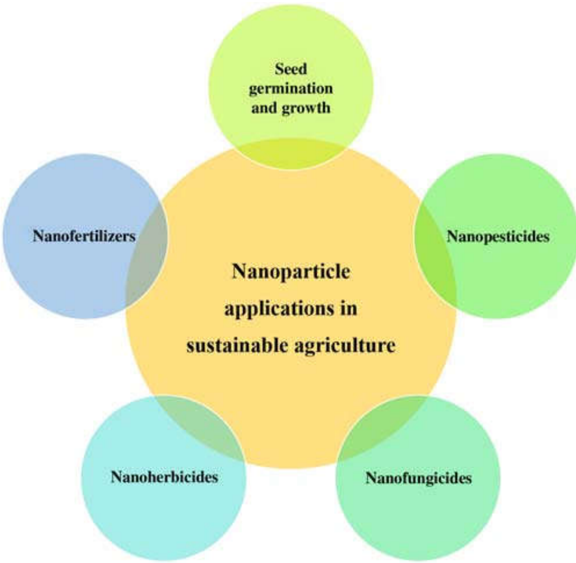

FIGURE 16.2 Nanoparticle (NP) applications in agriculture.

not germinate due to various external parameters inhibiting the germination process. NPs have been reported to rejuvenate the seeds from its dormancy stage [8]. The germination rate efficacy is found to be high in case smaller NPs, lesser the size higher rate of germination. The germination rate increase would result in enhancement of photo sterilization and photogeneration. The active oxygen generated viz., superoxide and hydroxide anions induce stress resistance and shell penetration level. The shell penetration would enable a higher intake of water and oxygen leading to accelerating germination rate [9−11].

During the past decade, researchers have focused on effect of nanomaterials on seed germination and growth to analyze the best possible applications in agriculture. The effect of nano and nonnano TIO_2 on spinach seeds was studied by Zheng et al. [12], they have reported that nonnano TIO_2 treatments resulted in plants having 73% more dry weight, high photosynthetic rate up to three times and high chlorophyll content of about 45% compared to control. The main reason for increased seed germination rate was observed due to extent of nanomaterial penetration into the seed. Lin and Xing [13] reported phytotoxicity of different nanomaterials comprising carbon, aluminium and zinc on germination rates in Corn, Cucumber, Radish, Rape canola and ryegrass. The results revealed concentration above 2000 mg/L inhibited the germination. The root length was inhibited with dose of 200 mg/L for nano-Zn and ZnO. However, phytotoxicity studies revealed nano-Al and Al_2O_3 affected root elongation of both ryegrass and corn. Whereas, nano-Al promoted radish and rape canola root growth. Khodakovskaya et al. [14] reported the effect of MWCNT on tomato seeds by penetrating the seeds thereby increasing the germination rate due to increase in seed water uptake. The seed germination rate was found to be around 90% compared to control (71%) in 20 days. Shah and Belozerova [15] studied the influence of different metal NPs such as silicon (Si), palladium (Pd), gold (Au), and copper (Cu) on lettuce seeds. The results indicated that NPs of Pd and Au at low concentrations, Si and Cu at higher concentrations had positive effect on seed germination. The combination of Cu and Au also showed positive results. The results were measured based on shoot to root ratio and growth of the seedlings. One of the main concerns regarding the application of nanomaterials in seed germination is its phytotoxicity which could either be positive or adverse effect [16]. Study conducted by Ma et al. [17] on the effect of oxide nanomaterials viz., CeO_2, La_2O_3, Gd_2O_3, and Yb_2O_3 on the plant species radish, rape, tomato, wheat, lettuce, cucumber, and cabbage. The CeO_2 nanoparticles did not affect root elongation except lettuce at 2000mg/L, other nanoparticles studied had effect on root growth. And also, the inhibitory effects of these NPs were observed at different stages of root growth. So, the phytotoxic effect of NPs needs to be understood completely before utilizing them under field conditions. The primary solution to avoid phytotoxicity to other species would be to grow the seedling in green house first and then transferring them to field later. Study by Nair et al. (2011) reported FTIC (Fluorescein isothiocyanate) labelled silver nanoparticles and photostable Cadmium-selenide (CdSe) on seed germination in rice. Results showed that FTIC labelled silica nanoparticles enhanced seed germination rate. Whereas, CdSe inhibited seed germination rate. Pariona et al. [19] studied the effect of citrate-coated magnetite nanoparticles on the germination rate of *Quercus macdougallii*. The results showed 33% increase in germination rate compared to control. The iron content present in nanoparticles made an impact in increasing the chlorophyll content thereby giving the positive result. Jhansi et al [20] synthesized magnesium oxide nanoparticles (MgO-NPs) using mushroom extract to check the effect on *Arachis hypogaea* L. The nanoparticles were synthesized with different sizes. The results showed that nanoparticles of size 15 nm showed enhanced effect on seed germination rate, by penetrating into the seeds. The mushroom extract was used to stabilize the MgO-NPs. Upadhyaya et al. [21] studied the physiological impact of zinc nanoparticles (ZnNPs) on a rice cultivar. Different concentrations of ZnNPs resulted in different effects on the plant. Among the different concentrations used, 15 mg/L gave the best results. The results showed a myriad of characters being enhanced namely increase in radical and plumule length, increase in moisture content and seed germination rate. Exposure to ZnNPs leads to resistance of plant to reactive oxygen species (ROS) because of the increased secretion of various antioxidant enzymes. Kumar et al. [22] reported the effect of carbon nanoparticles (CNT) on the flowering time in *Arabidopsis thaliana* by incorporating it in the growth medium with seeds being grown on Murashige and Skoog medium supplemented with CNTs. The accumulation of CNTs was observed highest in leaves, followed by stem and least in root tissues. The incorporation of CNTs not only increased the efficiency of seed germination it also had effect on chlorophyll content, elongated hypocotyl. Khati et al. [23] incorporated nanozeolite with growth-promoting rhizobacteria to check the growth of *Zea mays* seeds. Of note, 50 ppm nanozeolite was applied to seeds along with the inoculation of bacteria. The results showed the accumulation of total phenolic and acid esters after the treatment. Chlorophyll content, increase in leaf length was also observed.

16.2.2 Plant protection and production

16.2.2.1 Nanopesticides

Nanopesticides involve either active ingredients of the pesticidal activity or some other engineered structures having pesticidal activity. These materials exhibit properties such as rigidity, permeability, thermal stability, crystallinity, and biocompatibility needed for formulating nanopesticides. In recent years, delivery techniques such as nanoemulsions, nano encapsulated, nanocontainers and nanocages have been discussed for plant protection [24–26]. Nanoparticle formulated products should degrade rapidly in the soil and slowly in plants, thereby following the regulatory level criteria. One such study was done by Yan et al. [27] on cabbage and cucumber, developed a nano pesticide with sodium dodecyl sulfate (SDS) modified photocatalytic TiO_2/Ag nanomaterial conjugated with dimethomorph (DMM) which is a commonly used pesticide in crop production, like nanopesticides. The modified formulation with 96nm average granularity, had properties such as increased dispersivity and rapid decomposition and had positive effect on vegetable seedlings. The modification of the desired nanomaterials using SDS greatly affected the absorption of the DMM. Formulation stability is also an important aspect to be considered. Liu et al. [28] formulated stable nanopesticides known as bifenthrin using different polymers. Development of an encapsulated nano-imidacloprid was carried out by Guan et al. [29] for pest control during vegetable production. The modified nanoformulation was developed by using microencapsulation technique with the use of chitosan and alginate. The treatment on soybean plants, revealed the residues of this formulation degraded within 8 days and complete degradation was observed at 20 days. The toxicity of pesticides on plants and human beings is also a major concern in crop production. Zhang et al. [30] stated that nanoemulsions can be effective delivery medium because of following characters—kinetic stability, less particle size, low viscosity, and optical transparency. The employment of nanoemulsion as a carrier for pesticide delivery could offer better solubility and bioavailability of NPs. However, there is a need to check the effect of NPs uptake through inhalation by workers in agricultural fields. Wan-Jun et al. [32] worked on mice to check the toxicity of chlorfenapyr. The results showed that the concentration ranging from 4.84 to 19.36 mg/kg showed less toxicity. Therefore such nanoformulation pesticides may decrease the adverse effects on both environment and humans. Study by Mohamed and Khairou [31] reported photo-degradable Ag/TiO_2 particles having 5-7 nm, the nanoparticles synthesized from both SDS and POL towards the degradation of 2, 4-D under visible and UV radiation. The results showed that nanoparticles synthesized from POL degraded faster than the nanoparticles from SDS under same exposure time.

16.2.2.2 Nanofungicides

The fungal pathogens associated crop loss is a major concern to the agricultural sector. The employment of conventional fungicides has been successful to an extent but their associated environmental risks and their high usage requirement are both uneconomical along with having detrimental effects on human health [33,34]. The development of nanofungicides has been a ray of hope and has a crucial role in addressing this issue.

The first study on nanofungicides was conducted in 1997 with incorporations solid wood. Study conducted by Kumar et al. [35] synthesized nanoform of commercially available fungicide trifloxystrobin and tebuconazole. The combination of nanoform fungicide effectively inhibited *Macrophomina phaseolina* in dose dependant manner. Nano-azomethines using polyethylene glycol (PEG) as stabilizer successfully inhibited *Rhizoctonia solani*, *Rhizoctonia bataticola*, and *Sclerotium rolfsii* in pot experiments [36]. The study conducted by Manikandan [37] synthesized copper-chitosan NPs and applied on finger millet (*Eleusine coracana* Gaertn.) in two ways: foliar spray and combination method. Combination method comprised of sterilization of seeds with sterilants and then sprayed. The results showed the dual work of the NPs, that is., increase in growth and also 75% plants protected from disease. The NPs suppressed the blast disease by increasing the defensins. Foliar application CuZn of bimetallic NPs on tomato leaves inhibited *Saccharomyces cerevisiae* [38]. The evaluation of zinc oxide nanoparticles (ZnO-NPs) by green synthesis using extract of *Allium sativum* successfully inhibited *Mycena citricolor* and *Colletotrichum* sp. pathogenic fungi associated with coffee [39].

16.2.2.3 Nanoherbicides

The control of weeds is another major concern associated with agricultural related problems causing crop loss. The weeds utilize the soil nutrients in higher amounts, limiting the nutrients for crops in turn affecting plant growth and yield. Weed eradication by conventional methods include physical removal and usage of herbicides which is laborious and time-consuming. The commercial herbicides do not constitute targeted action their application in the fields could essentially induce damage to crops as well. In this regard nanoherbicides' application could eliminate weeds and is ecofriendly causing minimum damage when compared with conventional herbicides. Another issue associated with use of conventional herbicides includes harmful residual contaminants and prolong application would result in weed resistance [40–42].

16.2.2.4 Nanofertilizers

The employment of nanotechnology in formulation and development as nanofertilizers has been promising for sustainable agriculture. The nanofertilizers have been reported to be aiding in plant growth and also increasing plant yield [43,44]. One of the main advantages with respect to nanofertilizers is the controlled and targeted release. Nutrient entrapment with nanomaterials and its application on plants have been found to be more efficient than conventional fertilizers [45,46]. The nutrient entrapment of single or multiple which could enhance the plant uptake of nutrients due to its high adsorption property.

16.2.2.5 Nutrient management

The agriculture sector has its dependence on variable natural parameters like weather, season, water, soil condition, etc. Therefore monitoring of both the biotic and abiotic data is very much crucial in this regard. The integration of nano-based technologies could essentially address monitoring and analysis along with nano encapsulated nutrient delivery systems for slow and targeted release of nutrients. The nano-based nutrient delivery would facilitate plant growth along with increase in crop yield. The nanomaterials have been hypothesized to interact with plants in membrane transport, photogeneration of active oxygen in addition to targeted delivery [47].

16.3 Nanoparticle applications in poultry

Nanotechnology could offer poultry and meat products cost-effective with the natural properties and quality control of products. A new concept hypothesized with NP application is development "interactive" poultry meat that changes, color, flavor, or nutrients according to consumer. These characteristics are dependent on molecular structures which could be altered at the nano-size range. The smart nanomaterials would rearrange the atoms involved in order to obtain the desired color, flavor, and texture. At present the nanomaterials have been employed in treatment of poultry associated infections [48–50]. One of the major infections associated with poultry is prevalence of *Campylobacter* in carcasses. Previous studies with nano-based feed to turkeys reduced the *Campylobacter* prevalence [51]. Nanopolymers conjugated with PEG linker, polystyrene base and a mannose inhibited *Escherichia coli*. The nanomaterials were found to bind in gut preventing pathogen colonization. AgNPs based additive feeds on pigs had increase in growth. The study reported by [52] evaluated silver (Ag), zinc oxide (ZnO), and copper oxide NPs against poultry associated pathogens *Salmonella* and *Campylobacter*. The nanomaterials inhibited the pathogens in a dose-dependent manner.

16.4 Nanoparticle applications in food

Nano-based approaches have promised a great potential in combating issues such as food safety by improving its quality, nutrient delivery, enhancing packaging performance, and improving processing methods with pathogen detection [53,54].

Packaging is an integral part of food products for avoiding physical damage and avoid contamination along with increased shelf life. Various materials viz., metal, glass, laminated paper, and plastic have been used to date. However, at present synthetic polymeric materials have been employed more for their various advantages. Nanocomposites provide an opportunity for the development of a new generation of food packaging [55,56]. The nano-enabled packaging has been reported to maintain and assist hygiene during storage by microbial inactivation and inhibition of biofilm formation. The production instrumentation could be essentially coated with nanomaterials which could prevent the attachment of microbes to the surface, in turn, inhibiting their growth. The nanomaterials coatings in packing material are also known to provide better mechanical tensile strength and thermal ability ensuring the quality of food packages. The mechanical stability also aids in achieving superior gas barrier by limiting oxygen and preventing carbon dioxide leakage from the food package. The reactive oxygen species formation in packed food results in degradation of food quality employment titanium, selenium and cellulose nanocomposites can inhibit or retard the ROS enhancing shelf life and quality. The nanomaterials can be bonded to antioxidants and antimicrobial compounds as conjugates via intermolecular forces of attraction or by covalent bonds [57–59].

Incorporation of nanotechnology has resulted in development of various new generation biocompatible packaging with nanomaterials such as silver, carbon, zinc, titanium, clay, chitosan, cellulose, starch. The first nano-based packing was carbon nanotubes developed by Lijima et al. [60]. The carbon nanotubes-based package reported by Asgari et al. [61] was found to increase the shelf life upto 90 days of storage. However, the sensory attributes were low but reduced fungal associated contamination.

16.5 Nano-biosensors sustainable agriculture, poultry, and food

The smart biosensor systems driven by nanotechnology have been found to be potential in detection of pathogens, chemical contaminants, and inhibition of pathogens. These nano-biosensors can be integrated into agricultural, poultry, and food sectors. The nano-based sensor systems compose of chemical, physical, and biological components. In agricultural sector nanosensors envision precision and sustainable farming incorporation during both pre and postharvest sessions. During preharvest and postharvest the nanosensors could be employed in real-time monitoring of soil health and quality. Thus aiding farmers in taking relevant decisions with regard to their harvest. The detection biological contaminants such as viruses, bacterial pathogens, and their toxins could be detected in trace amounts enabling the farmers for prevention measures for protecting the harvest. In food sector biosensors would enable monitoring during production process also during transportation for detection of pathogens and other contaminants that may arise.

16.6 Regulatory aspects of nanotechnology in agriculture, poultry, and food

There is no finalized regulatory framework for nano-based products neither in Food and Drug Administration (FDA) nor in European Union (EU) countries because of the infant stage of research and development in the field. There are many organizations working on regulating nanomaterials by legislation or by recommendations and guidance. Nanomaterial regulatory issues should follow registration procedures, addressing risk management issues to increase the transparency and traceability for specific product regarding its commercial use viz., notifying a register for the products containing nanomaterials.

16.6.1 Regulatory aspects of nanomaterials in agriculture/food/poultry feed in the European Union

The legislation in the EU is sector-specific which constitutes separate binding regulations and frameworks for manufacturers, importers, and consumers (Table 16.1).

16.6.2 Risk management of pesticides

Pesticides are chemical compounds, mainly concerned with killing, repelling, or controlling pests and weeds, also in protecting crops until harvest. Pesticides are regulated by plant protection products regulation. These products require premarket authorization at

TABLE 16.1 Regulations of European Union (EU) countries in agriculture/feed/food applications.

Application	Authorization	Guidance documents
Agriculture—pesticides	(EC) No 1107/2009	EFSA guidance
Plant protection products		
Food/feed	(EC) 258/97	
Novel food/feed		
Biocides/chemicals	(EU) No 528/2013	Pending guidance
Biocides		

EU level for its bioactive components. The products are assessed based on active substances, formulants, and their influence on degradation and distribution.

16.6.3 Risk assessment of food and feed

The risk assessment has directives/regulations based on food types viz., ingredients, additives, supplements, vitamins, minerals, etc. There is additional regulation available with regard to provision of food information and its guidance for risk assessment of nanomaterials has to be developed.

16.6.4 Regulatory aspects of nanomaterials in agriculture/food/poultry feed in non-European Union countries

In the United States, the FDA is the regulatory body dealing with safety of food for the food products marketed under Federal Food, Drug, and Cosmetic Act (FFDCA). However, FFDCA does constitute any specific documentation for nano-based products and there is regulatory definition provided by FDA with regard to nanomaterial. The FDA has comprehensive approach with nano-based products. In regard to issues of nanotechnology FDA has several guidance documents viz., "Considering Whether an FDA-Regulated Product Involves the Application of Nanotechnology." In Canada Canadian Food Inspection Agency (CFIA) and Public Health Agency of Canada (PHAC) is responsible for food related regulations. At present there is so specific regulations for nano-based food products are framed yet but existing frameworks have been considered in this regard. However, Policy Statement on Health Canada's Working Definition for Nanomaterials has been published by health Canada in 2011. In Australia and New Zealand food products must adhere to rules of Food Standards Code. Food Standards Australia New Zealand (FSANZ) has amended Application Handbook for managing the potential risks associated with nanomaterial-based food risks. In India the key piece of regulation for food safety is the Food Safety and Standards Act [62]. 2001 Nano Science and Technology Initiative by the Government was established, followed by "Nano Mission" in 2007. The research activities have been conducted in this pretext and new initiatives has been employed in order to address risk issues. In China, food and its related products are governed under food safety

TABLE 16.2 Food legislation in non-European Union countries.

Country	Responsible organization	Key legislation
United States	US Food and Drug Administration (FDA)	Federal Food, Drug, and Cosmetic Act (FFDCA)
	Environmental Protection Agency (EPA)	Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)
Canada	Canada Canadian Food Inspection Agency (CFIA)	Food and Drugs Act
	Public Health Agency of Canada (PHAC)	
Australia and	Food Standards Australia New Zealand (FSANZ)	Australia New Zealand Food
New Zealand		Standards Code
Japan	Ministry of Health, Labour and Welfare	Food Sanitation Law
Korea	Ministry of Food and Drug Safety (MFDS),	Food Sanitation Act
	Korean food and Drug Administration (KFDA),	
	Korean Agency for Technology and Science (KATS)	
India	Food Safety Standard Authority of India (FSSAI)	Food Safety and Standards Act [62]
China	Ministry of Agriculture	Food Safety Law of China, 2009
	Ministry of Health	
	National Institute of Metrology	

law there is no specific regulations framed for nanomaterials. The National Centre for Nanoscience and Technology and the Commission on Nanotechnology Standardization are responsible for nano-based regulations. The document GB/T 19619-2004 published defines the nanomaterials. However, usage of nanomaterials as food ingredients has been not accepted to date in China by regulation. In South Korea, Food Sanitation Act is under legislation but regulatory frameworks have not been established yet regarding nano-based food products. But another agency Korean Food and Drug Administration is involved in establishing food standards such as "Food Code", "Food Additives Code" and "Food Labelling Standards". In Japan, the safety of food products is regulated by the Food Sanitation Law but no regulations have been framed with respect to nanomaterials (Table 16.2).

16.7 Conclusion and future perspectives

The application of nanomaterials in sustainable agriculture, poultry, and food is still at its infancy. The comprehensive research in this regard is crucial in exploring the benefits associated with nano-based technologies and also its risk assessment. The employment of nano-based formulations could offer targeted delivery of pesticides, fertilizers, nutrients along with plant protection. In food sector, pathogen detection, increase in shelf life, and also better sensory taste could be envisioned. The pathogen associated contamination risks with poultry and better growth of livestock could be addressed by nano-based strategies. The nano-based materials envision the sustainable economic and ecological approach.

Conflicts of interest

The authors confirm that this article content has no conflicts of interest.

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