Chapter 6
Nanobiotechnology and its Application in Agriculture and Food Production

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Contents

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D. Thangadurai et al. (eds.), *Nanotechnology for Food, Agriculture, and Environment*, Nanotechnology in the Life Sciences,
https://doi.org/10.1007/978-3-030-31938-0_6

6.1 Introduction

Nanobiotechnology integrates nanotechnology with biology. Nanobiotechnology is a new, emergent, and interdisciplinary field of research that refers to the use of nanotechnology to modify living organisms to enable the combinations of biological and nonbiological materials. The word "nano" refers to scale between 1 and 100 nm, and the term nanobiotechnology was coined by Lynn W. Jelinski, a biophysicist from Cornell University, USA. Nanobiotechnology finds application in genetic engineering and breeding programs (Scrinis and Lyons 2007). Variety of materials are used to synthesize nanoparticles (NPs) such as metal oxides, silicates, magnetic materials, semiconductor quantum dots (QDs), lipids, polymers, and emulsions (Niemeyer and Doz 2001; Oskam 2006; Puoci et al. 2008; Prasad et al. 2017a).

The use of nanobiotechnology is relevant in the current perspective because the widespread use of chemical pesticides and fertilizers has contaminated the environment, is hazardous for human health, and affects the biodiversity. To combat the problem, several nanotechnology-based products such as nanofertilizers, nanoherbicides, nanopesticides, nanosensors, nanofungicides and nanoinsecticides enhanced seed germination, and genetically modified crops are being developed (Jampilek and Kralova 2015; Bhattacharyya et al. 2016; Prasad et al. 2014, 2017a).

Nanotechnology holds great potential to increase global food production and food quality. Important areas of nanotechnology application in the food sector are food processing, food packaging (active, antimicrobial and smart packaging), nanoadditives, nanoencapsulation, nanosensors for contamination detection in food, and controlled release of nutraceuticals (Chellaram et al. 2014; Prasad et al. 2017b).

6.2 Application of Nanobiotechnology in Agriculture

Conventional agriculture uses agrochemicals, such as fertilizers, pesticides, fungicides, insecticides, and herbicides for crop growth and protection. However, their overuse is damaging the ecosystem by adding toxins in ground and surface water (Mukhopadhyay 2014). However, nanobiotechnology holds to promise to solve the agricultural problems and to restrict chemical overuse (Fig. 6.1). The applications of nanobiotechnology are described in this chapter (Table 6.1).

6.2.1 Nanofertilizers

Fertilizers are chemical compounds that provide nutrients to plant (Bottoms and Emerson 2013). Chemical fertilizers are in use since the early 1950s and have become the synonym of fertilzers. However, excessive use of chemical fertilizers has rattled the problem of water contamination, decreased soil fertility and

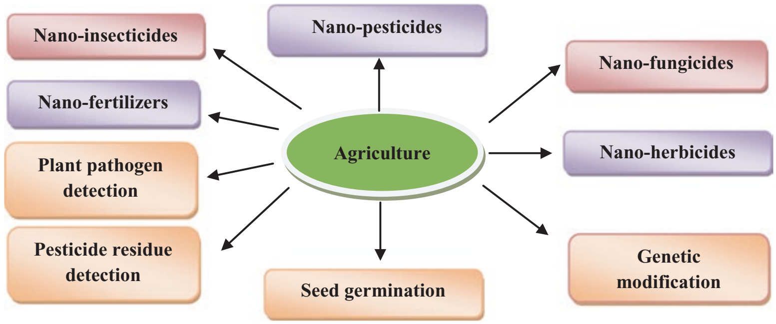

Fig. 6.1 Application of nanobiotechnology in agriculture. (Adapted from Mehrazar et al. 2015)

Table 6.1 Nanoparticle applications in agriculture

Nanomaterial	Type of nanoparticle	Application	References
Nanofertilizer	Synthetic apatite NP	Increase the plant growth rate and seed yield	Liu and Lal (2014)
	Iron chelate	Increase in wet weight and maximum leaf surface index and aerial organs dry weight	Moghadam et al. (2012)
	FeS_2	Breakdown starch in seeds resulting in increased in growth	Srivastava et al. (2014)
	EDTA-coated Fe_3O_4	Increased iron content in sunflower	Shahrekizad et al. (2015)
	Fe_3O_4	Increased the availability of iron to the plants	Rui et al. (2016)
	Fe_3O_4	Increase the iron and protein content and also used for the treatment of chlorosis	Siva and Benita (2016)
	Cu	Enhanced leaf area, chlorophyll content, fresh and dry weight and root dry weight of wheat	Hafeez et al. (2015)
	Nanochitosan-NPK fertilizer	Increased the growth and production of wheat growing in sandy soil	Abdel-Aziz et al. (2016)
	Nanozeourea fertilizer	Increased N content and enhanced the crude protein	Manikandan and Subramanian (2016)
	SiO_2 nanofertilizer	Enhanced the nitrogen and phosphorus content	Yassen et al. (2017)
	Zinc/boron nanofertilizer, prepared by loading $ZnSO_4$ and H_3BO_3 on a chitosan NPs emulsion	Increased the uptake of zinc, chlorophyll content and photosynthesis of the coffee was increased	Wang and Nguyen (2018)

(continued)

Table 6.1 (continued)

Nanomaterial	Type of nanoparticle	Application	References
	Chitosan–polymethacrylic acid (PMAA) NP	Starch accumulation at the root tip of pea. Major proteins such as convicilin, vicilin, and legumin β upregulated	Khalifa and Hasaneen (2018)
Nanoherbicides	Poly(epsilon-caprolactone) NP containing herbicide atrazine	Increased the mobility of atrazine in the soil resulting in increase herbicide effectiveness against *Brassica* sp.	Pereira et al. (2014)
	Chitosan/tripolyphosphate NPs loaded with paraquat herbicide	Control weeds	Grillo et al. (2014)
	Atrazine loaded nanocapsule	Decreased the root and shoot growth in *B. pilosa* and decrease in the photosystem II activity	Sousa et al. (2018)
Nanopesticides	Nanosilica	Effective against nuclear polyhedrosis virus (BmNPV) in silkworm industry	Barik et al. (2008)
	SiO_2	Effective against *Sitophilus oryzae*	Debnath et al. (2011)
	SiO_2	Effective against the stored grain pest *Corcyra cephalonica*	Vani and Brindhaa (2013)
	Ag	Effective against *Sitophilus oryzae* L. (pest of rice)	Abduz Zahir et al. (2012)
	Ag	Effective against the first to fourth instar larvae and pupae of the cotton bollworm (*Helicoverpa armigera*)	Durga Devi et al. (2014)
	CuO	Control cotton leafworm (*Spodoptera littorals*)	Shaker et al. (2016)
	ZnO	Delay in the larval and pupal development period of *Callosobruchus maculates*	Malaikozhundan et al. (2017)
Nanoinsecticides	ZnO	Effective against *Trialeurodes vaporariorum* (greenhouse whitefly)	Khooshe-Bast et al. (2016)
	Bio-silver and Au	Decreased the body weight of *Pericallia ricini* larvae	Sahayaraj et al. (2016)
	Ag and Zn	Effective against *Aphis nerii*	Rouhani et al. (2012)
	Ag	Control cotton leafworm (*Spodoptera littoralis*)	El-bendary and El-Helaly (2013)
	Nanoalumina dust	More effective against *S. oryzae* than *R. dominica*	Buteler et al. (2015)
	SiO_2	Effective against *Rhyzopertha dominica* F., and *Tribolium confusum* Jacquelin du Val.	Ziaee and Ganji (2016)

(continued)

Table 6.1 (continued)

Nanomaterial	Type of nanoparticle	Application	References
Nanofungicide	Ag	Effective against 18 different fungi (*Alternaria alternate*, *A. brassicicola*, *A. solani*, *Botrytis cinerea*, *Cladosporium cucumerinum*, *Corynespora cassiicola*, *Cylindrocarpon destructans*, *Didymella bryoniae*, *Fusarium oxysporum* f. Sp. *cucumerinum*, *F. oxysporum* f. Sp. *lycopersici, F. oxysporum*, *F. solani*, *Fusarium* sp., *Glomerella cingulata*, *Monosporascus cannonballus*, *Pythium aphanidermatum*, *P. ythium spinosum*, and *Stemphylium lycopersici)*	Kim et al. (2012)
	Ag	Effective against *Bipolaris sorokiniana* in wheat	Mishra et al. (2014)
	Ag	Effective against *Candida* spp., *Bipolaris sorokiniana*, *Magnaporthe grisea* and powdery mildews	Jo et al. (2009); Kim et al. (2009); Panacek et al. (2009); Lamsal et al. (2011)
	Chitosan	Effective against *F. solani*, and *A. niger*	Ing et al. (2012)
	Cu	Inhibited the activity of plant pathogenic fungi: *Phoma destructiva* (DBT-66), *Curvularia lunata* (MTCC 2030), *A. alternata* (MTCC 6572) and *F. oxysporum* (MTCC 1755)	Kanhed et al. (2014)
	Ag and Cu	Effective against two plant pathogenic fungi *Alternaria alternata,* and *Botrytis cinerea*	Ouda (2014)
	ZnO	Effective against two pathogenic fungi (*Botrytis cinerea*, and *Penicillium expansum*)	He et al. (2011)
	ZnO and MgO	Effective against *A. alternate*, *F. oxysporum*, *Rhizopus stolonifer*, and *Mucor plumbeus*	Wani and Shah (2012)
	Cu–chitosan	Effective against *A. solani* and *F. oxysporum* in tomato	Saharan et al. (2015)
	Nano trifloxystrobin 25% + tebuconazole 50%	Effective against *Macrophomina phaseolina*	Kumar et al. (2016)
	Combination between chitosan (CS) and silver (Ag), Ag@CS NPs	Effective against *Pyricularia oryzae* caused rice blast	Pham et al. (2018)

(continued)

Table 6.1 (continued)

Nanomaterial	Type of nanoparticle	Application	References
	ZnO	Effective against fungal phytopathogens, namely *A. alternata*, *A. niger*, *B. cinerea*, *F. oxysporum*, and *P. expansum*	Jamdagni et al. (2018)
Seed germination	Carbon nanotubes	Increased the germination of tomato seeds	Khodakovskaya et al. (2009)
	ZnO	Enhanced the germination rate	Singh et al. (2013)
	ZnO	Enhanced seed germination in rice and increased radical and plumule length	Upadhyaya et al. (2017)
	Au	Increased the seed germination rate of *Gloriosa superba*	Gopinath et al. (2014)
	Nanosilicon dioxide	Enhanced seed germination (22.16%), germination mean time (3.98%), and seed germination index in tomato	Siddiqui and Al-Whaibi (2014)
	Ag	Increased seed germination rate percent by 95% in *Boswellia ovalifoliolata*	Savithramma et al. (2012)
	Ag	Showed the highest percentage of seed germination in *Pennisetum glaucum*	Parveen and Rao (2014)
	TiO_2	Increased water absorption by the seeds resulting in accelerated seed germination	Feizi et al. (2012)
	Anatase	Enhance the germination of parsley seeds	Dehkourdi and Mosavi (2013)
	Binary mixtures of six metal oxide NPs (TiO_2, Fe_2O_3, CuO, NiO, Co_3O_4 and ZnO)	Enhanced seed germination in *Brassica*	Ko et al. (2017)
	Ag	Highest seed germination (98.6%) followed by copper (69.6%), and gold (56.5%), respectively	Hussain et al. (2017)
	SiO_2	Enhanced seed germination	Alsaeedi et al. (2018)

initiated eutrophication. Nanofertilizers hold the promise to alleviate the environmental problems caused by the use of chemical fertilizers. Nanofertilizers can improve plant growth as they contain nutrients and growth-promoting substances encapsulated in nanopolymers, chelates or emulsions. Nanofertilizers enjoy environmental and other benefits like less contamination of water bodies, reduced soil toxicity, delayed and steady nutrient release, increased production yield, improved photosynthesis, enhanced fertilizer effect period, and increased soil nutrients (Naderi and Danesh-Shahkari 2013; Mehrazar et al. 2015).

Several examples of successful application of metal-based nanofertilizers for improved plant growth are available in the scientific literature. For example, iron-chelated nanofertilizer application on two varieties of spinach, Varamin 88 and Viroflayand, respectively at 4 kg ha^{-1} showed 58% and 47% improvement in wet weight along with enhanced leaf surface index and aerial organs (Moghadam et al. 2012). In addition, the EDTA-coated Fe_3O_4 NPs increased iron content in sunflower (Shahrekizad et al. 2015). Similarly, iron pyrite NP treatment on spinach seeds improved plant growth and enhanced breakdown of starch in seeds (Srivastava et al. 2014). Iron oxide NPs improve peanut growth by augmenting the availability of iron (Rui et al. 2016). The Fe_2O_3 NP application increases the plant iron and protein content and reduces the frequency of chlorosis (Siva and Benita 2016). Copper (Cu) NP application increased the growth and yield of wheat cultivar Millat-2011 by enhancing leaf area, chlorophyll content, fresh and dry weight, and root dry weight (Hafeez et al. 2015).

Synthetic apatite NP application increases the soybean plant growth rate (32.6%) and seed yield (20.4%), respectively (Liu and Lal 2014). The nanozeourea fertilizer enhanced crude protein of maize plant growing in black soil by 26.1% and in red soils by 36.1%, which was higher than conventional urea fertilizer application (Manikandan and Subramanian 2016). The SiO_2 nanofertilizer application increased growth and yield in cucumber through improved nitrogen and phosphorus content in the plant (Yassen et al. 2017).

Recently, the demand for chitosan NP has increased based on their role as nanofertilizer. Chitosan is a biodegradable and biocompatible polymer of randomly distributed β-(1 → 4)-linked D-glucosamine and N-acetyl-D-glucosamine units. Several examples show an impressive plant growth result due to chitosan NP application. Nanochitosan-NPK fertilizer increases the growth and production of wheat growing in sandy soil (Abdel-Aziz et al. 2016). Application of zinc-boron nanofertilizer, prepared by loading $ZnSO_4$ on chitosan NP emulsion, on coffee leaves increased the level of Zn, N, and P uptake and improved chlorophyll content (Wang and Nguyen 2018). Chitosan–polymethacrylic acid (PMAA) NP application on pea plant increased starch accumulation in root tips. In addition, synthesis of proteins such as convicilin, vicilin, and legumin β was upregulated (Khalifa and Hasaneen 2018).

6.2.2 Nanoherbicides

Weeds are unwanted plants that reduce crop yield thus need timely removal from agricultural lands. Conventional herbicides kill weeds from the aboveground plant parts and do not remove tubers or roots that sprout another plant under favorable conditions (Ali et al. 2014). In addition, the absence of moisture in herbicides render them less effective in rainfed agriculture systems (Subramanian and Tarafdar 2011).

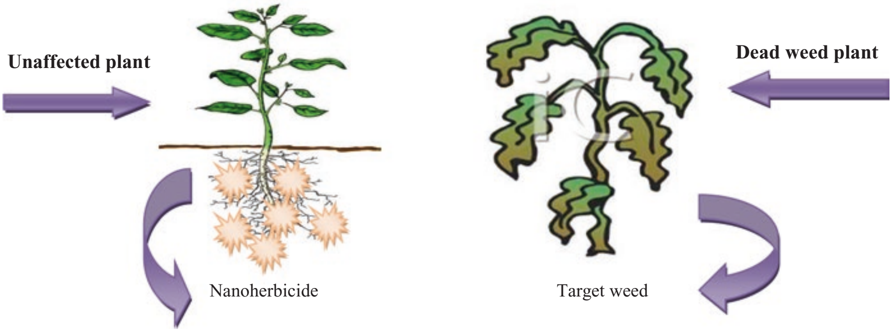

Fig. 6.2 Pathway showing the use of nanoherbicide to target weed plant. (Adapted from Elrahman and Mostafa 2015)

Nanoherbicides application could be an effective method to remove weeds (Fig. 6.2). The NP-based herbicide has several advantages over conventional herbicides such as increased water solubility, lower weed resistance, and decreased toxicity. NPs of poly(epsilon-caprolactone) containing the herbicide atrazine were tested on target (*Brassica* sp.) and nontarget (*Zea mays*) plants. Encapsulated herbicide did not harm a nontarget plant (*Zea mays*). The NPs increase the mobility of atrazine in the soil, resulting in increased herbicide effectiveness against *Brassica* sp. (Pereira et al. 2014). Chitosan/tripolyphosphate NP-based nanoherbicides are also under development. Chitosan/tripolyphosphate NPs loaded with paraquat herbicide are less toxic to crops and are safe in controlling weeds (Grillo et al. 2014). The 2000 g ha^{-1} application of atrazine-loaded nanocapsule effectively decreased the root and shoot growth in *B. pilosa* and reduced photosystem II activity (Sousa et al. 2018).

6.2.3 Nanopesticides

Plant pests are a major threat to crop production and require stringent control measures. The conventional methods for pest control employ several types of chemical pesticides, most of which are xenobiotic in nature. In addition, the excessive use of pesticides is causing adverse effects on organisms, environment, and nitrogen-fixing ability of plants (Ghormade et al. 2011; Elrahman and Mostafa 2015; Bhattacharyya et al. 2016).

NP-based pesticides enjoy several advantages over conventional pesticides. Nanosilica derived from the plant is effective in controlling the infection of nuclear polyhedrosis virus (BmNPV) of silkworm (Barik et al. 2008). Silica NPs used against *Sitophilus oryzae* provide 90% pest mortality (Debnath et al. 2011). In another study, 70–80-nm sized silica NP provided 100% mortality against *Corcyra cephalonica* (Vani and Brindhaa 2013). The Ag NPs, synthesized from aqueous leaf extracts of *Euphorbia prostrate*, demonstrated 100% mortality rate against *Sitophilus oryzae* L., a rice pest (Abduz Zahir et al. 2012). The Ag NPs synthesized from leaf extract of *Euphorbia hirta* provide protection against larvae and pupae of the cotton bollworm (*Helicoverpa armigera*). In addition, the longevity of male and female pest decreases after Ag NP treatment on larvae and pupae of the cotton bollworm (Durga Devi et al. 2014). The use of CuO NPs controls cotton leafworm larvae (*Spodoptera littorals*) with mortality of 100% (Shaker et al. 2016). The treatment of *Bacillus thuringiensis*-coated ZnO NPs delay the larval and pupal development period of *Callosobruchus maculatus*. The results show that Bt ZnO NPs are effective nanopesticide against *C. maculatus* (Malaikozhundan et al. 2017).

6.2.4 Nanoinsecticides

Insects are vectors of various plant diseases that damage crops and therefore require active control. Several chemical-based insecticides have been used to inhibit their reproduction or kill them (Ragaei and Sabry 2014). However, chemical-based insecticides suffer from several drawbacks as they are degraded by light, temperature, microorganism, and hydrolysis. Therefore, only a small quantity of these insecticides reaches the target site. As a result, repeated application of insecticides is necessary to control the insects, which increase the cost of crop production. In addition, the use of insecticides is known to damage ecosystems and human health (Perlatti et al. 2013).

To combat the practical problems associated with field application of chemical insecticide, several NP-based insecticides are being formulated and tested. For example, the ZnO NPs provide mortality rate of 91.6% against *Trialeurodes vaporariorum* (Greenhouse whitefly) (Khooshe-Bast et al. 2016). The use of biosilver and gold NPs affects the growth and decreases the body weight of *Pericallia ricini* larvae. Therefore, Ag and Au NPs could be used to control insects (Sahayaraj et al. 2016). The Ag and Zn NP application against *Aphis nerii* at 700 mg mL^{-1} provides the highest insect mortality rate (Rouhani et al. 2012). The Ag NP application on cotton leafworm (*Spodoptera littoralis*) provides more than 50% mortality of leafworms at 250 ppm and higher concentrations (El-Bendary and El-Helaly 2013). The nanoalumina dust, synthesized using a modified glycine-nitrate combustion process, displayed fair mortality rate against *Sitophilus oryzae* and *Rhyzopertha dominica* (pests of stored grain) (Buteler et al. 2015). The two SiO_2 NPs, namely Aerosil® and Nanosav, provided high-mortality rate of *Rhyzopertha dominica* and *Tribolium confusum* (Ziaee and Ganji 2016).

6.2.5 Nanofungicides

Phytopathogens attack plant tissues at different stages of growth. Some fungal pathogens like *Fusarium* spp., *Botrytis cinerea*, and *Phythophora* spp. infect aerial and few infect ground plant parts, causing a huge loss in crop yield. Conventional methods for phytopathogen control involve chemical fungicide application, which is highly toxic and nonbiodegradable in nature, contaminates the environment, and affects human health. To counter the problems associated with chemical fertilizer application in the field, the development of nanomaterial-based eco-friendly fungicide is underway for agriculture sustainability and greener environment (Abd-Elsalam and Alghuthaymi 2015). For achieving the goal, several nanofungicides have been tested against many plant pests.

Inhibition of several fungal pathogens by Ag NPs indicates their antifungal properties (Kim et al. 2012). For example, silver-based NPs were found to be effective against 18 fungal species (*Alternaria alternata*, *A. brassicicola*, *A. solani*, *Botrytis cinerea*, *Cladosporium cucumerinum*, *Corynespora cassiicola*, *Cylindrocarpon destructans*, *Didymella bryoniae*, *Fusarium oxysporum* f. sp. *Cucumerinum*, *F. oxysporum* f. sp. *lycopersici*, *F. solani*, *Fusarium* sp., *Glomerella cingulata*, *Monosporascus cannonballus*, *Pythium aphanidermatum*, *P. spinosum*, and *Stemphylium lycopersici*). The Ag NPs were also found effective against *Bipolaris sorokiniana* infection in wheat (Mishra et al. 2014). The antifungal activity of Ag NPs was also found against *Candida* spp. (Kim et al. 2009; Panacek et al. 2009), *Bipolaris sorokiniana*, *Magnaporthe grisea* (Jo et al. 2009), and powdery mildews (Lamsal et al. 2011). In addition, Ag and Cu NPs, used against *A. alternata* and *Botrytis cinerea*, showed maximum inhibition of the fungal hyphae growth at the concentration of 15 mg L^{-1} of Ag and Cu NPs (Ouda 2014).

High-molecular-weight chitosan NPs show antifungal activity against *F. solani* and *Aspergillus niger* (Ing et al. 2012). Cu–chitosan NP application at 0.12% concentration against *A. solani* and *F. oxysporum* in tomato caused 70.5% and 73.5% inhibition of fungal mycelia and spore germination by 61.5% and 83.0%, respectively (Saharan et al. 2015). Cu NPs inhibit the activity of plant pathogenic fungi like *Phoma destructive* (DBT-66), *Curvularia lunata* (MTCC 2030), *A. alternata* (MTCC 6572), and *F. oxysporum* (MTCC 1755). Since Cu NP can be quickly and conveniently synthesized using C-TAB-IPA method, it holds potential to be used as a commercial fungicide (Kanhed et al. 2014).

The ZnO NP application against *Botrytis cinerea* and *Penicillium expansum* causes deformation in fungal hyphae and inhibition of *B. cinerea* growth. In addition, ZnO NPs inhibit the growth of conidiophores and conidia of *P. expansum*, leading to the death of fungal hyphae (He et al. 2011). The ZnO and magnesium oxide (MgO)-based NP application has been reported to reduce spore germination of *Alternaria alternata*, *Fusarium oxysporum*, *Rhizopus stolonifer*, and *Mucor plumbeus* (Wani and Shah 2012).

More recently, the NP combinations are under use for effective nanofungicide preparation. For example, the combination of 25% nano trifloxystrobin with 50% tebuconazole (75 WG) fungicide made through ball milling produced better antifungal activity in comparison to conventional fungicide against *Macrophomina phaseolina* (Kumar et al. 2016). The combination of chitosan (CS) and silver (Ag) (also abbreviated as Ag@CS NPs) displayed significant antifungal activity against *Pyricularia oryzae*, responsible for rice blast (Pham et al. 2018). The ZnO NP combination with ciprofloxacin and ceftazidime demonstrated antifungal property against *A. alternata*, *A. niger*, *B. cinerea*, *F. oxysporum*, and *P. expansum*. The maximum antifungal activity was achieved when 0.25 mg mL^{-1} ZnO NPs was combined with 8 μg mL^{-1} ciprofloxacin and 32 μg mL^{-1} ceftazidime (Jamdagni et al. 2018).

6.2.6 Seed Science: Enhancing Seed Germination

Seed yield is the most important factor in determining crop productivity. Usually, the laboratory-tested germination seeds are distributed to farmers for cropping. However, most of the times the provided seeds show viability rate below the claim. The NP-based methods are being developed to improve the seed germination of stored seeds (Manimaran 2015).

The NPs of C, Zn, Au, Ag, and Si have been claimed to improve seed germination of several plants. For example, the carbon nanotube application at 10–40 μg mL^{-1} solvent increases tomato seed germination (Khodakovskaya et al. 2009). The ZnO NP application enhances the germination rate in many plants (Singh et al. 2013). The ZnO NP application at 15 mg L^{-1} enhances rice seed germination (Upadhyaya et al. 2017).

The Au and Ag are the nanoparticles of choice for many reasons. Au NP application at 1000 μM increased the *Gloriosa superba* germination rate (Gopinath et al. 2014). The Ag NP treatment increased seed germination percentage rate of *Boswellia ovalifoliolata* by 95% (Savithramma et al. 2012). The Ag NP treatment at 50 mg L^{-1} on *Pennisetum glaucum* seeds shows the highest germination percentage (93.33%) (Parveen and Rao 2014).

The TiO_2 NPs are preferred in plant sciences due to photocatalytic activity, stability, and lower costs. The 10 ppm nanosize TiO_2 treatment decreases the mean germination time (34%) in spinach seeds by facilitating water absorption (Feizi et al. 2012). Anatase NP (TiO_2) application at 40 mg mL^{-1} enhances the germination of parsley seeds (92.46%) (Dehkourdi and Mosavi 2013). TiO_2 NPs applied at 2000 mg L^{-1} in canola plants have been reported to enhance seed germination (Mahmoodzadeh et al. 2013).

Nanosilicon dioxide ($nSiO_2$) application at 8 g L^{-1} enhanced tomato seed germination percent (22.16%), germination meantime (3.98%), and seed germination index (22.15%) (Siddiqui and Al-Whaibi 2014). The SiO_2 (10–20 nm) and Mo NP (>100 nm) application in rice seeds also shows better germination (Adhikari et al. 2013). The 200 ppm silica NPs were reported to enhance cucumber seed germination (Alsaeedi et al. 2018).

In a recent study, several metallic NPs were reported to enhance the germination percentage of a medicinal plant *Artemisia absinthium.* In the study, the germination percentage of 98.6% was achieved with Ag NPs followed by Cu NPs (69.6%) and Au NPs (56.5%), respectively (Hussain et al. 2017). In another study, binary mixtures of six metal oxide NPs (TiO_2, Fe_2O_3, CuO, NiO, Co_3O_4, and ZnO) were used for evaluating seed germination in brassica. The 2–6% seed germination enhancement was achieved at 1000 and 2000 mg L^{-1} concentration of Ti, Co, and Fe metal oxide NPs. The CuO NP was found to be most toxic for brassica seed germination (Ko et al. 2017).

6.2.7 Nanobiosensors for Plant Pathogen Detection

Traditional microscopy-based and culture-dependent methods are available for detecting plant pathogens, which are time-consuming and often inaccurate (Fletcher et al. 2006). In addition, the immunological and molecular methods available for pathogen detection suffer from longer test time, weak signal strength, and bulky instrumentation (Kashyap et al. 2016). However, nanobiosensor application in plant pathology could provide a novel approach for detecting plant pathogens. The methods of pathogen detection are simple, rapid, and accurate (Sharon et al. 2010; Ismail et al. 2017). For example, fluorescent silica NPs, combined with antibody molecules were used to detect *Xanthomonas axonopodis* pv. *vesicatoria* that causes bacterial spot disease in Solanaceae family plants (Yao et al. 2009). Copper NP-modified gold electrode was used to detect oilseed rape infected with fungal pathogen *Sclerotinia sclerotiorum* (Wang et al. 2010). The TiO_2 or SnO NPs were used for detecting p-ethylguaiacol present in fruits and plants infected with fungi *Phytophthora cactorum* (Fang et al. 2014). Quantum dots fret-based biosensor was used to detect *Candidatus* phytoplasma aurantifolia that causes witche's broom disease of lime (Rad et al. 2012).

Nanobiosensors are also effective in detecting plant viral disease. The immunosensor shows high specificity and sensitivity for virus detection. For example, a chemiresistive sensor based on polypyrrole (PPy) nanoribbon was used to detect plant viruses (Chartuprayoon et al. 2013). Nanorod-based fiber-optic particle plasmon resonance immunosensor was utilized to detect orchid viruses (*Cymbidium mosaic virus* and *Odontoglossum ringspot virus*), which has several advantages such as faster analysis, good reproducibility, and lower detection limit than ELISA (Lin et al. 2014). A nanowire-based biosensor was developed for detecting plant diseases (Ariffin et al. 2014). Carbon nanotube-based Cu NPs are used to develop biosensor for detecting *Begomovirus* (CLCuKoV-Bur). The developed sensor detects viruses up to 0.01 ng μL^{-1} DNA concentration (Tahira et al. 2018).

6.2.8 Nanobiosensors for Pesticide Residue Detection

Nowadays pesticides are in heavy use for crop improvement. When pesticides degrade in environment, some toxic residues are released in the soil which may enter into the food chain through contaminated water and soil. Henceforth, accurate pesticide detection methods are required to measure the soil and plant contamination status. Conventional methods of pesticide residue detection include mass spectrometry, GC, HPLC, and UV-Vis spectrometry. However, these methods require skilled technicians and are time-consuming, therefore, not suitable for field analysis. As a result, newer methods are required for accurate pesticide residue detection in crop fields. Several nanobiosensor-based methods are under development that are cheaper, fast and do not require sample pretreatment (Vimala et al. 2016). For example, an electrochemical magnetoimmunosensing method was developed for detecting atrazine residue in samples (Zacco et al. 2006). Nanocomposite ZrO_2/Au film electrode is used for detecting parathion (Wang and Li 2008). Amperometric biosensor based on assembling acetylcholinesterase on poly(dimethylsiloxane)-poly(diallydimethylammonium)/gold NP composite film is used for detecting organophosphates (Zhao et al. 2009). The MnO_2 nanosheet-carbon dots are used for detecting organophosphorus pesticides (Yan et al. 2018). An optical biosensor was developed for detecting organophosphate pesticide using CdTe as fluorescent probe (Sun et al. 2011). Core-shell nanosensors based on localized surface plasmon resonance (LSPR) were developed for detecting atrazine (Yang et al. 2014). Recently, a fluorescence sensor was synthesized by combining copper (II) oxide and multiwall carbon nanotubes for detecting glyphosate. The detection was based on catalytic inhibition activity of the copper (II) oxide and multiwall carbon nanotubes (Chang et al. 2016). Sahoo et al. (2018) used zinc oxide quantum dots for detecting aldrin, tetradifon, glyphosate, and atrazine in water.

6.2.9 Production of Genetically Modified Crops

Nanobiotechnology also finds application in gene modification. For example, mesoporous silica nanoparticle (MSN) was used to transport DNA and chemicals into plant cells and leaves (Torney et al. 2007). The MSNs were used as carriers to deliver Cre recombinase protein into *Zea mays* cells for genome editing (Martin-Ortigosa et al. 2014). A fluorescent-conjugated polymer NP (CPN) was used for delivering siRNAs to knockdown a target gene in the cellulose biosynthesis pathway (NtCesA-1a and NtCesA1b) in plant protoplasts (Silva et al. 2010). Calcium phosphate NPs were used to deliver pBI121 harboring GFP driven by 35S promoter-encoding plasmid DNA into tobacco (Ardekani et al. 2014).

6.3 Application of Nanobiotechnology in Food Industry

The application of nanobiotechnology in the food sector is a newer concept with immense potential. Nanobiotechnology use in food has improved its taste, color, and flavor. Its application has also enhanced absorption and bioavailability of nutrients as well as health supplements. New food packaging materials are being developed using nanobiotechnology with improved mechanical strength, oxygen barrier, and antimicrobial properties. Nanosensors are used for detecting microbial contamination and toxic substances in food. The major areas of nanobiotechnology application in food sectors include food processing, food packaging, nanoemulsions, nanoencapsulations, nanoadditives, and nutraceutical delivery (Singh et al. 2017) (Fig. 6.3).

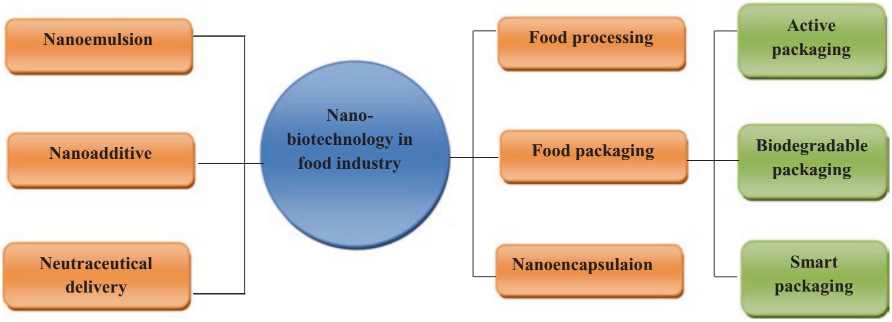

Fig. 6.3 Application of nanobiotechnology in food industry. (Adapted from Ravichandran 2010)

6.3.1 Food Processing

Food processing is done to maintain the nutritional quality of the food and enhance its shelf life. As a result, processed foods are less likely to get spoiled than fresh foods. In addition, such foods can be easily transported to long distances. Nowadays, commercially marketed food is processed using enzyme immobilization nanofiltration and other methods (Dasgupta et al. 2015) to improve the shelf life. Some of the common nanobiotechnology methods used in food processing are described further.

6.3.1.1 Enzyme Immobilization

Some food processing methods employ enzymes to modify food components for improving flavor, texture, and nutritional quality. The latest methods employ enzymes that are immobilized using NPs for thorough dispersal around food matrices to increase enzyme activity (Thangavel 2014). For example, SiO_2 NPs are used for triacylglycerol lipase immobilization in olive oil. The SiO_2 NPs, with reactive aldehyde groups, covalently bind to a porcine triacylglycerol lipase and help in hydrolyzing olive oil. The enzyme immobilization also helps in improving stability, adaptability, and reusability of food products (Bai et al. 2006). Similarly, magnetite NPs are used to immobilize lipase (Lee et al. 2009). In addition, polyacrylonitrile (PAN) nanofibrous membranes were used for immobilizing *Candida rugosa* lipase for the hydrolysis of soybean oil (Li and Wu 2009).

6.3.1.2 Nanofrying

The US-based Oilfresh Corporation is marketing a new nanoceramic product with several proclaimed benefits. The benefit includes reduced use of oil in restaurants and in fast food due to the larger surface area of the product (Momin et al. 2013).

6.3.1.3 Nanofiltration

Nanofiltration is a cost-effective separation method for product separation that stands somewhere between reverse osmosis and ultrafiltration. It separates substances less than 10 Å and removes divalent and multivalent ions. Nanofiltration is commercially used for desalination of seawater, concentration of juices (Warczok et al. 2004), demineralization, and removal of color from water. The technology is also applicable in wastewater treatment, water purification, and cheese making (Hussain and Al-Rawajfeh 2009). For example, the commercial cottage cheese whey making suffers from acidity, dilution, and saltiness. Nanofiltration of cottage cheese whey effectively concentrates solids by removing sodium, potassium salts, and some acids (Nguyen et al. 2003). Another commercial example of nanofiltration is of lactic acid separation, which is an important product of the food industry that requires costly purification system. Lactic acid enrichment with inorganic nanofiltration and molecular sieving membranes by pervaporation was achieved at much lower costs than vacuum evaporation and electrodialysis (Duke et al. 2008).

6.3.1.4 Nanolamination

Food is spoiled by the accumulation of moisture, gases, and lipids, which can be protected through nanolamination. Nanolaminates are thin, harmless protective films synthesized from polysaccharides, proteins, and lipids. These are barrier against carbon dioxide and oxygen that preserves food, improves food texture, flavor, and color. In addition nanolaminations enhance the level of nutrients and antioxidants in the food (Ali et al. 2014). For example, lipid-based nanolaminates are good barriers against moisture, while polysaccharide- and protein-based films protect from oxygen- and carbon dioxide-based damage (Ravichandran 2010).

6.3.2 Food Packaging

The packaging increases the shelf life of food by reducing microbial spoilage, decreasing gas and moisture exchange. Many commercial NP-based food packaging products are available and discussed further.

6.3.2.1 Active Packaging

The NP-based active packaging provides antimicrobial, antioxidation, and moisture scavenging properties to the food items (Yildirim et al. 2017). The main action of active packaging NPs lies in the inhibition of the microbial growth that leads to the spoiling of food (Chellaram et al. 2014).

The chitosan films are used in food preservation due to antimicrobial and nontoxic properties (Tripathi et al. 2008). Nanoclay is used in the packaging of food, beer bottles, carbonated drinks, and thermoformed containers. The packaged nanoclay acts as a gas barrier that keeps oxygen-sensitive foods fresh for longer time spans. The polyethylene terephthalate (PET) beer bottles use nanoclays produced by Nanocor® which enhance beer storage time from 11 weeks to about 30 weeks (Silvestre et al. 2011). The Ag NPs combined with hydroxypropyl methylcellulose (HPMC) matrix provide antimicrobial property, which is internally coated on food packaging material (Moura et al. 2012). In addition, the ZnO NPs are also used in food packaging as they are safe and hold antimicrobial activity (Espitia et al. 2012). Also, allyl isothiocyanate (AIT) and carbon nanotubes (CNT) are utilized as antimicrobial film for the packaging of shredded and cooked chicken meat. The diffusion of the AIT from the film in the packaged chicken decreases the microbial contamination, which allows controlled oxidation and reduces color change (Dias et al. 2013). In another study, the antimicrobial activity of ZnO NP/CS film provided about 1.5- to two-fold increase in the antimicrobial activity against *B. subtilis* and *E. coli* (Priyadarshi and Negi 2016). Durethan is a transparent plastic film, which contains clay NPs that block oxygen, carbon dioxide, and moisture to keep the food fresh. The use of nanoclay in durethan preparation makes the plastic lighter, stronger, and heat resistant (Davari et al. 2017). The Ag NPs synthesized by crosslinking with trisodium citrate enhanced shelf life of the grapefruit. The Ag NPs filled with hydroxypropyl methylcellulose (HPMC) and xanthan films show good antibacterial activity with decreased decay index (Kothari and Setia 2017). A variety of NP-reinforced polymers termed as nanocomposites are used in the food packaging industry (Momin et al. 2013). For example, the composite of Ag and ZnO NPs enhances the shelf life of fresh juice (Emamifar et al. 2010).

Fruits and vegetables degrade faster after harvest due to ethylene production. Therefore, ethylene adsorbent powders are added in packaging to maintain the freshness of food and food products. Alkali-treated halloysite nanotubes have the highest ethylene adsorption capacity because the treatment increases the nanotube pore size (Gaikwad et al. 2018). Polyethylene nanocomposite films containing combinations of organoclay (OC) NP are also used in antimicrobial packaging of food that are effective against *Escherichia coli* (Fasihnia et al. 2017). Sarwar et al. (2017) found the antimicrobial activity of PVA/nanocellulose/Ag nanocomposite films against *Staphylococcus aureus* (MRSA) and *E. coli* (DH5-α). The developed film was nontoxic and possessed high thermal stability and high mechanical strength.

6.3.2.2 Biodegradable Packaging

The use of nondegradable plastics change the soil nature and causes the accumulation of toxic gases in the atmosphere, which is responsible for environmental pollution and global warming. To counter the problem associated with nondegradable plastics, the production of biodegradable plastics has been initiated. However, the biodegradable plastic production at a commercial level is a costly affair, and also they are permeable to water and gas permeable and lack mechanical strength.

The newer methods employ natural or synthetic NPs to rectify the defects of biodegradable plastics because NP-based bioplastics have advantages like biodegradability and higher mechanical strength (Chellaram et al. 2014). For example, biodegradable starch/clay nanocomposite films hold higher mechanical strength and are used in food packaging (Avella et al. 2005). In addition, the incorporation of NPs in bioplastics impart antimicrobial nature to them. For example, laser-generated Cu NPs embedded in a biodegradable polymer matrix (polylactic acid) equip them with antibacterial nature, for better food storage capability (Longano et al. 2012). A biodegradable material, poly(lactic acid) used in food packaging, provides higher mechanical strength and antimicrobial activity (Gonzalez and Igarzabal 2013). Also, specialized bioplastics are available for thermal-sensitive foods. For example, pectin-TiO_2 nanocomposite aerogels are available for packaging thermosensitive food that lowers the thermal conductivity to food. The presence of TiO_2 enhances thermal stability and provides antimicrobial activity under UV light and dark conditions (Nesi et al. 2018).

6.3.2.3 Smart Packaging

In smart packaging, the nanosensors are used for detecting microbial and biochemical changes and release of antimicrobials, antioxidants, and enzymes in food. The smart food spoilage detection is based on the concept that unpleasant odors are generated from food and drinks when contaminated with bacteria. A chemical sensor system called electronic nose senses the odor released from spoiled food (Casalinuovo et al. 2006). In a more specified example, Concina et al. (2009) used an electronic nose to detect the volatile compounds released from spoiled tomato. Electronic tongues, based on amperometric sensors, are also in use for food analysis (Scampicchio et al. 2008). In addition, surface-enhanced Raman scattering (SERS) sensors made up of a graphene and Ag nanocomposite was developed to detect the prohibited color additives in food (Xie et al. 2012).

6.3.3 Nanocoating

Wax coating is widely used for improving the shelf life of apples and cheeses. Coating delays senescence and protects the fruit from decay (Ghosh et al. 2017). The recent development of nanoscale edible coatings was made possible through nanotechnology. Edible coatings and films are used on various foods including fruits, vegetables, meats, cheese, and bakery products (Momin et al. 2013). Nanocomposite edible coating is used for increasing the shelf life of olive (Ghosh et al. 2017).

6.3.4 Nanoadditives

Nanoadditives such as vitamins, antimicrobials, antioxidants, and preservatives are used to enhance taste, absorption, and bioavailability of nutrients (Momin et al. 2013). For example, food additive nanoscale silica powder increases the shelf life and bioavailability of specific nutrients (Canham 2007). The NPs containing calcium show effective absorption properties (Jeon and Lee 2009). The TiO_2 or E-171, a colored additive, produces a nontransparent white film that shows shielding against UV light (Latva-Nirva et al. 2009). The nanocrystalline powder of lycopene and resveratrol increases the absorption and bioavailability of nutrients in the body (Hsieh 2010). Nanoadditive, acyl ascorbates, synthesized through lipase condensation of ascorbic acid with fatty acids is used as antioxidant as it inhibits the oxidation of polyunsaturated fatty acid (Sharma and Pathak 2010). Aquasol preservative manufactured by AquaNova contains nanoscale micelle that increases absorption of nutritional additives and enhanced the preservation of food. Bioral™ omega-3 fatty acid nanocochleates, manufactured by BioDelivery Sciences International, is added to cakes, muffins, pasta, soups, cookies, cereals, chips, and confectionery. Synthetic lycopene, manufactured by BASF AG and DSM Nutritional Products Ltd., is an antioxidant and used in soft drinks, juices, breakfast cereals, instant soups, salad dressings, and yogurt (Kirdar 2015). Nisin-loaded chitosan-monomethyl fumaric acid (CM-N) NPs used as food additive show antibacterial activity against foodborne pathogens in orange juice (Khan et al. 2017).

6.3.5 Nanoencapsulation

Nanoencapsulation is the process to encapsulate substances at the nanoscale range (Lopez et al. 2006). The benefit of nanoencapsulation includes increased bioavailability of nutrients, preservation of the ingredients and additives during processing, removal of unpleasant tastes and flavors, and controlled release of additives (Chaudhry et al. 2010). Lipid-based nanoencapsulation systems such as nanoliposomes, archaeosomes, and nanocochleates can protect antioxidants from degradation and increase their solubility and bioavailability (Mozafari et al. 2006). Functional bread has been enriched with nanoencapsulated omega-3 fatty acids. Encapsulation decreased lipid oxidation during baking and reduces the formation of acrylamide and hydroxymethylfurfural (HMF) in bread (Gokmen et al. 2011). Donsi et al. (2011) used the high-pressure homogenization (HPH) method to prepare sunflower oil or oil-in-water nanoemulsions. A terpene and D-limonene mixture was encapsulated into sunflower oil or essential oil-in-water nanoemulsions. Encapsulation of terpenes and D-limonene inhibits the growth of microbes. Isolated lactoferrin from camel milk is encapsulated using calcium alginate. Calcium alginate nanocapsules help to control lactoferrin digestion (Raei et al. 2015).

Curcumin is a medically important compound produced by *Curcuma longa* plants. However, they are lipophilic in nature and unstable in gastrointestinal fluids. It has been shown that encapsulation of curcumin in nanoform enhances their antioxidant properties with increased absorption rate during digestion (Rao and Khanum 2016). In addition, nanoencapsulation could be used to encapsulate fish oils that deteriorate rapidly otherwise. As a result, nanoliposome system was developed to encapsulate fish oil (Ghorbanzade et al. 2017).

6.3.6 Nanoemulsions

The emulsion is a mixture of two immiscible liquid phases in which one phase disperses as droplets. Nanoemulsions consist of nanosize oil droplets of 10–100 nm. Nanoemulsions can be produced using high- and low-energy methods. A high-energy method uses mechanical devices (high-pressure valve homogenizers, microfluidizers, and sonication) to generate intense disruptive forces that breakdown the oil and water phases to form oil droplets. A low-energy method is based on the spontaneous formation of oil droplets within mixed oil-in-water emulsifier systems (Silva et al. 2012).

6.3.7 Nutraceutical Delivery

The major problem of the nutraceutical industry lies with the active components that poorly dissolve in oil or water, thus finding it difficult to reach target sites, thereby resulting in low bioavailability of nutrients (Putheti 2015). Nanobiotechnology employs a new strategy for the efficient delivery of nutraceuticals through nanoencapsulation. For example, nanoencapsulation of nutraceuticals is most commonly done using hydrophobins (Hyd), a small cysteine-rich amphipathic protein. The Hyd proteins bind to hydrophobic materials like vitamin D3 (VD3) with high affinity and protect the vitamin against degradation. The Hyd protein also acts as nanovehicle of hydrophobic nutraceuticals (Israeli-Lev et al. 2014). Dual nutraceutical nanohybrids consisting of folic acid and calcium were synthesized based on layered double hydroxide structure through exfoliation reassembly hybridization method. The report shows that the use of nutraceutical nanohybrids increases contents of essential nutrients in the human body (Kim and Oh 2016).

6.3.8 Nanobiosensor for Detection of Food Pathogen and Other Contaminants

Traditionally, the food pathogens are detected through microbial culture observation, PCR amplification, and immunology-based method (ELISA). Recently, many NP-based biosensor systems have been developed that are fast, inexpensive and require a little experience. Magnetic NPs coated with antibody (anti-AFM_1) are used to separate the bound and unbound fractions of the component. Nanosensors successfully detect a minute change in the food color and gases released due to spoilage (Pradhan et al. 2015).

Biosensor-based methods involve detection of foodborne pathogen antibodies bound to NPs (Popov et al. 2010). An electronic tongue or nose consisting of an array of nanosensors was developed to detect the food spoilage through signals of gases released by food items (Garcia et al. 2006). Several cited examples have used nanosensors for pathogen detection. For example, nano-biosensors were used to detect food pathogens such as *Staphylococcus* spp., *Bacillus* spp., *Clostridium* spp., *Shigella*, and *E. coli* (Otles and Yalcin 2010). A gold NP-based biosensor with graphite-epoxy composite electrodes was used for the identification of *Salmonella* IS200 (Oliveira Marques et al. 2009). Streptavidin-coated magnetic NPs were used for detecting foodborne pathogens like *Escherichia coli* O157: H7, *Salmonella enterica*, *Vibrio cholera*, and *Campylobacter jejuni* (Song et al. 2013). Shelby et al. (2017) used magneto-fluorescent nanosensor for detecting foodborne pathogen *E. coli* O157: H7. Piezoelectric biosensor based on an Au NP was used for detecting *Escherichia coli* O157: H7 in apple juice, milk, and ground beef. An Au/Si hetero-nanorod biosensor was used to detect *Salmonella* sp. based on the fluorescence (Fu et al. 2008). Electrically active polyaniline-coated magnetic (EAPM) NP-based biosensor was used to detect endospores of *Bacillus anthracis* in food samples (Pal and Alocilja 2009).

Nanosensors find huge application in toxin detection from various products. For example, an electrochemical immunosensor was used for detecting aflatoxin M_1 (AFM_1) in milk. The sensor was based on a competitive immunoassay in which the enzyme horseradish peroxidase (HRP) was used as a tag (Paniel et al. 2010). Optical biosensor based on competitive dispersion of gold nanorods (GNRs) detect aflatoxin B1 (AFB_1) in food products (Xu et al. 2013). The Au NP-based aptasensor was used for detecting AFB_1 in food samples (Hosseini et al. 2015). The use of Au NP in biosensor amplifies the signal frequency change due to the relatively large mass of the NPs (Chen et al. 2008). An optical carbon nanotube (CNT) immunosensor detects *Staphylococcal* enterotoxin B (SEB) in food. The deployment of CNT has lowered the detection limit of SEB and increased the immunosensor sensitivity at least sixfold (Yang et al. 2008).

Recently, the aptamer-based biosensors are under the course of development. Aptamers are single-stranded nucleic acids (DNA and RNA) or peptides that bind to the targeted molecules with high affinity and specificity (Song et al. 2012). In a classical example, luminescent assay, based on aptamer sensors, was used for detecting toxins in food (McKeague et al. 2011). In addition, aptamer-based nanosensors successfully detect acetamiprid pesticides in food (Verdian 2017). Besides aptamer biosensors, NP-based fluorescence resonance energy transfer methods are also used for detecting organophosphorus pesticides in food samples (Long et al. 2015).

6.4 Nanoparticles: Risks and Regulations

Besides various advantages of nanobiotechnology in the food industry, some safety issues are associated with the use of NPs. Several vivid nanotechnological application can impart accidental effects on plants and animals, thus need a thorough evaluation. NPs may accumulate within body organs and tissues due to smaller dimensions (Savolainen et al. 2010). Animals may inhale NPs into the lungs, resulting in severe disorders. The NPs may deposit on leaves and floral plant parts to create a toxic layer that prevents pollen tube penetration on stigma. They may also affect the translocation of water and minerals (Tarafdar 2015). Exposure of human endothelial cells with NPs could lead to cytotoxicity, genotoxicity, and dysfunction of nitric oxide signaling (Cao 2018). The NPs can enter the human body through the lungs, intestinal tract, and skin. Skin contact with toxic NPs and their inhalation are major risks in agriculture practices (Hoet et al. 2004). Inhaled NPs may reach the brain to cause neurodegeneration (Win-Shwe and Fujimaki 2011). Some studies reported the neurotoxic nature of NPs (Wu et al. 2013; Chin-Chan et al. 2015; Coccini et al. 2015; Migliore et al. 2015).

As a result, special regulations are required for NP preparation and application in agriculture and food industries (Amenta et al. 2015). In 2011, the guidance draft on risk assessment for nanotechnology use in food, feed applications, and pesticides was issued by the European Food Safety Authority (EFSA Scientific Committee). Environmental Protection Agency (EPA), USA, issued a proposal to use Sect. 6(a)(2) of the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) to obtain information on the use of nanomaterials in pesticide products and its potential effect on humans or the environment (EFSA Scientific Committee 2011). As a result, National Institute for Occupational Safety and Health (NIOSH), USA, issued warning against occupational exposure to carbon nanotubes and nanofibers during research and development (Howard 2013).

6.5 Conclusion

Nanobiotechnology involves the use of nanotechnology to modify living organisms and to enable the combination of biological and nonbiological materials. Nanobiotechnology has multiple applications in agriculture, food, and other sectors. The NP-based herbicides, pesticides, fertilizers, fungicides, and insecticides are needed for improving the crop productivity in an eco-friendly way. In seed science, nanotechnology is used to enhance seed germination. The role of nanobiosensors has also been proved useful in pathogen diagnosis, pesticide residue detection, and food contaminant determination. The nanobiotechnology application in food includes food processing (improving texture, color and shelf life), packaging (antimicrobial, oxygen and aroma scavenger), application of nanoadditives, nanoencapsulation, and controlled nutraceuticals delivery at the time of digestion. The

NPs have been effectively used in developing food storage packaging materials that can decrease pathogenic growth of stored food. Nanobiosensors are also used to detect the contamination of foodborne pathogens, toxic substance, and pesticide in food. However, extensive studies are required to understand the NP-associated toxicity and involved mechanism to avoid application-based harmful effects on the environment and human health.

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