Chapter 13
Application of Nanotechnology in Plant Protection by Phytopathogens: Present and Future Prospects

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13.1 Introduction

Crop losses due to plant disease and pests are a major threat to food security worldwide (Savary and Willocquet 2014). Plant diseases are caused by viruses, bacteria, insects, bacteria, and nematodes. Worldwide, insect pests and plant diseases are responsible for losses ranging between 14% and 13%, respectively (Agrios 2005). Recently, pathologists determined top ten list of scientifically and economically important plant pathogens including plant parasitic nematodes, fungi, viruses, and bacteria (Jones et al. 2013; Mansfield et al. 2012; Scholthof et al. 2011; Dean et al. 2012) (Table 13.1).

The correct identification and quantification of pathogen causing disease is of major importance in plant health monitoring. However, the detection of plant pathogens based on traditional laboratory techniques such as cultural techniques and microscopy is time-consuming and requires complex sample handling and specialized skills. Because of the importance of the damage caused by plant pathogens, many strategies have been widely developed for diagnosing plant pathogens with a high degree of specificity and sensitivity including DNA-based methods and immunological techniques (Kashyap et al. 2016). In spite of these advantages, most of these technologies have some limitations in detecting pathogens and cannot be applied directly on site detection (Kashyap et al. 2016). Another limitation is related to the high price of some molecular biology reagents, such as primers and enzymes.

By 2050, the population growth is expected to increase from 6 billion to 9 billion, and the global demand for food is expected to grow over the next 40 years due to climate change; limited natural resources such as soil fertility, water, and land; and environmental issues such as the excessive accumulation of pesticides in agri-

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Table 13.1 Top ten important pathogens (nematode, bacteria, virus, and fungi)

S.No.	Nematode (Jones et al. 2013)	Bacteria (Mansfield et al. 2012)	Virus (Scholthof et al. 2011)	Fungi (Dean et al. 2012)
1	*Meloidogyne* spp.	*Pseudomonas syringae*	*Tobacco mosaic virus*	*Magnaporthe oryzae*
2	*Heterodera* spp., *Globodera* spp.	*Ralstonia solanacearum*	*Tomato spotted wilt*	*Botrytis cinerea*
3	*Pratylenchus* spp.	*Agrobacterium tumefaciens*	*Tomato yellow leaf curl*	*Puccinia* spp.
4	*Radopholus Similis*	*Xanthomonas campestris*	*Cucumber mosaic*	*Fusarium graminearum*
5	*Ditylenchus dipsaci*	*Xanthomonas campestris*	*Potato virus Y*	*Fusarium oxysporum*
6	*Bursaphelenchus xylophilus*	*Xanthomonas axonopodis*	*Cauliflower mosaic*	*Blumeria graminis*
7	*Rotylenchulus reniformis*	*Erwinia amylovora*	*African cassava mosaic*	*Mycosphaerella graminicola*
8	*Xiphinema index*	*Xylella fastidiosa*	*Plum pox*	*Colletotrichum* spp.
9	*Nacobbus aberrans*	*Dickeya*	*Brome mosaic*	*Ustilago maydis*
10	*Aphelenchoides besseyi*	*Pectobacterium carotovorum*	*Potato virus x*	*Melampsora lini*

cultural soils (Chen and Yada 2011). Traditional plant protection strategies such as integrated pest management often prove insufficient, and application of chemical pesticides leads to various environmental and human health issues. In addition, the resistance of some plant pathogens and pests against the indiscriminate use of pesticides is rapidly becoming a serious problem (Sangeetha et al. 2017a). To preserve biodiversity, there is an urgent need to achieve pest and disease management by alternate strategies such as nanotechnology. "Nano" word originated from Latin word, which means dwarf. According to International Standards Organization (ISO), nanomaterial is defined as a material with an external dimension in the nanoscale or having an internal structure or surface structure in the nanoscale (1–100 nm). Then the nanotechnology was defined as the science of materials and devices whose structures and constituents demonstrate novel and considerably altered physical, chemical, and biological phenomena due to their nanoscale size (Bhatia 2016). Recently, nanotechnology in agriculture has been increasingly applied to promote food security, food safety, and food production throughout the world (Sangeetha et al. 2017b). In agriculture, nanotechnology has a broad range of applications including nanoparticles (NPs) to manage different plant diseases and pests (Sangeetha et al. 2017b).

Nano-based materials have been widely used to increase the efficacy of pesticides during their applications by allowing minor doses to be used (Abd-Elsalam 2013). In agriculture, particularly, numerous publications and patents have shown the potential benefits of nanotechnological strategies for disease management and crop productivity (Prasad et al. 2012; Parisi et al. 2015; Kah and Hofmann 2014; Mishra and Singh 2016), such as nanofertilizer for enhanced crop productivity, nanopesticides for pest and plant disease management, and nanosensors for detection of plant pathogens and soil monitoring (Barik et al. 2008; Wilson et al. 2008; Oliveira et al. 2015; Prasad et al. 2014, 2017a, b, c; Bhattacharyya et al. 2016; Ismail et al. 2017; Gupta et al. 2018). In this review, we highlighted the potential of nanotechnology applications in the control of plant diseases through the use of metallic nanoparticles and nanosensors for the detection of pests and plant pathogens in different agricultural situations.

13.2 Nanotechnology in Agriculture

With the advancement of industrialization and urbanization, the use of cutting-edge technologies such as nanotechnology and new materials to promote the original innovation of agricultural science and technology is conducive to the sustainable development of agriculture. Recently, nanotechnology has been applied in agriculture and shows good prospects. The development of nanotechnology has led to many new disciplines related to nanometers, such as nanomedicine, nanochemistry, nanoelectronics, nanomaterials, nanobiology, etc., which naturally gave birth to nano-agriculture. Conceptually, nanotechnology agriculture is a material in the field of nanotechnology and agriculture, scientific innovation, and agricultural application of nanomaterial research. Indeed, the application and potency of nanotechnology in agriculture seem to be promising; however, some technical and economic issues should be dealt with. Nanotechnology enables to produce higher yields with lower input costs by streamlining agricultural management and by this way reducing waste and labor costs (increase the level of production at low cost) (Sheykhbaglou et al. 2010). Nevertheless, there is a need to deal with these aims adopting precision farming practices and effective application of nanotechnology (Chowdappa and Gowda 2013).

In fact, the application of integrated innovation and nanotechnology in agriculture is not new. In order to overcome food security, resource scarcity, and environmental issues, in 2000, the National Nanotechnology Innovation Initiative officially incorporated agricultural nanotechnology into the research agenda. In 2003, the US Department of Agriculture launched a special study on the application of nanotechnology in agriculture and food. In the past 10 years, the European Union, Brazil, Canada, China, and other major agricultural countries have strengthened research and development in nano-agriculture. FAO, WHO, and other international organizations are also very concerned about nanotechnology for global agriculture and food security. Practically, nanotechnology can be used to improve the production process and to improve the effectiveness of the new varieties in organic crop cultivation. It is also adopted to enjoy targeted delivery and controlled release of functional nanomaterials in order to improve chemical fertilizers and pesticides and for effective use of other agricultural inputs such as veterinary drugs and animal feeds to reduce residues and pollution. In addition, it can also benefit from the use of nanotechnology to improve monitoring and diagnostic analysis capabilities for major agricultural “epidemics,” food safety, and food nutrition. At a quality scale, the content, flavor, and external quality can be improved using nanomaterials in the agricultural production process.

Applications of nanotechnology in the research filed related to agriculture have made important strides especially in reducing pesticide particles from the traditional 5 microns to 100 nm. The small size effect can reduce the shedding of pesticides on the foliage and advance the application of pesticides. Concurrently, the use of nanomaterials to load pesticide particles can achieve controlled release through microencapsulation technology according to the aging characteristics of crop control and extend the duration of application, thus reducing the number of pesticide application times, thereby avoiding food safety issues caused by pesticide abuse. Nanotechnology can also enhance the water solubility and dispensability of poorly soluble pesticides and reduce the use of organic solvents in pesticide formulations (Zhao 2014). The process of nanomaterial production involves cut-edge technologies to engineer nanostructure devices with minimum dimensions less than 100 nm. Several studies report that nanoprocessing methods are based on an unprecedented growth of knowledge and deep understanding of the characteristics, properties, and their integration with engineered nanomaterials into multifunctional devices (Schäffer et al. 2000; Lee et al. 2003; Smith et al. 2003; Ginger et al. 2004; Gates et al. 2005; Biswas et al. 2006; Acharya et al. 2008; Ariga et al. 2007, 2008, 2010, 2011; Rogers and Lee 2008; Sakakibara et al. 2011; Ando et al. 2010; Kraemer et al. 2009; Li et al. 2009; Mailly 2009; Marrian and Tennant 2009; Schmid et al. 2009; Yaman et al. 2011).

Based on the ultrasmall size of nanomaterials, nanotechnology could be less harmful to the environment and human health; however, there are studies showing the potential health hazards and toxic effects since these nanomaterials when entered into a human body lead to tissue damage by the easiness to reach all vital organs.

13.3 Nanotechnology for Plant Disease Detection

A rapid and reliable diagnostic test to identify and quantify pathogens in samples is an essential step toward managing plant disease. However, the diagnostic of these pathogens based on traditional method is time-consuming, lacks high sensitivity, and requires specialized skills. Therefore, molecular tools have been widely used for diagnosing plant diseases including DNA-based molecular diagnostics (PCR with species-specific primers, quantitative PCR, sequencing, etc.) and immunoassays for the detection of pathogen nucleic acid and proteins extracted from infected plants (Lopez et al. 2003; Khater et al. 2017). Several previous studies addressed pathogen detection using immunoassays (serological assays) and nucleic acid-based methods (Nolasco et al. 2002; Anwar Haq et al. 2003; Teixeira et al. 2005; Lacava et al. 2006; Li et al. 2006; Ruiz-Ruiz et al. 2009). Despite these advantages, molecular techniques have some limitations in detecting pathogens directly in the field. Moreover, another limitation is related to false-negative results which can be produced by PCR failure due to degraded DNA, presence of inhibitors, or other reasons (Louws et al. 1999; Lopez et al. 2003; Waeyenberge et al. 2009; Martinelli et al. 2015). To overcome such limitations, there is an urgent need for accurate and early detection of pathogens with the help of effective application of nanotechnology in agriculture. An early diagnosis of disease plays a significant role in health monitoring. It allows to reduce the risk of disease transmission and spread, prevent introduction of new pathogens at country border, and minimize crop loss (Strange and Scott 2005; Miller et al. 2009). Several previous studies addressed rapid diagnostic tools for the detection of plant pathogens using quantum dots, nanoparticles, nanosensors, and nano-based kits (Khiyami et al. 2014; Fan et al. 2003; Arya et al. 2005; Yao et al. 2009; André Lévesque 2001; Duhan et al. 2017; Abd-Elsalam and Prasad 2018). Quantum dots have been widely used to detect different plant pathogens (Arya et al. 2005; Khiyami et al. 2014). Quantum dots are semiconductor nanoparticles which are rapid than organic fluorescent dyes used as proteins for visual detection or markers on nucleic acids (Duhan et al. 2017). A method was developed to identify vector of beet necrotic yellow vein virus using quantum dots-fluorescence resonance energy (Safarpor et al. 2012). Rad et al. (2012) used the same method "Quantum dots-fluorescence resonance energy transfer based sensors" to detect *Phytoplasma aurantifolia* on lime with high sensitivity.

In the last years, biosensors have been widely used as diagnostic tools in food to improve pathogen and environmental analyses. They allow to improve pathogen detection techniques in different crop systems (Khater et al. 2017). Biosensor strategies are applied through different receptors including DNA probe and antibody-based biosensors (Singh et al. 2013; Khiyami et al. 2014). Moreover, nanosensors can detect rapidly the presence of plant viruses, bacteria, and crop pathogens with precise quantification (Otles and Yalcin 2010; Brock et al. 2011; Khater et al. 2017). Several previous studies addressed plant disease detection such as fungi (Chartuprayoon et al. 2010), virus (Yao et al. 2009), and bacteria (Boonham et al. 2008) using nanoparticles. Recently, gold nanoparticle (AuNP) aggregation-based DNA analyses have widely been used for the detection of plant pathogens' DNA (Khater et al. 2017). Various studies reported the application of DNA-based biosensors for diagnosing plant pathogens with high degree of sensitivity and specificity (Table 13.2)

13.4 Application of Nanotechnology for Controlling Pest and Pathogens

Nanotechnology has been provisionally defined as relating to materials, systems, and processes which operate at a scale of 100 nm or less. A nanometer is one billionth of a meter. Overall nano refers to a size scale between 1 and 100 nm. For comparison, the wavelength of visible light is between 400 and 700 nm. A leukocyte has the size of 10,000 nm, a bacteria 1000–10,000 nm, virus 75–100 nm, protein

Table 13.2 DNA-based biosensors used for plant pathogen detection

Assay format detection	Sensing plant disease	References
AuNP aggregation-based DNA	*Pseudomonas syringae*	Vaseghi et al. (2013)
	Fusarium oxysporum	Wee et al. (2015)
	Botrytis cinerea	
Fluorescent approach in microfluidics based on silver NPs	*Phytophthora* species	Schwenkbier et al. (2015)
Turbidity-based microfluidic system	*Cymbidium mosaic virus*	Chang et al. (2013)
DNA microarray technology	*Botrytis cinerea* *Botrytis squamosa*	Wang and Li (2007)
	Cucumber mosaic virus	Zhang et al. (2005)
	Potato viruses	Boonham et al. (2003), Bystricka et al. (2003)
	Cucumber mosaic virus	Deyoung et al. (2005)
Electrochemiluminescence-based DNA	*Banana bunchy top virus* *Banana streak virus* *Papaya leaf curl virus*	Tang et al. (2007)

5–50 nm, deoxyribonucleic acid (DNA) ~2 nm (width), and an atom ~0.1 nm. Nanotechnology considers the topics with viruses and other pathogens scale. So, it has the high potential to identify and eliminate pathogens (Predicala 2009; Prasanna 2007). The utilization of nanomaterials as a pesticide to control and prevent plant disease is an effective tool that may be adopted, meaning several methods and the evident methods would be the direct application in soil and on seeds and foliage (Khan and Rizvi 2014). The mode of action of nanomaterials for direct application is the same as conventional pesticides. However, the physicochemical characteristics are strictly different from conventional pesticides to formulated ones as nanomaterials. Based on this finding, the effect on pathogens (bacteria, fungi, and virus) evolved more attention to test and evaluate the effect on these nanopesticides. To elucidate this particularity, Khan and Rizvi (2014) reported that the use of silver at its normal form has no effect on the microorganisms. However, a formulated silver at nanoform was shown to be toxic on *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Escherichia coli*, and *Klebsiella pneumonia*. The possible explanation according to the same study was that the nanoform of silver has a definite effect on the inhibition of colonization of bacteria and fungi.

In recent years, several plant pathologists harnessed the benefits of nanomaterials for controlling pests and plant diseases. A number of exciting results were obtained for controlling plant pests, especially nematodes, insects, bacteria, and fungi by application of different techniques of nanomaterials.

13.4.1 Plant-Parasitic Nematodes

Plant-parasitic nematodes (PPNs) are one of the main biotic causes of plant stress and yield loss in world agriculture (Nicol and Rivoal 2008). Global yield losses due to damage by plant-parasitic nematodes are estimated at 7%, representing annual monetary losses of 5.8 billon US $ (Sasser and Freckman 1987). Many attempts are being developed for managing PPNs, including chemical control, cultural practices, and development of resistant varieties which cause reduction of nematode population densities to levels below damage thresholds (McSorley and Duncan 1995). Since the1950s, synthetic pesticides have been traditionally used by farmers for managing nematodes. However, the indiscriminate and unsafe use of pesticides is hazardous to environment and agro-ecosystems. To expand the choice of effective management methods, the search for benefits of nanomaterials against PPNs is gaining interest.

13.4.1.1 Nanosilver-Silicon

Silver nanoparticle (AgNP) has shown a great potential as an effective nematicide for controlling PPNs (Roh et al. 2009), and its nematicide effect is related with induction of oxidative stress in the cells of PPNs and disrupting cellular mechanism of membrane permeability and ATP synthesis (Ahamed et al. 2010; Lim et al. 2012). Cromwell et al. (2014) evaluated the nematicidal effect of silver nanoparticles (AgNPs) in laboratory and field experiments. They concluded that high application doses ($\geq$90.4 mg/m^2) of AgNP have been found to be effective in reducing the number of juveniles of *Meloidogyne graminis* in turfgrass. In addition, several researchers reported the effect of high concentrations of AgNP in reducing the entomopathogenic nematodes including *Steinernema abbasi*, *S. arenarium*, and *Heterorhabditis indica* (Taha and Shady 2016). Nasar (2016) evaluated the efficacy of Ag-nanoformulations of extracts of *Urtica urens* against root-knot nematodes (*Meloidogyne incognita*), and he revealed that the effect of petroleum ether extract and its Ag nanoparticles offers a satisfactory and environmentally friendly way of reducing *Meloidogyne incognita.* Abdellatif et al. (2016) reported that the use of green silver nanoparticles reduced significantly root galls caused by root-knot nematode (*Meloidogyne javanica*) in eggplant. They concluded that 12.75 mg 100 mL^{-1} of green silver nanoparticles was effective for controlling *M. javanica* without any phytotoxicity in eggplants. Moreover, Taha (2016) evaluated the effect of silver nanoparticles (AgNPs) against *Meloidogyne incognita* in screen house and laboratory. The same author concluded that the nematode populations of *M. incognita* associated with tomato were lower in soil treated with the concentration (1500 ppm) of AgNP. Finally, Goswami (1993) showed that the nematode populations of *Meloidogyne incognita* associated with cowpeas were lower in soil amended with *Azadirachta indica* than in dried and autoclaved soils

13.4.1.2 Plant Virus Nanoparticle (PVN)

Recently, several biological nanoparticles based on plant virus have been used for controlling PPNs. This method allows to deliver more pesticides to the roots by using plant virus and shows promising results for controlling crop diseases including nematodes (Chariou and Steinmetz 2017). Cao et al. (2015) developed a new method for increasing the mobility of Abamectin (biological pesticide) within the soil by loading it into a *Red clover necrotic mosaic virus* (RCNMV)-derived plant virus nanoparticle (PVN), and they showed egg masses and root galling caused by *Meloidogyne hapla* in tomato seedlings. Moreover, Charioui and Steinmetz (2017) evaluated the effect of a nematicide called crystal viol that encapsulated a *Tobacco mild green mosaic virus* (TMGMV)-derived plant virus nanoparticle. The authors showed that the virus allowed to obtain more diffusion of the pesticide to the root level, which causes a reduction of nematodes.

13.4.1.3 Iron Nanoparticles

Iron nanoparticles are a prominent example among nanomaterials due to their wide scope of application in health care, wastewater, medicine, agriculture and food, and energy (Ali et al. 2016). Iron NPs (FeNPs) were used in medicine and biology due to their strong magnetic properties including the magnetic guidance for drug delivery and separation of cells and biological products (Estelrich et al. 2015). Recently, Sharma et al. (2017) evaluated the potential of FeNPs as nematicides against *Meloidogyne incognita* associated with Okra (*Abelmoschus esculentus*), and they concluded that the FeNPs reduced significantly the number of *M. incognita* in Okra due to their high reactivity.

13.4.1.4 Gold Nanoparticles (AuNPs)

For centuries, gold nanoparticles have found their importance as important components for biomedical applications (Yeh et al. 2012). The range of application of the AuNPs has been growing rapidly and includes electronics, photodynamic therapy, therapeutic agent delivery, sensors, probes, diagnostics, and catalysis (Huang et al. 2007; Stuchinskaya et al. 2011; Brown et al. 2010; Ali et al. 2012; Perrault and Chan 2010; Peng et al. 2009; Thompson 2007). Recently, Kucharska et al. (2011) evaluated the effect of gold nanoparticles on the mortality of *Steinernema feltiae* (entomopathogenic nematodes), and they concluded that the concentration of AuNP (5 ppm) caused 78% mortality of nematode after 5 days of experiment.

13.4.2 Insect Pest

Nanoparticles have a great potential for the management and control of pests in modern agriculture. Several previous studies addressed the applications of different nanoparticles (NPs) for controlling insect pests (Yasur and Rani 2015; Murugan et al. 2016; Buhroo et al. 2017). Yang et al. (2009) reported that garlic essential oil with polyethylene glycol-coated nanoparticles reduced significantly the number of *Tribolium castaneum*. Stadler et al. (2010) tested the effect of nanostructured alumina on two insect pests (*Rhyzoperthadominica* and *Sitophilus oryzae* L.). The same authors concluded that after 3 days of exposure, the mortality of both insects was significantly higher. Debnath et al. (2011) concluded that amorphous silica nanoparticles were found to be very effective and can be used as insecticides against rice weevil *Sitophilus oryzae*. Guan et al. (2008) developed a new photodegradable insecticide based on nanoparticles. Various studies reported the application of different nanocomposites and nanomaterials used against insect pests (Table 13.3).

13.4.3 Effect of Nanoparticles on Bacteria

Even though nanotechnology has many applications, cytotoxicity remains the potential concern currently (Chatterjee et al. 2011). The antibacterial effects of nanomaterials on several species of bacteria were confirmed (Fu et al. 2005; Prasad et al. 2016; Aziz et al. 2014, 2015), but the mechanism of action is still not yet understood. Indeed, Warheit (2008) reported that different factors (synthesis, shape, size, composition, and stabilizer) can lead to different results even for close nanosuspensions. Jayaseelan et al. (2012) reported that zinc as a nanoparticle has an antibacterial activity on *P. aeruginosa*, and the maximum diameter of inhibition obtained in this study was 22 mm by using 25 ng mL^{-1} ZnO as a nanoparticle. The nanomaterials composed of silver and PVP (polyvinylpyrrolidone) showed a good control of three pathogenic bacteria, *S. aureus* (Gram-positive), *E. coli* (Gram-negative), and *P. aeruginosa* (Gram-negative), and one beneficial bacteria *Bacillus subtilis* (Bryaskova et al. 2011). The same effect was observed after using CuO as a nanomaterial (Azam et al. 2012; Guzman et al. 2009). Khan and Rizvi (2014) reported that nanomaterials were dependent on concentration, physiology, metabolism, intracellular permeability, and the type of microbial cell.

13.4.4 Effect of Nanoparticles on Fungi

Fungicidal activity of nanomaterials was reported on fungi (Bryaskova et al. 2011; Sharma et al. 2009; Sondi and Salopek-Sondi 2004; Aziz et al. 2016). Singh et al. (2013) have found among 15 micronutrients in their nanoforms, only $CuSO_4$ and

Table 13.3 List of different nanocomposites and nanomaterials used against insect pests

Metal	Pest(s)	References
Synthesis of bionanoparticles (NPs) using plant extract		
AgNPs—Aqueous leaf extracts of *Euphorbia prostrata*	*Sitophilus oryzae*	Zahir et al. (2012)
NPs loaded with garlic essential oil	*Tribolium castaneum* (Herbst)	Yang et al. (2009)
Silver NPs—Aqueous leaf extract of *Tinospora cordifolia*	*Pediculus humanus*, *Anopheles subpictus*	Jayaseelan et al. (2011)
Silver—*Avicennia marina*	*Sitophilus oryzae*	Sankar and Abideen (2015)
PCL nanospheres—*Zanthoxylum rhoifolium*	*Bemisia tabaci*	Christofoli et al. (2015)
Polyethylene glycol NPs loaded with garlic essential oil	*Tribolium castaneum*	Yan et al. (2009)
NPs loaded with neem (*Azadirachta indica*) extracts	*Plutella xylostella*	Forim et al. (2013)
Chemical nanomaterials		
CdS nanoparticle, Nano-Ag, Nano-TiO_2	*Spodoptera litura* larvae	Chakravarthy et al. (2012)
Nanosilica	*Spodoptera littoralis*	El Bendary and El Halaly (2013)
Ag and Zn particles	*Aphis nerii*	Rouhani et al. (2012)
SNPs	*Spodoptera litura* larvae	Debnath et al. (2012)
AgNPs	*Acheta domesticus*	Louder (2015)
Nanosulfur	*Tetranychus urticae*	Gopal et al. (2012)
Aluminum oxide NPs	*Sitophilus oryzae*	Goswami et al. (2010)
Silica nanoparticles	*Spodoptera littoralis* Boisd.	Borei et al. (2014)
Silica nanoparticles	*Sitophilus oryzae*, *Lipaphis pseudobrassicae*	Nitai (2012)
Silica nanoparticles	*Spodoptera littoralis*	El Helaly et al. (2016)
DNA-tagged nanogold	*Spodoptera litura*	Chakravarthy et al. (2012)
Nano-Ca	*Bactrocera dorsalis*	Christenson and Foote (1960)
Calcium carbonte NPs	*Aonidiella aurantii* and *Bactrocera dorsalis*	Hua et al. (2015)
SiO_2 NPs	*Sitophilus oryzae*	Goswami et al. (2010)
SNPs	*Sitophilus oryzae*	Debnath et al. (2011)
Permethrin NPs	*Culex quinquefasciatus*	Anjali et al. (2010)
Nano-Al_2O_3 dusts	*Sitophilus oryzae* and *Rhyzopertha dominica*	Stadler et al. (2010), Buteler et al. (2015)
TiO_2 NPs	*Hippobosca maculata* and *Bovicola ovis*	Velayutham et al. (2012)

(continued)

Table 13.3 (continued)

Metal	Pest(s)	References
Bionanomaterials		
Chitosan nanoparticles	*Spodoptera litura*	Arvind Bharani et al. (2014)
Chitosan nanoparticles	*Callosobruchus maculatus*	Sahab et al. (2015)
Nano-diatomaceous earth	*Tribolium confusum* and *T. castaneum*	Sabbour and Abd El Aziz (2015)
Novaluron nanoparticles	*Spodoptera littoralis*	Elek et al. (2010)
Pheromone nanogels		
A nanogel prepared from the pheromone methyl eugenol	*Bactrocera dorsalis*	Baghat et al. (2013)
Carum copticum essential oil-loaded myristic acid-chitosan nanogels	*Sitophilus granarius*, *Tribolium confusum*	Ziaee et al. (2014)
Cellulose acetate nanofibers	*Lobesia botrana*	Bansal et al. (2012)
Cypermethrin nanofibers	*Grapholita molesta*	Czarnobai De Jorge et al. (2017)

$Na_2B_4O_7$ were found to have fungicidal activity on rust disease of peas (*Uromyces* sp.). In sunflower crop, the damping off and charcoal diseases were suppressed by nanoforms of manganese and zinc (Abd El-Hai et al. 2009). Other nanoparticles have been reported to cause a deformation in the hyphae of *B. cinerea* and prevented the development of conidiophores and conidia in *P. expansum* which eventually led to the death of fungal hyphae (Prasad et al. 2017b). Krishnaraj et al. (2012) tested the effect of silver nanoparticles on plant pathogenic fungi, *Alternaria alternata*, *Sclerotinia sclerotiorum*, *Macrophomina phaseolina*, *Rhizoctonia solani*, *B. cinerea*, and *Curvularia lunata*, and found that 15 mgL^{-1} concentration has a fungicidal activity on all the tested pathogens.

13.5 Future Prospects and Conclusion

In recent decades, the fast development of nanotechnology has paved the way for developing new approaches for various agricultural problems including plant protection and detection of diseases. Indeed, with a wide range of applications of nanotechnology in the future, we might expect nanoparticles will be extensively used for the management and control of plant pathogens. Nanomaterials can be used in plant protection and management of farm practices based on their small size.

Despite the wide application scope of nanotechnology and its benefits in plant disease management, there are several challenges in the field, about the potential risk in the use of nanoparticles in managing plant pathogens which is required to be solved prior to use in agricultural systems. The most pressing problem is the phytotoxicity of nanomaterials in the plant pathogen management which needs to be ascertained during plant growth.

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