Chapter 6
Nanoparticles' Synthesis and Their Application in the Management of Phytonematodes: An Overview



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Abstract One of the most effective novel areas of research is nanotechnology. It is a field that is improving daily, especially in the subject of agriculture. Crop production is hindered by several pests of economic importance, which are responsible for huge crop losses and invariably contributing to global food insecurity with attendant consequences such as malnutrition, starvation, social isolation, and other overlapping issues that cannot be overemphasized. Crops are predisposed to losses from agricultural pests and diseases because the peasant farmer lacks efficient soil, virile seeds, and environmental management techniques. The citizens are subjected to poverty and hunger owing to the devastating effect of huge crop losses in the field and storage. The synthetic-based approach, though highly indispensable in agricultural crop pest management, is laden with severe environmental pollution and has brought various diseases to the human race. This necessitated the development of safer alternative pesticidal substances with the aim of improving crop production. Prodigious attention has been paid by the researcher toward application of nanoparticles (NPs) and their application in sustainable agriculture. NPs are new methods that could be used to redeem the environment from its polluted state. Materials act differently in their nano form, which improves their activity as pesticidal agents. In agriculture, nanomaterials have been used in livestock and crop protection; they exhibit properties like biodegradability, solubility, permeability, and thermal stability. They also possess surface areas that increase their affinity to the target organism. Nanomaterials are available in different forms such as nano-containers, nano-encapsulates, nano-cages, and nano-emulsions for pest management use, and their potency has been established in crop disease control. NPs are

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good sources of controlled release mechanisms, which is a way of reducing the amount of pesticides or fertilizers injected into the environment while crops are on the field. NP biomarkers can be used in detecting bacteria, viruses, fungi, and nematodes of economic importance in agriculture; as diagnostic tools, nano sensors can indicate certain compounds in plants that are elicited by the plants only in disease conditions. The use of nano sensors as pesticide residue detectors comes up with accurate and reliable information. Nanotechnology consists of two major aspects, that is, the synthesis of nano-sized materials and the application or use of the synthesized nanomaterials for the intended purpose. Phytonematodes cause a wide range of losses to agricultural crops; they are a major threat to world food production as they cause yield losses in all areas of the world. Considerable yield losses are caused annually by several nematode species on crops. In order to increase yield, NPs have been employed in the control of nematodes. This overview highlights synthesis, characterization of NPs, and successes in the area of phytonematode management.

Keywords Nanoparticles · Plants · Phytonematodes · Control · Nanoshapes

6.1 Introduction

Nanoparticles (NPs) are particles that could be obtained by conversion of macromolecules into nano-sized particles or by breaking up of bulk materials into atoms or ions after which they are allowed to condense into NPs whose size ranges from 1 to 100 nm in size (Khan and Rizvi 2014). The NPs' behavior is quite different from the macro material and they exhibit properties that are absent in the bulk material. Nanoparticles have surface-to-volume ratio that is generally high and that helps in the enhancement of their biochemical properties and reactivity (Dubchak et al. 2010). For example, 1 g of gold (Au) converted to nano-sized particles will cover an area of about 100 km^2. A gold nanoparticle of 2.5 nm particle size melts at a lower temperature (~300 °C) compared to a gold slab that melts at 1064 °C (Buffat and Borel 1976). The macro gold has no toxic effect, whereas the gold NPs exhibit toxic effect on bacteria, *Salmonella typhimurium* (Wang et al. 2011). Similarly, the macro silver (Ag) lacks antibacterial and antifungal properties, while the NPs possess all these (Sofi et al. 2012). Synthesis of nanoparticles requires skill and facilities based on the method chosen. The characterization of the resulting NPs is another crucial step that determines the size and uniformity of the particles produced. NPs are characterized by their surface area, dispersity, size, and shape. The homogenization of all these properties is necessary in the application of NPs (Jiang et al. 2009). The common techniques for the characterization of NPs include but are not limited to: energy-dispersive spectroscopy (EDS), transmission electron microscopy (TEM), scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), dynamic light scattering (DLS), ultraviolet-visible (UV-vis) spectrophotometry, and powder X-ray diffraction (XRD; Shahverdi et al. 2007). For measurement

of size distribution, surface charge, crystallinity, phase identification, and phase distribution of biosynthesized NPs in liquid medium, dynamic light scattering (DLS) and X-ray diffraction methods are used (Strasser et al. 2010; Gunalan et al. 2011). In UV-visible spectroscopy, light wavelength ranging 300–800 nm is generally used for characterization of metal nanomaterials in the range of 2–100 nm; for gold and silver NPs, absorption measurements range between 500 and 550 and 400 and 450, respectively. Absorption peaks of zinc oxide (ZnO) NPs produced from *Aloe vera* had peaks ranging from 358 to 375 nm. Another important technique, that is, energy dispersive spectroscopy, is applied in nanotechnology to ascertain the elemental composition of NPs (Sun et al. 2000; Feldheim and Foss 2002; Pal et al. 2007). The nature of functional groups clinging on the surface of NPs could be the reason behind stabilization and production of metal NPs. The FTIR is employed in the identification and characterization of functional groups. Generally, functional group bands observed at 3450, 3266, and 2932 cm are assigned to stretching of alcohols and C–H stretching of alkanes, respectively. *Solanum torvum* mediated silver NPs depicted peaks at 1648, 1535, 1450, and 1019 cm and further study revealed that the peak at 1450 cm of carboxylate ions was accountable for the stabilization of the silver NPs produced. The morphological characterization of NPs at the nanometer and nanoscale ranges are measured with SEM and TEM (Eppler et al. 2000; Govindaraju et al. 2010; Dhandapani et al. 2012; Sankar et al. 2014). NPs cannot be viewed under optical microscope; they are smaller in size compared to bacteria cells and virus particles. The shape may be spherical, rod shaped, or polyhedral (Khan and Rizvi 2014).

6.2 Synthesis of Nanoparticles

The method of NPs' synthesis varies widely; this influences the efficiency and properties. The most common ways of NPs' preparation include physical, biological, and chemical.

6.2.1 Physical Method

This involves the use of evaporation condensation, radiolysis, UV irradiation, ultrasonication, and laser ablation. During the process of synthesis, the metal atoms evaporate, followed by condensation; the metallic atoms are then rearranged and aggregated into tiny clusters of metal NPs (Hurst et al. 2006). The cost of production is usually very high with physical synthesis of NPs, because of the need for sophisticated equipment, radiative heating, high power consumption, and chemicals (Khandel et al. 2018).

6.2.2 Chemical Methods

The Chemical methods of NPs' synthesis could be mechanical milling, etching, laser ablation, sputtering, or thermal decomposition. In this process, chemicals are used in the reduction of metal ion in solution. Metal ions may help in either nucleation or aggregation for the formation of small clusters of metals, which depends on the reaction mixture condition. Sodium borohydride, hydrazine, and hydrogen are some of the chemicals employed as reducing agent (Egorova and Revina 2000). Stabilizing agents like cellulose, natural rubber, chitosan, and co-polymer micelles are used with the reducing agents. Furthermore, organic solvents such as ethane, dimethyl, formaldehyde, toluene, and chloroform need to be added to these chemicals because of their hydrophobic nature. Formation of toxic or benign byproducts usually occurs during the process of reaction. The toxicity of these chemicals to the surface of the NPs has made them unpopular in medical applications. In view of the problems associated with the physical and chemical methods of NPs' synthesis, research is redirecting to biological methods of synthesis that are not as expensive and dangerous as former, that is, chemical methods (Patel et al. 2015).

6.2.3 Biological Method

The process includes various plants and microorganisms such as actinomycetes, fungi, and bacteria. The antioxidant and reducing properties present in such agents are responsible for NPs' reduction (Abd El-Rahman and Mohammad 2014). The biogenic synthesis of NPs can be divided into two stages. The first stage is bioreduction where the metal ions are reduced chemically to stable forms via a biological process (Mukunthan and Balaji 2012). Several organisms have the ability to reduce metals, through a process where the metal ion reduction is synchronized with enzyme oxidation, during which a stable and inert metal NPs are produced (Deplanche et al. 2010; Mukunthan and Balaji 2012). The second stage is biosorption involving binding of metal ions in aqueous or soil medium on to the cell wall of the organism, which does not require energy input (Yong et al. 2002). The modified cell walls of plants, fungi, and bacteria contain peptides that automatically bind to metal ions from which stable metal complexes as NPs are formed (Yong et al. 2002). Biologically synthesized NPs are better defined in size and morphology than what has been obtained from physico-chemical methods (Azizi et al. 2013). Invention of efficient and eco-friendly process for the synthesis of NPs is an important and emerging aspect of bio-nanotechnology (Khan et al. 2009; Azizi et al. 2013). Microbially synthesized NPs are eco-friendly, scalable, and compatible with pharmacological application. However, synthesis with microorganisms is more expensive than plant-based synthesis. The requirement of special maintenance and high aseptic conditions makes it unacceptable for large-scale production (Dhuper et al. 2012). Apart from this, plant-based synthesis does not require the use of toxic

chemicals, high temperature, and pressures as in the case of the chemical and physical methods. It has a unique advantage over them because it is more eco-friendly, cheaper, and can easily be scaled-up for mass level NPs' synthesis (Shankar et al. 2004). Within the last 30 years, the use of plant or whole plant extract has gained more attention due to its simplicity (Park et al. 2011). Research on plant-mediated synthesis is increasing rapidly because it is a one-step process synthesis.

6.2.3.1 Biosynthesis with Bacteria

As far as formation of metallic NPs are concerned, there are various mechanisms that sometimes significantly vary with each other with different bacteria. Pure gold nanoparticles were synthesized with the bacterium *Delftia acidovorans* (Johnston et al. 2013). Synthesis of Ag NPs is done by reduction of Ag ions with the supernatant culture of *Escherichia coli*, and purified by using sucrose density gradient centrifugation. A uniform distribution of NPs with average size of 50 nm was achieved using TEM characterization; further characterization using UV-vis spectra produced maximum absorbance peak at 420 nm (Gurunathan et al. 2009). An extremophilic yeast strain isolated from acid mine drainage yielded 20 nm and 30–100 nm for Ag and Au NPs, respectively. The bacterium *Bacillus licheniformis* acted as reducing agent in the biosynthesis of silver NPs of 50 nm size; similarly *Aspergillus niger* was employed in the extracellular biosynthesis of silver NPs (Gade et al. 2008; Kalimuthu et al. 2008; Mourato et al. 2011). *Geobacter sulfurreducens* reduced Ag(I) as insoluble Ag(+) ions, through c-type cytochrome mechanism. *Morganella morganii*, a Gram-positive bacteria, produced silver NPs of 30 nm, while 20 nm sized gold NP was synthesized from *Rhodopseudomonas capsulata* (He et al. 2007; Law et al. 2008; Abd et al. 2013). Likewise, culture filtrate of *Lactobacillus* sp. (extracellular) is considered to produce NPs of titanium at room temperature, which are generally spherical and ranges from 40 to 60 nm (Prasad et al. 2007). Sintubin et al. (2009) centered the research on the gold NPs' synthesis by lactic acid producing bacteria. Several members of bacteria were tested to know the potentiality related to Au NPs' synthesis. Bacterial genera such as *Lactobacillus* spp., *Pediococcus pentosaceus*, *Enterococcus faecium*, and *Lactococcus garvieae* were only found to produce the Au NPs. There were two steps that were considered to be helpful in the gold NPs' formation. Firstly, gold ions were observed to get accumulated at the cell wall through biosorption followed by reduction of those ions that formed the metallic NPs. Sintubin et al. (2009) also suggested that the cell wall was the capping agent for the NPs, providing them stability and preventing from aggregation. Enhancement of pH of the media exhibited increased reduction rate of NPs. *Bacillus licheniformis* produces intracellular Ag NPs, which was confirmed by the appearance of dark brown color of culture after addition of silver ions that was found to be dispersed quietly in the solution (Kalimuthu et al. 2008). Pugazhenthiran et al. (2009) reported the synthesis of Ag NPs intracellularly when *Bacillus* sp. were allowed to multiply in the medium containing silver trioxonitrate. This reaction was considered slower process as the incubation time was 7 days and may not be

recommended for industrial purpose (Pugazhenthiran et al. 2009). Meanwhile, despite the new extraction step, the method proposed by Kalimuthu et al. (2008) reported the process that was industrially significant, and it took only 24 h for *Bacillus licheniformis* to produce silver NPs. *Stenotrophomonas maltophilia* SELTE02, an isolate of *Astragalus bisulcatus* rhizosphere, exhibited the transformation of selenite to elemental selenium (Di Gregorio et al. 2005). In addition, *Pseudomonas aeruginosa* was isolated from rhizosphere of seleniferous soil. *P. aeruginosa* synthesized nanostructured selenium by the process of biotransformation of selenium oxyanions (intracellularly and extracellularly) to spherical amorphous allotropic elemental red selenium (Yadav et al. 2008). Likewise, synthesis of copper nanoparticles (Cu NPs) was a challenging job for the scientists with the available methods because of non-stability of Cu at the nanometer scale, as it oxidizes rapidly to form copper oxide (Baco-carles et al. 2011). Therefore, the stability of Cu is much more important for the synthesis of Cu NPs. *Morganella morganii* was used to synthesize Cu NPs, which happens to be due to intracellular uptake of the Cu ions together with binding of the ions to either a metal ion reductase or similar protein (Ramanathan et al. 2013). Manonmani and Juliet (2011) reported about biosynthesis of Ag NPs by using *Escherichia coli*, and further characterization of the synthesized NPs was established by UV-visible spectroscopy, FTIR (Fourier-transform infrared spectroscopy), and SEM (scanning electron microscope). *Desulfovibrio desulfuricans* (sulfate reducing bacterium) anaerobically bioreduced and biocrystallized palladium (2+) ions to palladium NPs in the presence of formate as an exogenous electron donor on the cell surface within a minute (Yong et al. 2002) (Table 6.1).

6.2.3.2 Biosynthesis Using Fungi

The production of NPs using fungi as reducing agent has attracted significant attention because of the advantages over the use of bacteria due to various important reasons like ease in scaling up, downstream processing, economic feasibility, and the presence of mycelia that provides enhanced surface areas (Mukherjee et al. 2001). Generally, fungi release more proteinaceous compounds than the bacteria that helps in the amplification of NPs' production. *Fusarium oxysporum* has been widely used in the studies pertaining to synthesis of Ag NPs at a size of 5–15 nm, and it was found that NPs were capped with the help of proteinaceous matter released from fungi. In addition, *Fusarium oxysporum* has also been encountered producing various NPs such as cadmium sulfide (CdS), lead sulfide (PbS), zinc sulfide (ZnS), and molybdenum sulfide (MoS), subject to the addition of suitable appropriate salts in the growth medium (Ahmad et al. 2002). Later on, *Aspergillus fumigatus* was used to produce extracellular Ag NPs in the size of 5–25 nm, which was longer as compared to what was reported in the case of *F. oxysporum*. Nevertheless, *A. fumigatus* exhibited very attractive prospect as the organism took only 10 min to reduce silver ions into NPs after exposure (Bhainsa and D'Souza 2006). *Trichoderma reesei* has also been found to synthesize extracellular Ag NPs within

Table 6.1 Microbe-mediated NPs' synthesis

Microorganisms	NPs	Size	Shape	References
Bacillus krulwichiae M2.5 and *Bacillus cellulosilyticus* M4.1	Silver	25.88 ± 10.49 nm	Spherical, irregular	Galvez et al. (2019)
Bacillus licheniformis strain GPI-2	Gold	20–45 nm	Triangular, irregular, hexagonal	Thakur et al. (2018)
Pleurotus ostreatus	Silver	30.5 ± 4.0 nm	Spherical	Al-Bahrani et al. (2017)
Trichoderma viride (MTCC 5661)	Silver	2–5 nm	Spherical	Kumari et al. (2017)
		40–65 nm	Rectangular	
		50–100 nm	Pentagonal and hexagonal	
Penicillium nalgiovense AJ12	Silver	25 ± 2.8 nm	Spherical	Maliszewska et al. (2014)
Macrophomina phaseolina	Silver	5–40 nm	Spherical	Chowdhury et al. (2014)
Humicola sp.	Silver	5–25 nm	Spherical	Syed et al. (2013)
Aspergillus terreus	Silver	1–20 nm	Spherical	Li et al. (2012)
Trichoderma Reesei	Silver	5–50 nm	–	Vahabi et al. (2011)
Penicillium brevicompactum	Silver	58.35 ± 17.88 nm	–	Shaligram et al. (2009)
Penicillium fellutanum	Silver	5–25 nm	Spherical	Kathiresan et al. (2009)
Phoma glomerata	Silver	60–80 nm	Spherical	Birla et al. (2009)
Cladosporium cladosporioides	Silver	35 nm	Polydisperse and spherical	Balaji et al. (2009)
Coriolus versicolor	Silver	25–75, 444–491 nm	Spherical	Sanghi and Verma (2009)
Aspergillus flavus	Silver	8.92 nm	Spherical	Vigneshwaran et al. (2007)
Pleurotus sajor-caju	Silver	30.5 ± 4.0 nm	Spherical	Vigneshwaran et al. (2007)
Pediococcus pentosaceus	Silver	28.2–122 nm	–	Shahverdi et al. (2007)
Phanerochaete chrysosporium	Silver	5–200 nm	Pyramidal	Vigneshwaran et al. (2006)
Aspergillus fumigatus	Silver	5–25 nm	Spherical, triangular	Bhainsa and D'Souza (2006)
Fusarium oxysporum	Silver	20–50 nm	Spherical	Durán et al. (2005)

72 h (Vahabi et al. 2011). Despite slower process of *T. reesei* in terms of NPs' synthesis, it is still used due to various facts. This fungus can be manipulated to produce high levels of enzymes, which may be up to 100 g/L, that helps in enhancing NPs' production.

6.2.3.3 Biosynthesis Using Plant or Plant Extracts

Different parts of plant, such as root, leaves, stem, shoot, flower, bark, and seeds, and their metabolites have been used successfully in biosynthesis of NPs. Production of simple silver NPs from silver trioxonitrate salts by using *Jatropha curcas* extracts was fairly homogenous (10–20 nm), and within 4 h the silver NPs were produced (Bar et al. 2009). Silver and gold NPs were produced using phyllanthin, which was extracted from the plant *Phyllanthus amarus*. This is a novel study as the metallic NPs were synthesized using only a single constituent of a plant extract, which is contrary to other studies described earlier in which whole plants or extracts were used. Phyllanthin concentrations played a vital role in the development of shape and size of the NPs because low concentrations produce triangular and hexagonal gold NPs while higher concentrations of phyllanthin develop greater levels of spherical NPs (Kasthuri et al. 2008). The synthesis of silver NPs with plant extracts was also initiated with leaf extracts from *Acalypha indica*. Silver NPs with 30 nm particle size, which was significantly homogenous, were produced. The antimicrobial properties of the Ag NP produced were tested on *Escherichia coli* and *Vibrio cholerae*; there was maximum growth inhibition at 10 μg/mL concentrations. Extract of *Artemisia nilagirica* (Asteraceae) was used to synthesize silver NPs of 70 nm with silver nitrate and hydrazine hydrate used as metal precursor and reducing agent, respectively (Vijayakumar et al. 2013). Extracts of various plants like *Ocimum tenuiflorum*, *Solanum trilobatum*, *Syzygium cumini*, *Centella asiatica*, and *Citrus sinensis* were also used in the production of silver NPs (Ag NPs) from silver nitrate solution. *Ocimum tenuiflorum* extracts were used in the reduction and stabilization of Ag NPs of the range 25–40 nm (Patil et al. 2012). An extensive research pertaining to the synthesis of NPs from various plants' leaf extracts, such as Pine, Persimmon, Ginkgo, Magnolia, and Platanus, was conducted. Out of all, Magnolia leaf broth exhibited to be the best silver reducer due to short time taken, that is, 11 min, for the reduction of 90% of the Ag+. During the process, the temperature was constantly monitored as it affects the shape, rate, and size of the NPs (Song and Kim 2009). Moreover, Parker et al. (2014) provided a method related to synthesis of NPs with the help of *Arabidopsis thaliana*. In an important example, the medium of *Arabidopsis* was replaced with potassium tetrachloropalladate (K_2PdCl) and allowed for the incubation for 24 h in salt sole solution. TEM analysis revealed palladium of 2–4 nm range, which were later on used in Suzuki-Miyaura coupling reactions. The results showed the higher catalytic activity as compared to commercial palladium NPs (Parker et al. 2014). Niraimathi et al. (2013) reported the microorganism-mediated synthesis of silver NPs from aqueous extract of *Alternanthera sessilis* and reported that leaf extract contains various important organic compounds, viz.,

carbohydrates, tannins, alkaloids, ascorbic acid, and proteins. These compounds play important role in the synthesis of NPs where they act as capping and reducing agents as well. Tippayawat et al. (2016) provided the report on the synthesis of Ag NPs from *Aloe vera* plant extracts that were characterized by various techniques such as UV-vis, SEM, TEM, and XRD. In brief, Ag NPs were confirmed on the basis of the appearance of a sharp peak at 420 nm in UV-vis region of the spectrum. In addition, they illustrated that reaction time and temperature played very important role in the synthesis of Ag NPs. Results revealed that the synthesized NPs were spherical in shape, which ranged from 70.70 ± 22 to 192.02 ± 53 nm. Aqueous leaf extract of *Trichodesma indicum* served as reducing agent in preparation of Ag NPs at 60 °C for 24 h. The NPs produced were spherical with cubic centered face structure and particle size of 50 nm; they exhibited larvicidal activity against *Mythimna separata* larvae, an army worm of many cereal crops at LC_{50} of 500 ppm (Buhroo et al. 2017). Nano-emulsion with acaricidal properties was synthesized from rosemary essential oil through sonication. The droplet size was 139.9 nm, with high acaricidal activity against adult spotted mites of *Tetranychus urticae*; 54.14 and 52.69% toxicity were established for immature and adult mites, respectively (Abdel-Tawab et al. 2019). The entomotoxic potential of zinc and silica NPs prepared through solvo-thermal method was assayed against *Sitophilus granarius* (Coleoptera: Curculionidae). Silica NPs were highly effective against *S. granarius* resulting in 100% mortality after 2 weeks of exposure; however, moderate activity was exhibited by Zn NPs (Mohammad et al. 2019). Latex from plants is used in the rapid preparation of NPs; latex of *Achras sapota* L. was used as medium in the synthesis of mono- and bimetallic silver and copper NPs (Thakore et al. 2015).

6.3 Application of NPs in Management of Plant-Parasitic Nematodes

Application of NPs in the management of various diseases of plant including plant nematodes is a new and holistic approach (Ladner et al. 2008). There is a potential prospect for the use of nanotechnology in plant disease management in various ways including in nematode infested plants. Direct application of NPs in the soil on seeds or foliage to stop the entry or multiplication of the pathogens is the simplest way. Pathogens may be eliminated in the way similar to pesticide application. However, direct soil application of NPs also affects the non-target beneficial microorganisms that provide many important ecological services. Nanomaterials such as carbon tubes, and cups might be used as carriers of some fancy chemicals such as pheromones, systemic acquired resistance (SAR)-inducing chemicals, polyamine synthesis inhibitors, or even concentrated active ingredients of pesticides for their controlled release especially under flooded conditions (Khan et al. 2014). Therefore, scope and application of NPs in diseases management can be managed through two major points, that is, (a) direct effects of NPs on pathogens, and (b) nanomaterials in

nanopesticide formulations. In addition, NPs may also be helpful in the plant disease diagnosis and pesticide residue analysis. It can also be used in killing or paralyzing the nematodes and therefore could be good option in the management of nematode. The chemical and physical properties of NPs play very crucial role in controlling the nematodes. NPs of ultrasmaller size provide better results against plant-parasitic nematodes (PPNs; Gatoo et al. 2014). NPs like gold and silver may participate in the management of nematode disease and, therefore, it may provide alternatives to killer synthetic nematicides or consistent use of biological control agents. Combination of silver NPs with other agricultural practices such as irrigation system especially fertigation or tank-mixture with suitable chemicals, which may replenish the Ag NPs, may increase applicability of silver NPs in the management of PPNs (Thakur and Shirkot 2017). Plant extract-mediated NPs have been reported to be active against pests in agriculture; the small size allows easy penetration into the cell walls of bacteria, fungi, and plant-parasitic nematodes, which leads to cell deaths of the microorganisms (Sondi and Salopek-Sondi 2004). Maggie et al. (2016) reported successful control of *Meloidogyne incognita* using silver NPs. Atef and Nassar (2016) illustrated the effectiveness of *Urtica urens* mediated silver NPs against *Meloidogyne incognita*. Agricultural wastes such as corncobs, guinea corn chaff, and rice husk were used as stabilizers for the preparation of silver NPs. The waste-mediated silver NPs were applied on rice plants infested with *Heterodera sacchari* (rice cyst nematode) in screenhouse trials. Treated rice plants were robust with the 75 and 50 g treatment, which resulted in a considerable reduction in numbers of cysts at harvest. Silver NPs were also evaluated in the control of *Belonolaimus* spp. (sting nematodes) and the *Meloidogyne* spp. infecting Bermuda grass putting, where there was improvement in the quality of the turf grass. In laboratory studies, silver NPs consistently decreased the activity of *Meloidogyne incognita* juveniles. The effectiveness of silver nanoparticles mediated with extracts of *Ficus mucoso* under field studies revealed significant reduction in populations of *M. incognita* infesting groundnuts. Consistent improvement was observed in *M. incognita* infested groundnut plants treated with silver NP solution in a dose-dependent manner (Young-Ki et al. 2013; Cromwell et al. 2014; Fabiyi and Olatunji 2018; Fabiyi et al. 2018). Silver boron nanoparticles (AgB NPs) synthesized with gamma rays and polyvinylpyrrolidone (PVP) polymer as a cost-effective and eco-friendly method were found to possess in vitro and in vivo nematicidal activity. AgB NPs displayed 74.20% mortality of *M. incognita* juveniles after 96 h of exposure. There was a significant decrease in root gall formation and number of egg masses on tomato roots. The AgB NPs were characterized with energy-dispersive X-ray (EDX) mapping analysis, high-resolution topographic mapping (HRTM), DLS, XRD, FTIR, and UV-vis, to determine the morphology, crystallinity, purity, distribution, and the average particle size. Cu NPs prepared through chemical reduction method were established to be toxic to second-stage juveniles of *M. incognita*; mortality was found to be dose dependent; 100% mortality of juveniles was recorded at 0.2 g/L concentration of Cu NPs (Mohamed et al. 2019). The shape of the AgB NPs was spherical and was 2.55 nm in size (El-Batal et al. 2019). The growth and reproduction of *M. incognita* on tomato were truncated by the

application of silver NPs synthesized with latex from *Euphorbia tirucalli*, which acted as the reducing agent in the formulation of Ag NPs. The NPs were lethal to second-stage juveniles of *M. incognita* and there was a high percentage egg hatch inhibition. Infestation of tomato roots by nematodes was significantly reduced when Ag NPs were used as root dip on tomato plants before transplanting. Treated tomato plants had healthier growth and reduction in overall gall formation (Kalaiselvi et al. 2019). Graphene oxide (GO) and zinc oxide (ZnO) nanoparticles (NPs) were examined at two concentrations, 0.05 and 0.10 mg/mL, on *M. incognita* infecting carrot. The application of GO and ZnO NPs significantly increased the vegetative growth of carrot plants. Carotenoids and proline contents were higher in carrot plants treated with ZnO NPs. In general, galling and nematode reproduction were significantly reduced by the application of the two NPs (Siddiqui et al. 2019). Silicon carbide (SiC) nanoparticles, though widely used in industrial applications, were evaluated against the proliferation of *M. incognita*. The synthesized SiC NPs with semi-crystalline shape and particle size of 50 nm affected the survival of first-stage larvae of *Caenorhabditis elegans*; the uptake of SiC NPs was feasible in the intestine of dead nematodes displaying a color change to black (Al Banna et al. 2018).

6.4 Conclusions and Future Prospects

Nanoscience is one of the most fascinating and emerging research areas that promises to deliver more pest management options. The use of NPs in nematode management is a good option for the farmers and the research in this direction is still on. It has been seen that synthesis of NPs is not an easy task, especially where facilities are inadequate. Out of all methods of synthesis, biological methods sound to be very good, environmentally safe, cheap, and easy to deliver to the farmers. Therefore, in the upcoming era these NPs may be used in the bio-nano formulation of various pesticides, including nematicides, which may be proven to be a reliable method of green technology. Although some lacunas are yet to be sorted out, this might be condoned in the future. Application of NPs in the intensification of agricultural commodities could also open a new road map to the researchers. Judicious utility of NPs in various plant-based cropping systems may improve our current understanding of sustainable agriculture.

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