Utilization of Nanotechnology for the management of plant-parasitic nematodes

Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

Abstract

Plant-parasitic nematodes are the major problem in food production. Management methods are based on mainly synthetic chemicals. Chemical nematicides are undesirable due to health and environment issues. Therefore, other novel technologies or materials are needed to be evolved for the management of plant-parasitic nematodes. Nanotechnology is one of the potential and innovative technologies for the management of various phytopathogens. Many nanoparticles have a useful nematicidal effect. This review presents the mode of action of different nanoparticles which are being used for the management of plant-parasitic nematodes.

Key words:Plant-parasitic nematodes(PPNs), Nanoparticles(NPs),Management. Mode of action, Methods of utilization.

INTRODUCTION

"Plant-parasitic nematodes (PPNs) are important pest causing significant yield loss to the majority of agricultural crops. Due to the PPNs an estimated over USD$80 worth of crop losses occur globally" (Nicol et al. 2011). Wide range of symptoms, viz., stunting, wilting, yellowing, reduction of flowering, fruit set, and fruit development, dieback, or plant death shows due to their different mode of parasitism. Due to their microscopic size and non-specific symptoms produced, farmers are unaware about their damage potential. Once the PPNs are established in the soil, control of these nematodes is very difficult. Chemical nematicides are commonly used for the management of PPNs. Problems of residual toxicity, environmental pollution, and public health hazards and also cost is associated to the application of synthetic nematicides. Therefore, conventional method of management is not sufficient, so alternative method or novel technologies and materials are needed to be evolved for the management of pest and disease issues including those created by plant nematodes. Among all the technologies so far emerged, nanotechnology is one of the most effective technologies.

NANOTECHNOLOGY

"Nanomaterials or nanoscale materials are generally defined as an object having at least one dimension between 1 and 100 nanometers which have unique properties like optical, electronic, magnetic, mechanical, thermo-physical, or biochemical. Nanotechnology has great utility in biology, medicine, pharmacology, and agricultural science" (Jeevanandam et al.2018). "Nanostructured materials, as well as their presence in nanosystems, are normally found in nature or purposely designed and formulated as nano-capsules, nanoparticles, and nano-suspension. Nanoparticles are gaining recognition as novel entities due to its low toxicity, low cost, and less time requirement. In agriculture, nanomaterial is an alternative to synthetic pesticide, many nanoparticles shows effective pest control potential especially plant-parasitic nematodes.Various studies shows that many nanoparticles of metals, metal oxides, and nonmetals have an effective nematicidal potential. These nanoparticles can also provide other benefits such as nutrient delivery or growth promotion to plants" (Makirita et al., 2020).

MODE OF ACTION OF NANOPARTICLES

"In agriculture, nanoparticles utilization inhibits pathogen infection, reduced disease severity, promotes plant growth, and increased crop production" (Masry et al., 2021). "Furthermore, nanoparticles have distinct physicochemical properties that improve plant metabolism and increase plant resistance to plant pathogens. Through the induction of systemic acquired resistance (SAR) which is associated with an increase in antioxidant activity helps in increased plant resistance" (Abdel khalek and Al-Askar, 2020). Nanoparticles have a direct toxic effect on nematodes which can penetrate the body of nematodes, leads to death within a short period of time. Nanoparticles with active ingredients act against soil populations of PPNs which penetrate the root system and prevent nematodes from feeding or establishing on the host and also inhibite the development and reproduction of the parasite in the roots.

Various studies have been conducted on silver nanoparticles. Silver nanoparticles disrupts various cellular mechanisms including membrane permeability, ATP synthesis, and response to oxidative stress in both eukaryotic (Roh et al., 2009; Ahamed et al., 2010; Lim et al., 2012) and prokaryotic cells (Choi and Hu, 2008). "AgNPs release $Ag+$ ions that bind to proteins and DNA within nematode cells. These ions inhibit the activities of enzymes crucial for vital activity, including DNA replication and transcription" (El-Batal et al., 2019). "Further, these ions catalyze the formation of ROS, causing oxidative stress that degrades cellular components, resulting in necrosis" (El Batal et al., 2019; Kalaiselvi et al., 2019; El-Deen & El-Deeb, 2018; Fouda et al., 2020). "AgNPs impair nematode reproduction by damaging reproductive tissues, reducing fertility and egg viability" (Fouda et al., 2020; Cromwell et al., 2014; Ghareeb et al., 2020). "AgNPs treated plants having more lignin deposition in cells of vascular bundles, therefore AgNPs might alter the behavior PPNs which influence feeding and root penetration. Thus, AgNPs exhibit neurotoxic effects that impair nematode motility, preventing host searching ability in the host plants" (Bernard, 2019). "Furthermore, AgNPs can trigger systemic resistance in several plants against various diseases" (Bernard, 2019; Danish et al., 2021). "However, the effectiveness of AgNPs in the environment are influenced by both biological and chemical attributes in the soil, viz., soil pH, organic matter content, and microbial activity and ultimately affect the interactions of AgNPs with nematodes" (Daramola et al., 2023; Abdellatif et al., 2016).

METHODS OF PREPARATION OF NANOMATERIALS

"A plethora of chemical (e.g. combustion, chemical co-precipitation, thermal decomposition, microemulsion, hydrothermal synthesis), physical (e.g. gas phase deposition, power ball milling, pulsed laser ablation, laser ablation synthesis in solutions), and biological (e.g. fungi, bacteria, plant extracts, or protein-mediated) techniques continues to develop leading to the production of various nanoparticles" (Sabry, 2019). "The choice of the method depend on the quantity of synthesized nanoparticles and the control of the desired morphological and micro structural properties (size, shape, structure, colloidal stability, and physicochemical properties)" (Kharissova et al., 2013; Samrot et al.2021). "However, the requirement of the capping agents for size stabilization necessitates a costly and toxic method which is also unsuitable for many biological and agriculture applications. Both inorganic and organic nanoparticles have been projected for different applications. However, nanoparticle toxicity depends on the physicochemical properties and the synthesis origin" (Samrot et al.2021). "Sometimes, chemically synthesized nanoparticles are agglomerized which cause inefficiency of the nanoparticles" (Krishna and Maringanti 2016). Silver chloride nanoparticles are prepared by chemical agents (Guzmán *et al*. 2009), host-guest nanocomposite materials (Zhao *et al*., 2008), radiation (Deekonda *et al*. 2016), photochemical methods (Henglein 1998) and electro-spinning (Nguyena *et al*., 2010) technique. These techniques require expensive equipment, high energy as well as space.

Sabry(2019) described the method of Flash Nano Precipitation (FNP). FNP is a simple and basic method to rapidly assemble nanosized drug-loaded particles by copolymer-directed assembly. FNP involves rapid micromixing of organic solutions of the hydrophobic drug and amphiphilic block copolymers (BCP) with water (anti-solvent) in a multi-inlet vortex mixer to create high super saturations of the drug in milliseconds, and then rapidly form the hydrophobic core (drug) in the mixed solvent. These hydrophobic cores are then stabilized and protected from aggregation by the BCP. The FNP method has been demonstrated to be powerful for the preparation of drug-loaded nanoparticles (e.g., abamectin-loaded nanoparticles) with relatively narrow size distribution, and tunable nanometer particle size, and with high drug-loading capacity.Poly(caprolactone)-b-poly(ethylene glycol) (PCL-b-PEG) are used as the stabilizer to prevent the nanoparticles from aggregation. Spindle-like nanoparticles obtained with PCL-b-PEG as the stabilizer were found significantly more efficient (98.4% mortality at 1 ppm particle concentration) against *M. incognita* (Fu et al.,2018; Kalaba et al.,2021).

"Diverse microorganism models have been employed in green synthesis of nanoparticles. Biological organisms including plants, bacteria, fungus, yeast, virus and seaweed play a precious role in the biosynthesis of metal and metal oxide NPs. Green synthesis of nanoparticles with desired shape and size have been suggested as safe alternatives to the physical and chemical methods" (Abbassy et al.2017; Wu et al.2019). "The process of synthesis is simple, cost-effective, and eco-friendly" (Alamdari et al., 2020). "Plants with antimicrobial properties have a high potential for green synthesis of silver nanoparticles due to their complex phytochemical composition such as carbohydrates, polyphenols, esters, polysaccharides, and terpenoids" (Joshi et al., 2018). "Similarly, Cyanobacteria (e.g., *Anabaena* spp., *Calothrix* sp., *Leptolyngbya* sp.) as well as the green microalgae (e.g., *Chlamydomonas reinhardtii* , *Chlorella vulgaris*) have been reported to biosynthesize intracellular gold, silver, palladium and platinum NPs" (Ferreira *et al*., 2016).

NANOMATERIALS USED AGAINST PLANT-PARASITIC NEMATODES

Various studies showed the nematicidal effect of several nanoparticles, i.e., silver nanoparticles, nano sulfur (Cromwell et al.2014), gold nanoparticles (Thakur et al. 2018), silica carbide nanoparticles and copper nanoparticles (Mohamed et al.2019) against plant-parasitic nematodes. The nematicidal effect of silver nanoparticles is well-established. AgNPs can be easily integrated into existing agricultural systems, and can be engineered for enhanced efficacy and specificity against nematodes. AgNP (30-150 lg/mL) inactivate J_2 of root-knot nematodes (*M. incognita*) (Cromwell et al. 2014).

Elarabi et al., (2022) prepared "silver nanoparticles (AgNPs) and Zinc oxide nanoparticles (ZnONPs) for nematicidal (*M. incognita*) activity. ZnONPs showed LC_{50} value 63.56 ppm while AgNPs recorded 11.78 ppm, respectively. AgNPs at concentrations 100 ppm showed *M. incognita* mortality rate 66%, whereas ZnONPs at the same concentrations caused a 58% mortality rate, respectively. Analysis of gene expression showed dose-dependent downregulation of each parasitism gene after treatment with either AgNPs or ZnONPs. However, the oxidative stress response gene showed upregulation with all of AgNPs and ZnONPs concentrations".

“Laboratory tests showed reduced egg hatching and increased mortality of larvae of sugar beet cyst nematode (*Heterodera schachtii*) due to the use of Silver and Zinc oxide Nanoparticles at a concentration of 100 mg/l mixed with soil” (Tehrani and Fathi, 2020).

“Laboratory assays revealed 100% irreversible nematode mortality (*M.graminicola*) after 12 hr at 0.1 μg/ml concentration of AgNP in water screening test. Sand screening test indicated 100% nematicidal effect of AgNP at 2 μg/ml after 24 hr of incubation. In glasshouse assays in soilless system of rice cultivation, 1 μg/ml concentration of AgNP applied directly to the trays achieved significant suppression of root gall formation. The effective dosage to kill nematodes in field soil assays was determined to be 3 μg/ml” (Baronia et al., 2019).

“Nanonematicides in the form of nanocapsules have proven to be very effective against endoparasitic nematodes” (Zinovieva et al.,2023).

“Green biosynthesis of silver nanoparticles (AgNPs) using *Acalypha wilkesiana* aqueous leaf extract was achieved. The efficiency of bio-AgNPs reduced the nematode activity, mortality, egg hatching, and movement of larvae of M. *incognita”* (Heflish et al.,2021).

AgNPs synthesized from *Trachyspermum ammi* had nematicidal (*M.incognita*) activity (Danish et al.2021).

“Application of n-HAP significantly increased the juveniles’ mortality and egg hatching inhibition percentage of *M. incognita* compared to the untreated control” (Alamri et al.,2022).

Chitosan nanoparticles are superior ecofriendly material and they possess bioactivity against *M.incognita* (Divya and Jisha,2018; Alfy et al.,2020).

Abamectin (Abm) is a biological pesticide with a strong activity against a wide variety of plant parasitic nematodes. Cao et al., (2015) manipulated Abm's soil physical chemistry by encapsulating Abm within the Red clover necrotic mosaic virus (RCNMV) to produce a plant virus nanoparticle (PVN) delivery system for Abm. PVNAbm enlarged the zone of protection from root knot nematodes (*M. hapla*) in the soil as compared to treating with free Abm molecules Tomato seedlings.

“Parkia biglobosa leaf (PL-AuNPs) and stem (PS-AuNPs) mediated gold nanoparticles were used as antimicrobials against some isolated symbiotic bacteria (*Pseudomonas syringae, Escherichia coli, Staphylococcus aureus and Bacillus anthracis*) from pine wood nematode (*Bursaphelenchus xylophilus*). This had shown the potential of biosynthesized AuNPs to shorten the lifespan of the *B. xylophilus* associated symbiotic bacteria by inhibiting their growth, thereby preventing further damage to pinewood” (Davids et al.,2021).

“Zinc oxide nanoparticles (ZnO-NPs) biosynthesized from the alga (*Ulva fasciata*), were found to be effective against *M. incognita*. Scanning electron microscopy (SEM) reports displayed the distributions and accumulations of ZnO-NPs on the nematode (J2s) body under direct exposure, which might be the reason of NP-mediated toxicity and disruption for *M. incognita”* (El-Ansary et al.,2022).

“CuO nanoparticles treated J_2 revealed the distorted, crinkled cuticle in comparison to control J_2 of *M. incognita*. CuO nanoparticles before the nematode inoculation at 100 ppm concentration exhibited healthier growth attributes besides concurrent reduction in nematode parameters in comparison to plants treated with *M. incognita”* (Tauseef et al.2021).

“Second stage juveniles of *M. incognita* treated with MgO nanoparticles (50 and 100 ppm) exhibited indentations, roughness and distortions in the cuticular surface, in comparison to the control untreated juveniles. MgO nanoparticles, in varying concentrations (50, 100 and 200 ppm), were dispensed into the plants by root dip, soil drench and foliar spray methods and their efficacy was assessed in terms of morphological characteristics, yield parameters and biochemical attributes of M. incognita infected plants. In plant trials revealed that 100 ppm dose of MgO nanoparticles, as root dip application, demonstrated reduced nematode fecundity, decreased number and smaller size of galls; enhanced plant growth, increased chlorophyll, carotenoid, seed protein, and root and shoot nitrogen contents" (Tauseef et al.2021).

"Application of titanium dioxide NPs (TiO_2-NPs) and silicon dioxide NPs (SiO_2-NPs) were tested against root-knot nematode. Application of SiO_2-NPs was more efficient against *M. incognita* in comparison to TiO_2-NPs. the administration of 0.20 mg/mL foliar spray of SiO_2-NPs in plants with *M. incognita* improves up to 37.92% of shoot dry weight and increases 70.42% of chlorophyll content. The reductions in egg hatching and *M. incognita* (J2) mortality were greater in SiO_2-NPs than in TiO_2-NPs" (Khan et al.2022).

The nematicidal effect of Silicon nanoparticles (SiNPs) from *Fusarium oxysporum* against egg hatching and second-stage juveniles (J_2) of root-knot nematode (RKN) (*M.incognita*) was evaluated on eggplant (*Solanum melongena*). SiNPs (100 and 200 ppm) significantly inhibited the percentage of egg hatching and increased percent mortality of J_2 *M. incognita* ranged from 87.00 % to 98.50 %(El-Ashry et al.,2022). SiNPs have a strong lethal effect on *M. incognita* J_2 when used with minimum effective dose of nematicides and confirmed by number of galls, egg masses and final population of J_2 in pot soils as evidence to *M. incognita* reproduction (Shekoohi et al, 2021). Conversely, Al Banna et al., (2018) reported that silicon carbide nanoparticles (SiCNPs) of the size of 50 nm ± 21.5 (with a concentration of 172 mg/L) did not exhibit a lethal effect even on J_2 or egg hatching of *M. incognita*. Likewise, Ardakani, (2013) reported that silica oxide nanoparticles (SiO_2NPs) did not exhibit any *M. incognita* J_2 mortality in laboratory experiments.

"AgNP of *Eucalyptus officinallis* reduced nematode (*Heterodera sacchari*) population in root and soil, increased vegetative growth of rice plant, with a significant increase in yield" (Oluwatoyin et al.,2020).

Oluwatoyin and Olatunji (2018) could efficiently used *Ficus mucoso* AgNP in *M.incognita* management on groundnut fields.

"AgNP synthesized from *Senna siamea* at 50 ppm exhibited significant increases in plant growth, and activities of defense enzymes such as peroxidase, catalase, superoxide dismutase, and ascorbate peroxidase over the inoculated control *Trachyspermum ammi* plant. Furthermore, the maximum reduction in the number of galls, egg masses, and root-knot indices of *M. incognita* was recorded in plants" (Danish et al.2021).

"Silver and silver chloride nanoparticles (Ag and AgCl-NPs) using the crude aqueous extract of the green microalga (*Parachlorella kessleri*) having nematicidal proficiency against the J_2 and egg hatchability of *M. incognita"* (Hamed et al.2016).

Fabiyi *et al.*,(2021) prepared "20 and 30% concentrations of nano supernatant liquid agricultural wastes corncob and found to be decrease in egg hatch rate *M. javanica"*.

Fouda et al., (2020) prepared "microcrystalline cellulose embedded silver nanoparticles (Ag-NPs). By using 40 ppm of Ag-NPs *M.incognita* J_2 mortality reached 95.53 % after 72 h of exposure time".

Copper nanoparticles (Cu NPs) are successfully prepared using biosynthesis from stem extract of Holoparasitic plant (*Orobanche aegyptiaca*). Cu NPs (50 μg/mL to 800 μg/mL) were found to be toxic to J_2 of *M. incognita*, causing mortality up-to 91.5% at 16 h(Akhter et al.2020).

Reneeta et al.(2015) prepared "Ag-NPs with banana leaf extract and found to be effective against *Pratylenchus coffeae"*.

Ghareeb *et al*.(2020) and Ghareeb *et al*.(2022) synthesized silver nanoparticles with two marine algae (*Colpomenia sinuosa* and *Corallina mediterranea*) and their namaticidal activity against root-knot nematodes (*M. incognita; M. javanica*) in tomato plants was investigated. *C. sinuosa* silver nanoparticles reduced the number of nematode galls, egg-masses per root, and eggs/egg mass, *M. incognita* and *M. javanica* while improving plant growth parameters of tomato.
CuFeNPs were found to be effective at 0.03 μg ai g/soil against *M. incognita* and *M. javanica* in terms of arrested biological cycle in tomato (Gkanatsiou et al.,2019).
Shang et al.,(2022) studied "the killing mechanism of SeNPs @ CS in *B. xylophilus*. The SeNPs@CS had an LC_{50} of 15.627 mg L^{-1} against *B. xylophilus*, and was killed by reactive oxygen species".

CONCLUSION AND FUTURE PERSPECTIVES

Nanotechnology with novel applications in many fields has created various prospects to researchers. Nanoparticles hold promise of innovative application method or targeted delivery of agrochemicals. Research should focus on enhancing their effectiveness and reducing wastage , leading to optimizing nanoparticles synthesis methods to enhance bioactivity while minimizing toxicity. Additionally, it is critical to develop biodegradable nanoparticles to minimize their ecological impact once they are disposed of in the environment. Bio-material coatings for nanoparticles could also reduce potential toxicity and improve stability in soil, benefiting non-target organisms. Integrating nanoparticles into IPM programs, along with other biological control agents, holds promise as an efficient and environmentally friendly option. Therefore, multidisciplinary research in nanotechnology, agronomy, ecology, and toxicology is necessary to advance these technologies. One essential advancement in managing plant health is the development of multifunctional nanoparticles. Future research directions are proposed on molecular interactions between AgNPs and nematodes extensive focusing on more field experiments on larger areas .The potential breakthroughs and unmet research need in nanoparticle technology for nematode control are promising and could significantly change future farming communities.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

Abbassy, M. A., Abdel-Rassoul M.A., Nassar, A.A.M.K.,& Soliman, B.S.M. (2017). Nematicidal activity of silver nanoparticles of botanical products against root-knot nematode, *Meloidogyne incognita*. *Archives of Phytopathology and Plant Protection*, 50 (17-18), 909-926.

Abdelkhalek, A.,& Al-Askar, A.A. (2020). Green synthesized ZnO nanoparticles mediated by *Mentha Spicata* extract induce plant systemic resistance against tobacco mosaic virus. Applied Sciences,10 (15), 5054. DOI:10.3390/ app10155054.

Abdellatif, K., Abdelfattah, R., & El-Ansary, M. (2016). Green nanoparticles engineering on root-knot nematode infecting eggplants and their effect on plant DNA modification. *Iranian Journal of Biotechnology*, 14, 250 - 259. DOI:10.15171/ijb.1309.

Ahamed, M., Posgai, R., Gorey, T.J., Nielsen, M., Hussain, S.M., & Rowe, J.J. (2010). Silver nanoparticles induced heat shock protein 70, oxidative stress and apoptosis in Drosophila melanogaster. *Toxicology and Applied Pharmacology*, 242, 263–269.

Akhter, G., Khan,A., Ali, S.G., Khan, T.A., Siddiqi, K.S., Khan, H.M.(2020). Antibacterial and nematicidal properties of biosynthesized Cu nanoparticles using extract of holoparasitic plant. *SN Applied Sciences*, 2(7), 1268. DOI: 10.1007/s42452-020-3068-6

Alamdari, S., Sasani, G. M., Lee, C., Han, W., Park, H.H., Tafreshi, M.J. (2020). Preparation and characterization of zinc oxide nanoparticles using leaf extract of *Sambucus ebulus*. *Applied Sciences*, 10 (10), 3620. DOI:10.3390/app10103620.

Alamri, S., Nafady, N.A., El-Sagheer, A.M., El-Aal, M.A., Mostafa, Y.S., Hashem, M., Hassan, E.A. (2022). Current utility of Arbuscular Mycorrhizal Fungi and Hydroxyapatite Nanoparticles in suppression of tomato root-knot nematode. *Agronomy*, 12(3), 671.DOI: 10.3390/agronomy 12030671

Alfy, H., Ghareeb, R.Y., Soltan, E., Farag, D.A.(2020). Impact of chitosan nanoparticles as insecticide and nematicide against *Spodoptera littoralis*, *Locusta migratoria*, and *Meloidogyne incognita*. *Plant Cell Biotechnology and Molecular Biology*, 21(69&70),126-140.

Ardakani, A.S. (2013). Toxicity of silver, titanium and silicon nanoparticles on the root-knot nematode, *Meloidogyne incognita*, and growth parameters of tomato. *Nematology*, 15(6), 671-677.

Baronia, R., Kumar, P., Singh, S., & Walia, R. (2020). Silver nanoparticles as a potential nematicide against *Meloidogyne graminicola*. *Journal of Nematology*, 52. DOI:10.21307/jofnem-2020-002

Bernard, G., Fitch,,J., Min,B., Shahi,N., Egnin,M., Ritte,I. et al. (2019). Potential nematicidial activity of Silver Nanoparticles against the Root-Knot Nematode (*Meloidogyne Incognita*). *Online Journal of Complementary & Alternative Medicine*, 2(2), DOI:10.33552/ ojcam.2019.02.000531

Cao, J., Guenther, R.H., Sit.T.L., Lommei,S.A., Opperman,C.H., Willoughby,J.A. (2015). Development of abamecten loaded plant virus nanoparticles for efficacious plant parasitic nematode control.*ACS Applied Materials & Interfaces*, 7(18), 9546-9553. DOI: 10.1021/acsami.5b00940

Choi, O., & Hu, Z. (2008). Size dependent and reactive oxygenspecies related nanosilver toxicity to nitrifying bacteria. *Environmental Science and Technology*, 42, 4583–4588.

Cromwell, W.A., Joopil, Y,Starr, J.L., & Young-Ki Jo. (2014). Nematicidal effects of Silver nanoparticles on root-knot nematode in Bermuda grass. *Journal of Nematology*, 46(3), 261-266.

Danish, M., Altaf, M., Robab, M.I., Shahid, M., Manoharadas, S., Hussain, S.A. et al.(2021). Green synthesized Silver Nanoparticles mitigate biotic stress induced by *Meloidogyne incognita* in *Trachyspermum ammi* (L.) by improving growth, biochemical, and antioxidant enzyme activities. *ACS Omega*, 6, 11389-11403. DOI: 10.1021/acsomega.1c00375.

Daramola, F., Lewu, N., Nkiko, J., & Lewu, F. (2023). Nematicidal effects of silver nanoparticles (AG-NPs) on the root-knot nematode, *Meloidogyne javanica* associated with Swiss chard (*Beta vulgaris* L.). *Helminthologia*, 60, 189 - 195. DOI: 10.2478/helm2023-0018.

Davids, J.S., Ackah, M., Okoampah, E., Fometu, S.S., Guohua, W., Jianping, Z. (2021). Biocontrol of Bacteria Associated with Pine Wilt Nematode, *Bursaphelenchus xylophilus* by using Plant mediated Gold Nanoparticles. *International Journal of Agriculture & Biology*, 26,517-526.

Deekonda, K., Muniyandy, S., Lima, Y.Y., Janarthanan, P. (2016). Electron beam radiation mediated green synthesis of silver nanoparticles using carboxymethyl sago pulp obtained from sago waste. *Polymer*, 86, 147- 156.

Divya, K., & Jisha, M.S.(2018). Chitosan nanoparticles preparation and applications. *Environmental Chemistry Letters*, 16(1),101-112.

El-Ansary.M.S., Hamouda, M.RA., El shamy, MM. (2022).Using biosynthesized zinc oxide nanoparticles as pesticide to alleviate the toxicity on banana infested with parasitic nematode.*Waste Biomass Valorization*,13,405-415.

Elarabi, N.I. , Abdel-RahmanAA , Abdel-Haleem H, Abdel-Hakeem M. (2022). Silver and zinc oxide nanoparticles disrupt essential parasitism, neuropeptidergic, and expansion-like proteins genes in *Meloidogyne incognita. Experimental Parasitology.* 243, 108402. https://doi.org/10.1016/j.exppara.2022.108402.

El-Ashry, R.M., El-Saadony, M.T., El-Sobki, A.E.A ., El-Tahan, A.M., Al-Otaibi, S., El-Shehawi, A.M. et al.(2022). Biological silicon nanoparticles maximize the efficiency of nematicides against biotic stress induced by *Meloidogyne incognita* in eggplant. *Saudi Journal of Biological Science*, 29, 920-932. DOI:10.1016/j.sjbs.2021.10.013.

El-Batal, A., Attia, M., Nofel, M., & El-Sayyad, G. (2019). Potential nematicidal properties of silver boron nanoparticles: Synthesis, characterization, in vitro and in vivo root-knot nematode (*Meloidogyne incognita*) treatments. *Journal of Cluster Science,* 30, 687-705. DOI:10.1007/s10876-019-01528-5.

El-Deen, A., & El-Deeb, B. (2018). Effectiveness of silver nanoparticles against root-knot nematode, Meloidogyne incognita infecting tomato under greenhouse conditions. *The Journal of Agricultural Science*, 10, 148. https://doi.org/10.5539/jas.v10n2p148.

Fabiyi, O.A., Claudius-Cole, A.O., Olatunji, G.A., Abubakar, D.O.,& Adejumo, O.A. (2021). Response of *Meloidogyne javanica* to Silver Nanoparticle liquid from agricultural wastes. *AGRIVITA Journal of Agricultural Science*, 43(3), 507-517. DOI:10.17503/agrivita.v43i3.1936

Ferreira, D.V.S., Conz, M.E.F., Lima, L.M., Fraśes, S.,de Sauza, W., & Sant'Anna,C., (2016). Green production of microalgae-based silver chloride nanoparticles with antimicrobial activity against pathogenic bacteria. *Enzyme and Microbial Technology*, 97,114-121.DOI: 10.1016/j.enzmictec.2016.10.018.

Fouda, M., Abdelsalam, N., Gohar, I., Hanfy, A., Othman, S.,& Zaitoun, A., et al.(2020). Utilization of High throughput microcrystalline cellulose decorated silver nanoparticles as an eco-nematicide on root-knot nematodes. *Colloids and surfaces. B, Biointerfaces,* 188, 110805. https://doi.org/10.1016/j.colsurfb.2020.110805.

Fu, Z. , Chen, K. , Li, L. , Zhao, F., Wang, Y., & Wang, M., et al.(2018). Spherical and spindle-like abamectin-loaded nanoparticles by flash nanoprecipitation for Southern Root-Knot nematode control: Preparation and Characterization. *Nanomaterials*, 8, 449; doi:10.3390 /nano8060449

Ghareeb, R.Y., Alfy, H., Fahmy, A., Ali, H., & Abdelsalam, N. (2020). Utilization of *Cladophora glomerata* extract nanoparticles as eco-nematicide and enhancing the defense responses of tomato plants infected by *Meloidogyne javanica*. *Scientific Reports,* 10. https://doi.org/10.1038/s41598-020-77005-1.

Ghareeb, R.Y., El-Din, N.G., El-Maghraby, D.M., Ibrahim, D.S.S., Megeed, A.A., & Abdelsalam, N. (2022). Nematicidal activity of seaweed synthesized silver nanoparticles and extracts against *Meloidogyne incognita* on tomato plants. *Scientific Reports*,12:3841. | https://doi.org/10.1038/s41598-022-06600-1.

Gkanatsiou, C.H., Ntalli, N., Menkissoglu-Spiroudi, U., Dendrinou, S.C.(2019). Essential metal-based nanoparticles (Copper/Iron NPs) as potent nematicidal Agents against *Meloidogyne* spp. *Journal of Nanotechnology Research* ,1 (2), 044-058. DOI: 10.26502/fjnr.004.

Guzmán, M.G., Dille, J.,& Godet, S. (2009). Synthesis of silver nanoparticles by chemical reduction method and their antibacterial activity. *International Journal of Chemical and Biomolecular Engineering*, 2, 3.

Hamed, S.M., Mostafa, A.M.A., Abdel-Raouf, N., Ibraheem, I.B.M. (2016). Biosynthesis of silver and silver chloride nanoparticles by *Parachlorella kessleri* SAG 211-11 and evaluation of its nematicidal potential against the root-knot nematode; *Meloidogyne incognita. Australian Journal of Basic and Applied Sciences*, 10(18) ,354-364

Heflish, A.A., Hanfy, A.E. , Ansari, M.J., Dessoky, E.S., Attia, A.O.,& Elshaer, M.M. (2021). Green biosynthesized silver nanoparticles using *Acalypha wilkesiana* extract control root-knot nematode. *Journal of King Saud University-Science*, 33, 101516. DOI: 10.1016/j.jksus.2021.101516.

Henglein, A. (1998). Colloidal Silver Nanoparticles: photochemical Preparation and Interaction with O2, CCl4, and Some Metal Ions. *Chemistry of Materials,* 10(1), 444-450.

Jeevanandam, J., Barhoum, A., Chan, Y.S., Dufresne, A., & Danquah, M.K. (2018). Review on Nanoparticles and Nanostructured Materials:History, Sources, Toxicity and Regulations. Beilstein J. Nanotechnol., 9, 1050–1074.

Joshi N., Jain N., Pathak A., Singh J., Prasad R., & Upadhyaya CP. (2018). Biosynthesis of silver nanoparticles using *Carissa carandas* berries and its potential antibacterial activities. *Journal of Sol-Gel Science and Technology*, 86 , DOI:10.1007/s10971-018-4666-2

Kalaba, M.H., Moghannem, S.A., El-Hawary, A.S., Radwan, A.A., Sharaf, M.H. & Shaban A.S.(2021). Green Synthesized ZnO Nanoparticles Mediated by *Streptomyces plicatus*: Characterizations, Antimicrobial and Nematicidal Activities and Cytogenetic Effects. *Plants* , 10(9),1760. DOI: 10.3390/plants10091760.

Kalaiselvi, D., Mohankumar, A., Shanmugam, G., Nivitha, S., & Sundararaj, P. (2019). Green synthesis of silver nanoparticles using latex extract of *Euphorbia tirucalli*: A novel approach for the management of root knot nematode, *Meloidogyne incognita*. *Crop Protection*,117,108-114. DOI:10.1016/J.CROPRO.2018.11.020.

Khalil, M.S., El-Aziz, M.H.A.,& Selim R.(2022). Physiological and morphological response of tomato plants to nano-chitosan used against bio-stress induced by root-knot nematode(*Meloidogyne incognita*) and tobacco mosaic tobamovirus (TMV). *European Journal of Plant Pathology*,163,799-812.DOI: 10.1007/s10658-022-02516-8

Khan, M., Siddiqui, Z.A., Parveen, A., Khan, A.A., Moon, I.S., & Alam, M.(2022). Elucidating the role of silicon dioxide and titanium dioxide nanoparticles in mitigating the disease of the egg-plant caused by *Phomopsis vexans*, *Ralstonia solanacearum*, and root-knot nematode *Meloidogyne incognita*. Nanotechnol.Rev, 11:1606-1619. https://doi.org/10.1515/ntrev-2022-0097

Kharissova, O.V., Dias, H.V.R., Kharisov, B.I., Pérez, B.O., & Pérez, V.M.J.(2013). The greener synthesis of nanoparticles. Trends in Biotechnology, 31 (4), 240–248.DOI: 10.1016/j.tibtech.2013.01.003

Krishna, G. & Maringanti, S.C.(2016). Synthesis of silver nanoparticles by chemical and biological methods and their antimicrobial properties. *Journal of Experimental Nanoscience*,11(9),714-721. DOI: 10.1080/17458080.2016.1139196.

Lim, D., Roh, J. Y., Eom, H. J., Hyun, J. W., & Choi, J. (2012). Oxidative stress-related PMK-1 P38 MAPK activation as a mechanism for toxicity of silver nanoparticles to reproduction in the nematode *Caenorhabditis elegans. Environmental Toxicology and Chemistry*, 31:585–592.

Makirita, W., Yong, L., He, N., Mbega, E., Chacha, M., Li, X., et al. (2020). Effects of nanoparticles of metal oxides on the survival of the entomopathogenic nematode: *Steinernema carpocapsae*. *Journal of Nanoscience and Nanotechnology*, 20(3), 1434-1439. DOI: 10.1166/jnn.2020.17164.

Masry, S.H., Taha, T.H., Botros, W.A., Mahfouz, H., Al-Kahtani, S.N., Ansari, M.J. et al. (2021). Antimicrobial activity of camphor tree silver nano-particles against foulbrood diseases and finding out new strain of *Serratia marcescens* via DGGE-PCR, as a secondary infection on honeybee larvae. *Saudi Journal of Biological Sciences*, 28 (4), 2067–2075.

Mohamed, E.A.,Elsharabasy, S.F.,Abdulsamad, D.(2019). Evaluation of *in vitro* nematicidal efficiency of copper nanoparticles against root-knot nematode *Meloidogyne incognita*. *South Asian Journal of Parasitology*,2,1-6.

Nguyena, T.H., Leeb, K.H., & Lee, B.T. (2010). Fabrication of Ag nanoparticles dispersed in PVA nanowire mats by microwave irradiation and electro-spinning. *Materials Science and Engineering: C*, 30(7), 944-950

Nicol, J.M., Turner, S.J., Coyne, D.L., denNijs, L., Hockland, S.,& Tahna, M.Z. (2011). Current nematode threats to world agriculture. In: Genomics and Molecular Genetics of Plant-Nematode Interactions, J.Jones, G.Gheysen, and C. Fenoll (Eds.). Heidelberg:Springer, 347–367.doi:10.1007/978-94-007-0434-3.

Oluwatoyin, F., Gabriel, O., Olubunmi,A.,& Olanike, O.(2020). Preparation of bio-nematicidal nanoparticles of *Eucalyptus officinalis* for the control of cyst nematode (*Heterodera sacchari*). *Journal of Animal and Plant Sciences*, 30(5),1172-1177. https://doi.org/10.36899/JAPS.2020.5.0134.

Oluwatoyin, F.,& Olatunji, G.A.(2018). Application of green synthesis in nano particles preparation: *Ficus mucoso* extracts in the management of *Meloidogyne incognita* infecting groundnut *Arachis hypogea*. *Indian Journal of Nematology*,48,13-17.

Rani, K., Devi, N., Banakar, P., Kharb, P., Kaushik, P. (2022). Nematicidal potential of green silver nanoparticles synthesized using aqueous root extract of *Glycyrrhiza glabra*. *Nanomaterials*, 12(17), 2966. doi: 10.3390/ nano 12172966

Reneeta, N.P., Krishnan, M., Achiraman, S., Sundararaju, P. (2015). Green synthesis of silver nanoparticles using cultivar Nendran leaf extracts and evaluation of their antinemic activities against *Pratylenchus coffeae*. *Indian Journal of Nematology*, 45(2),138-146.

Roh, J.Y., Sim, S.J., Yi, J., Park, K., Chung, K.H., Ryu, D.Y. et al.(2009). Ecotoxicity of silver nanoparticles on the soil nematode *Caenorhabditis elegans* using functional ecotoxicogenomics. *Environmental Science and Technology*, 43,3933–3940.

Sabry, A.K.H. (2019). Role of nanotechnology applications in plant-parasitic nematode control. In: Nanobiotechnology Applications in Plant Preotection, Nanotechnology in the Life Sciences. Springer Nature Switzerland AG. pp.223-240.doi.org/10.1007/978-3-030-13296-5_12.

Samrot, A.V., Sahithya, C.S.,Selvarani, A.J., Purayil, S.K., & Ponnaiah, P. A (2021).Review on Synthesis, Characterization and Potential Biological Applications of Superparamagnetic Iron Oxide Nanoparticles. *Current Research in Green and Sustainable Chemistry*, 4, DOI: 10.1016/j.crgsc.2020.100042.

Shang, H., Zhang, H., Zhao, R., Meng, Y., Yingjian, M., Zhe, S., et al. (2022). Selenium nanoparticles are effective in penetrating pine and causing high oxidative damage to *Bursaphelenchus xylophilus* in pine wilt disease control. *Pest Management Science*,78(8),3704-3716. https:// doi.org/ 10.1002/ ps.7013.

Shekoohi, S.S., Charehgani, H., Abdollahi, M.,& Rajabi, H.R.(2021). Combined effect of β-aminobutyric acid and silver nanoparticles on eggplants, *Solanum melongena*, infected with *Meloidogyne javanica*.*Nematology*, 23(9), 1077-1092.

Shoaib, R.M., Abdel-Razik, A.B., Ibrahim, M.M., Al-Kordy,M.A., & Entsar,H.T.(2022).Impact of engineered nano silver on plant parasitic nematode and measurement of DNA damage. *Egyptian Journal of Chemistry*, 65(4), 43-51. DOI: 10.21608/EJCHEM.2021.99035.4605

Tauseef, A., Hisamuddin., Gupta, J., Rehman,A. (2021). Differential response of cowpea towards the CuO nanoparticles under *Meloidogyne incognita* stress. *South African Journal of Botany*, 139,175-182.

Tauseef, A., Hisamuddin, Khalilullah, A., Uddin, I.(2021). Role of MgO nanoparticles in the suppression of *Meloidogyne incognita*, infecting cowpea and improvement in plant growth and physiology.*Experimental Parasitology*, 220,108045.

Tehrani, F.A.A.,& Fathi, Z. (2020). Effect of Silver and Zinc Oxide Nanoparticles on Sugar Beet Cyst Nematode (*Heterodera schachtii*). *Journal of Applied Researches in Plant Protection*, 8(4), 47-59. SID. https: //sid.ir /paper /376124/en

Thakur, R., & Shirkot, P. (2017). Potential of biogold nanoparticles to control plant pathogenic nematodes. *Journal of Bioanalysis & Biomedicine*, 9, 1-3. https://doi.org/10.4172/1948-593X.1000182

Tryfon, P., Kamou, N.N., Ntalli, N., Mourdikoudis, S., Karamanoli, K., Karfaridis, D. et al.(2022).Coated Cu-doped ZnO and Cu nanoparticles as control agents against plant pathogenic fungi and nematodes. *NanoImpact*, 28,100430. DOI: 10.1016/j.impact.2022. 100430

Udalova, Z.V., Folmanis, G.E., Khasanov, F.K., Zinovieva, S.V.(2018). Selenium nanoparticles-An inducer of tomato resistance to the root-knot nematode, *Meloidogyne incognita* (Kofoid & White,1919) Chitwood 1949, *Doklady Biochemistry and Biophysics*, 482, 264-267.

Udalova, Z.V., & Zinovieva, S.V. (2022). Effects of silicon nanoparticles on the activity of antioxidant enzymes in tomato roots invaded by *Meloidogyne incognita* (Kofoid & White,1919) Chitwood, 1949. *Doklady Biochemistry and Biophysics*, 506,191-194.

Wu, T., Xu, H., Liang, X.,Tang, M.(2019).*Caenorhabditis elegans* as a complete model organism for biosafety assessment of nanoparticles. *Chemosphere* ,221,708-726.

Zhang, D., Liu, G., Jing, T., Luo, J., Wei, G., Mu, W. et al. (2020). Lignin-modified electronegative epoxy resin nanocarriers effectively deliver pesticides against plant root-knot nematodes(*Meloidogyne incognita*).Journal of Agricultural and Food Chemistry,68(47),13562-13572. 10.1021/acs.jafc.0c01736.

Zhao, L., Wang, Y., Chen, Z., Zou, Y.J. (2008). Preparation, characterization, and optical properties of host- guest nanocomposite material SBA-15/AgI. Physica B: Condensed Matter. 403(10-11); p. 1775-1780.DOI: 10.1016/j.physb.2007.10.004

Zinovieva, S.V., Udalova, Z.V.,& Khasanova, O.S. (2023). Nanomaterials in Plant Protection against Parasitic Nemates. *Uspehi sovremennoj biologii,* 143(3), 278-299. doi: 10.31857/S0042132423030110.

Zohra, E., Ikram, M., Omar, A.A., Hussain,M., Satti,S,H., Raja,N.I.(2021). Potential applications of biogenic selenium nanoparticles in alleviating biotic and abiotic stresses in plants: A comprehensive insight on the mechanistic approach and future persepectives. *Green Processing and Synthesis*,10,456-475.DOI: 10.1515/gps-2021-0047.