Review Article

Application of Nanotechnology for the management of plant-parasitic nematodes

Abstract

Plant-parasitic nematodes are the major threat to food production. Management methods based on synthetic chemicals are undesirable due to health and environment issues. Therefore, other innovative technologies and materials are needed to be evolved for the management of plant-parasitic nematodes. Nanotechnology is one of the most promising and innovative technology. Many nanoparticles have an effective nematicidal potential.This review presents the mode of action and different nanoparticles been 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 damage to the majority of agricultural crops, and reduce their yield valuing over USD$80 world over(Nicol et al. 2011). PPNs with different mode of parasitism cause a wide range of symptoms including stunting, wilting, yellowing, reduction of flowering, fruit set, and fruit development, dieback, and sometimes even plant death. 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 pesticides are commonly used for the management of PPNs. The chemical nematicides are undesirable due to problems of residual toxicity, environmental pollution, and public health hazards and also cost. Therefore, conventional method of management is not sufficient, so alternative method or innovative 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 promising and innovative technologies.

Nanotechnology

Nanomaterials or nanoscale materials are unique nano-objects, generally defined as having at least one dimension between 1 and 100 nanometers, having unique optical, electronic, magnetic, mechanical, thermo-physical, or biochemical properties. Nanotechnology has great potential for application in biology, medicine, pharmacology, and agriculture (Jeevanandam et al.2018). Nanoparticles and nanostructured materials, as well as their assemblies in nanosystems, are normally found in nature or deliberately designed and formulated as nano-capsules, nanoparticles, and nano-suspension. Nanoparticles are gaining popularity due to its low toxicity, cost efficiency, environmental friendliness, and less time requirement. In agriculture, nanomaterial is an alternative to chemical pesticide, many nanoparticles shows effective pest control potential especially plant-parasitic nematodes. Many nanoparticles of metals, metal oxides, and nonmetals have an effective nematicidal potential. These nanoparticles in addition to their pest control potential, 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 microbes. Increased plant resistance is through the induction of systemic acquired resistance (SAR), which is associated with an increase in antioxidant activity (Abdel khalek and Al-Askar, 2020). Active ingredients of various nanoparticles have also shown evidence of being potentially effective nematicides. Nanoparticles act against soil populations of PPNs which penetrate the root system and prevent nematodes from feeding or establishing on the host and lead to inhibition of reproduction and development of the parasite in the roots. Nanoparticles have a direct toxic effect on nematodes which can penetrate the body of nematodes, causing nematodes to die within a short period of time.

Various studies have been conducted on silver nanoparticles. Silver nanoparticles disrupts multiple 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 apoptosis or 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 exhibit neurotoxic effects that impair nematode motility, preventing them from infecting host plants (Bernard, 2019). 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. Furthermore, AgNPs can trigger systemic disease 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 concentration, 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, and hydrothermal synthesis), physical (e.g. gas phase deposition, power ball milling, pulsed laser ablation, and laser ablation synthesis in solutions), and biological (e.g. bacteria, plant extracts, and protein-mediated) techniques continues to evolve leading to the production of noble nanoparticles. The choice of the method determines 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 constituted a costly and toxic method making it toxic for the environment and unsuitable for many biological and agriculture applications. Both inorganic and organic nanoparticles have been proposed for different applications. Nanoparticle toxicity depends on the physicochemical characteristics and the synthesis origin, whether chemical or biological synthesis of the nanoparticles (Samrot et al.2021). Sometimes, chemically synthesized nanoparticles are agglomerized which cause inefficiency of the nanoparticles (Krishna and Maringanti 2016). For synthesis of silver chloride nanoparticles recent techniques are: 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. Such techniques require expensive equipment, high energy, and space. However, chemical synthesis of AgNPs is frequently prohibitively expensive, necessitates the use of toxic and hazardous chemicals, and poses potential environmental risks and biological risks.

Flash nano precipitation (FNP) is a simple and generic method to rapidly construct nanosized drug-loaded particles (abamectin-loaded nanoparticles) 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 subsequently stabilized and protected from aggregation by the BCP. The FNP method has been demonstrated to be powerful for the preparation of drug-loaded nanoparticles with high drug-loading capacity, relatively narrow size distribution, and tunable nanometer particle size. Poly(caprolactone)-b-poly(ethylene glycol) (PCL-b-PEG) are used as the stabilizer to prevent the nanoparticles from aggregation(Sabry,2019). 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).

Biological organisms including plant, fungi, bacteria, virus and seaweed are an ideal source for green synthesis of nanoparticles with desired shape and size and have been suggested as safe alternatives to the physical and chemical methods (Abbassy et al.2017; Wu et al.2019).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). They offer simplicity in the process of synthesis, cost-effective, eco-friendly, biocompatible with nature (Alamdari et al., 2020). Cyanobacteria, such as *Anabaena* spp., *Calothrix* sp., and *Leptolyngbya* sp., as well as the green microalgae including *Chlamydomonas reinhardtii* and *Chlorella vulgaris* have been reported to biosythesize intracellular gold, silver, palladium and platinum NPs (Ferreira *et al*., 2016).

Types of nanomaterials used against nematodes

Many nano-products or nanomaterials such as nano-silver and nano sulfur are used against plant-parasitic nematodes (Cromwell et al.2014). Various studies showed the nematicidal effect of several nanoparticles, i.e., silver nanoparticles, gold nanoparticles (Thakur et al. 2018), silica carbide nanoparticles and copper nanoparticles (Mohamed et al.2019) against root-knot nematodes. AgNPs can be easily integrated into existing agricultural systems, and can be engineered for enhanced efficacy and specificity against nematodes.

The nematicidal effect of silver nanoparticles is well-established. AgNP (30-150 lg/mL) caused inactivate J_2 of root-knot nematodes (*M. incognita*)(Cromwell et al. 2014).

Silver nanoparticles (AgNPs) and Zinc oxide nanoparticles (ZnONPs) have efficient nematicidal activity (Elarabi et al.,2022). ZnONPs showed LC_{50} value 63.56 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 *Xyl-1*, *16D10*, and *msp-20* genes, neuropeptidergic gene (Ace-2), and expansion-like proteins *MAP-1* after treatment with either AgNPs or ZnONPs. On the other hand, the oxidative stress response gene *GSTS-1* showed upregulation with all of AgNPs concentrations and ZnONPs).

Laboratory tests showed increased mortality of larvae, and reduced egg hatching 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).

Lab 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 (195.67%) and egg hatching inhibition percentage (80.71%) *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. 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 J2 and egg hatchability of *M. incognita* and were recommended as biological control 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

Due to their unique physical and chemical properties, nanoparticles have created much attention to researchers. Nanotechnology holds the promise of controlled release and site-targeted delivery of agrochemicals. Research should focus on enhancing their effectiveness and reducing wastage toward, leading to optimizing nanoparticles synthesis methods to enhance bioactivity while minimizing toxicity. Additionally, it is crucial 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.

References

1. Abbassy, M. A.; Mona, A. Abdel-Rassoul; Nassar, AA.M. K.and 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.
2. Abdelkhalek, A., Al-Askar, A.A., (2020). Green synthesized ZnO nanoparticles mediated by *Mentha Spicata* extract induce plant systemic resistance against tobacco mosaic virus. Appl. Sci. 10 (15), 5054. https:// doi.org/ 10.3390/ app10155054.
3. 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. https://doi.org/10.15171/ijb.1309.
4. Ahamed, M., Posgai, R., Gorey, T. J., Nielsen, M., Hussain, S. M., andRowe, J. J. (2010). Silver nanoparticles induced heat shock protein 70, oxidative stress and apoptosis in Drosophila melanogaster. Toxicologyand Applied Pharmacology 242:263–269.

5. Akhter G.,KhanA.,Ali SG.Khan TA,Siddiqi KS,Khan HM.(2020).Antibacterial and nematicidal properties of biosynthesized Cu nanoparticles using extract of holoparasitic plant.SN Appl.Sci.2:1268. https://doi.org/10.1007/s42452-020-3068-6
6. Alamdari S., Sasani Ghamsari M., Lee C., Han W., Park HH., Tafreshi MJ. (2020). Preparation and characterization of zinc oxide nanoparticles using leaf extract of *Sambucus ebulus*. Appl. Sci. 10 (10), 3620.https://doi.org/10.3390/app10103620.
7. Alamri S, Nafady NA, El-Sagheer AM, El-Aal MA, Mostafa YS, Hashem M, Hassan EA. (2022). Current utility of Arbuscular Mycorrhizal Fungi and Hydroxyapatite Nanoparticles in suppression of tomato root-knot nematode. *Agronomy*.12(3):671.https://doi.org/10.3390/agronomy 12030671
8. Alfy H, Ghareeb RY, Soltan E .,Farag DA.(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.
9. 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.
10. Baronia, R., Kumar, P., Singh, S., & Walia, R. (2020). Silver nanoparticles as a potential nematicide against *Meloidogyne graminicola*. Journal of Nematology, 52. https://doi.org/10.21307/jofnem-2020-002
11. Bernard, G. (2019). Potential Nematicidial Activity of Silver Nanoparticles Against the Root-Knot Nematode (Meloidogyne Incognita). Online Journal of Complementary & Alternative Medicine. https://doi.org/10.33552/ ojcam.2019.02.000531
12. Cao J.,Guenther RH.,Sit.TL.et al.,(2015).Development of abamecten loaded plant virus nanoparticles for efficacious plant parasitic nematode control.ACS Appl.Mater.Interfaces.7:9546-9553.
13. Choi, O., and Hu, Z. (2008). Size dependent and reactive oxygenspecies related nanosilver toxicity to nitrifying bacteria. EnvironmentalScience and Technology 42:4583–4588.
14. Cromwell, W. A.; Joopil Yang; Starr, J. L. and Young-Ki Jo (2014). Nematicidal effects of Silver nanoparticles on root-knot nematode in Bermuda grass. J. Nematol. 46(3) 261-266.
15. Danish M, Altaf M, Robab MI, Shahid M, Manoharadas S, Hussain SA, and Shaikh H.(2021). Green Synthesized Silver Nanoparticles Mitigate Biotic StressInduced by *Meloidogyne incognita* in *Trachyspermum ammi* (L.) by Improving Growth, Biochemical, and Antioxidant Enzyme Activities. ACS Omega 2021, 6, 11389−11403. https://doi.org/10.1021/acsomega.1c00375.
16. 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. https://doi.org/10.2478/helm2023-0018.
17. Davids JS., Ackah M, Okoampah E., Fometu SS, 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.

18. Deekonda, K., S. Muniyandy, Y.Y. Lima, P. Janarthanan, 2016. Electron beam radiation mediated green synthesis of silver nanoparticles using carboxymethyl sago pulp obtained from sago waste. Polymer, 86: 147- 156.
19. Divya K, Jisha MS.(2018). Chitosan nanoparticles preparation and applications. Environmental Chemistry Letters. 2018;16(1):101-112.
20. El-Ansary.M.S.M.,Hamouda 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.
21. Elarabi NI , 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.
22. El-Ashry RM.,El-Saadony MT.,El-Sobki AEA et al.,(2022). Biological silicon nanoparticles maximize the efficiency of nematicides against biotic stress induced by *Meloidogyne incognita* in eggplant. Saudi J.Biol.Sci.29:920-932. https://doi.org/10.1016/j.sjbs.2021.10.013.
23. 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. https://doi.org/10.1007/s10876-019-01528-5.
24. 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.
25. Fabiyi OA., Claudius-Cole AO., Olatunji GA., Abubakar DO., Adejumo OA. (2021). Response of *Meloidogyne javanica* to Silver Nanoparticle Liquid from Agricultural Wastes. J of Agricultural Sci. 43(3):507-517.
26. Ferreira, D.V.S., M.E.F. Conz, L.M.T.R. Lima, S. Fraśes, D.S. Wanderley, C. Sant'Anna, (2016). Green production of microalgae-based silver chloride nanoparticles with antimicrobial activity against pathogenic bacteria. Enzyme and Microbial Technology. doi.org/10.1016/j.enzmictec.2016.10.018.
27. Fouda, M., Abdelsalam, N., Gohar, I., Hanfy, A., Othman, S., Zaitoun, A., Allam, A., Morsy, O., & El-Naggar, M. (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.
28. Fu Z. , Chen K , Li Li , Zhao F , Wang Y , Wang M , Shen Y , Cui H, Liu D ., Guo X. (2018). Spherical and spindle-like abamectin-loaded nanoparticles by flash nanoprecipitation for Southern Root-Knot nematode control: Preparation and Characterization. Nanomaterials 2018, 8, 449; doi:10.3390 /nano8060449
29. Ghareeb, RY., 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.
30. Ghareeb, RY., El-Din NG., El-Maghraby DM., Ibrahim DSS., Megeed AA., & 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.

31. Gkanatsiou Ch, Ntalli N, Menkissoglu-Spiroudi U, Dendrinou-Samara C.(2019). Essential metal-based nanoparticles (Copper/Iron NPs) as potent nematicidal Agents against *Meloidogyne* spp. J Nanotechnol Res .1 (2): 044-058. DOI: 10.26502/fjnr.004.
32. Guzmán, M.G., J. Dille, S. Godet, 2009. Synthesis of silver nanoparticles by chemical reduction method and their antibacterial activity. International Journal of Chemical and Biomolecular Engineering, 2: 3.
33. Hamed SM, Mostafa AMA, Abdel-Raouf N, Ibraheem IBM.(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
38. Heflish AA, Hanfy AE , Ansari MJ, Dessoky ES, Attia AO, Elshaer MM. (2021). Green biosynthesized silver nanoparticles using *Acalypha wilkesiana* extract control root-knot nematode. Journal of King Saud University – Science. 33, 101516. https://doi.org/10.1016/j.jksus.2021.101516
39. Henglein, A., 1998. Colloidal Silver Nanoparticles: photochemical Preparation and Interaction with O2, CCl4, and Some Metal Ions. Chemistry of Materials, 10(1): 444-450.
44. 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.
45. 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. J. Sol-Gel Sci. Technol. 86 (3): 682-689.
46. Kalaba MH , Moghannem SA, El-Hawary AS , Radwan AA , Sharaf MH et al., (2021). Green Synthesized ZnO Nanoparticles Mediated by *Streptomyces plicatus*: Characterizations, Antimicrobial and Nematicidal Activities and Cytogenetic Effects. Plants (Basel). 25;10(9):1760. doi: 10.3390/plants10091760.
47. 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. https://doi.org/10.1016/J.CROPRO.2018.11.020.
48. Khalil MS.,El-Aziz MHA.,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).Eur J.Plant.Pathol.163:799-812.
49. Khan M, Siddiqui ZA, Parveen A, Khan AA, Moon IS, 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
50. Kharissova, O.V., Dias, H.V.R., Kharisov, B.I., Pérez, B.O., Pérez, V.M.J.(2013). The greener synthesis of nanoparticles. Trends Biotechnol. 31 (4), 240–248.

51. Krishna G. and Maringanti SC.(2016). Synthesis of silver nanoparticles by chemical and biological methods and their antimicrobial properties. Journal of Experimental Nanoscience. http://dx.doi.org/10.1080/17458080.2016.1139196.
52. Lim, D., Roh, J.-Y., Eom, H.-J., Hyun, J. W., and Choi, J. (2012). Oxidativestress-related PMK-1 P38 MAPK activation as a mechanism fortoxicity of silver nanoparticles to reproduction in the nematode Caenorhabditis elegans. Environmental Toxicology and Chemistry 31:585–592.
53. Makirita, W., Yong, L., He, N., Mbega, E., Chacha, M., Li, X., & Zhang, F. (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. https://doi.org/10.1166/jnn.2020.17164
54. Masry, S.H., Taha, T.H., Botros, W.A., Mahfouz, H., Al-Kahtani, S.N., Ansari, M.J.,Hafez, E.E.(2021). Antimicrobial activity of camphor tree silver nano-particles against foulbrood diseases and finding out new strain of *Serratia marcescens* viaDGGE-PCR, as a secondary infection on honeybee larvae. Saudi J. Biol. Sci. 28 (4),2067–2075.
57. Mohamed EA,Elsharabasy SF,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.
58. Nguyena, T-H., K-H. Leeb, B-T. Lee, 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
59. 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.
60. Oluwatoyin F, Gabriel O, Atolani, Olubunmi, 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.
61. Oluwatoyin F., Olatunji GA.(2018). Application of green synthesis in nano particles preparation: *Ficus mucoso* extracts in the management of *Meloidogyne incognita* infecting groundnut *Arachis hypogea*. Indian J Nematol.48:13-17.
65. 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
66. Reneeta NP, 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.
67. Roh, JY., Sim, SJ., Yi, J., Park, K., Chung, KH., Ryu, DY., and Choi, J. (2009). Ecotoxicity of silver nanoparticles on the soil nematode Caenorhabditis elegans using functional ecotoxicogenomics. Environmental Science and Technology 43:3933–3940.
68. Sabry AKH. (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.

69. 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. Curr. Res. Green Sustain. Chem., 4, 100042.
70. Shang H,Zhang H,Zhao R., Meng Yu, Yingjian Ma, Zhe Sun, Xuemin Wu, Yong Xu (2022). Selenium nanoparticles are effective in penetrating pine and causing high oxidative damage to *Bursaphelenchus xylophilus* in pine wilt disease control. Pest Manage.Sci.78(8):3704-3716. https:// doi.org/ 10.1002/ ps.7013.
71. Shekoohi SS,Charehgani H,Abdollahi M,Rajabi HR.(2021).Combined effect of β-aminobutyric acid and silver nanoparticles on eggplants, Solanum melongena, infected with Meloidogyne javanica.Nematology.23(9):1077-1092.
72. Shoaib RM,Abdel-Razik AB,Ibrahim MM.et al.(2022).Impact of engineered nano silver on plant parasitic nematode and measurement of DNA damage.Egypt.J.Chem.65(4):43-51.
75. Tauseef A, Hisamuddin, Gupta J. Rehman A.(2021). Differential response of cowpea towards the CuO nanoparticles under *Meloidogyne incognita* stress.S.Afr.J.Bot.139:175-182.
76. 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.Exp.Parasitol.220,108045.
77. Tehrani, FA.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
78. 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
79. Tryfon P, Kamou NN, Ntalli N et al.,(2022).Coated Cu-doped ZnO and Cu nanoparticles as control agents against plant pathogenic fungi and nematodes.NanoImpact.28,100430.
80. Udalova ZV, Folmanis GE, Khasanov FK, Zinovieva SV.(2018). Selenium nanoparticles-An inducer of tomato resistance to the root-knot nematode, *Meloidogyne incognita* (Kofoid & White,1919) Chitwood 1949, Dokl. Biochem.Biophys.482:264-267.
81. Udalova ZV,Zinovieva SV.(2022).Effects of silicon nanoparticles on the activity of antioxidant enzymes in tomato roots invaded by *Meloidogyne incognita* (Kofoid & White,1919) Chitwood, 1949. Dokl.Biochem.Biophys.506:191-194.
82. 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.
83. Zhang D,Liu G,Jing T,et al.,(2020).Lignin-modified electronegative epoxy resin nanocarriers effectively deliver pesticides against plant root-knot nematodes(*Meloidogyne incognita*).J.Agric.Food Chem.68:13562-13572.
84. Zhao, L., Y. Wang, Z. Chen, Y.J. Zou, 2008. Preparation, characterization, and optical properties of host– guest nanocomposite material SBA-15/AgI. Physica B: Condensed Matter.
85. Zinovieva SV., Udalova ZV., Khasanova OS. (2023). Nanomaterials in Plant Protection against Parasitic Nemates. Uspehi sovremennoj biologii. 143(3): 278-299. doi: 10.31857/S0042132423030110.

86. Zohra E,Ikram M,Omar aa .et al.(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 Process Synth.10:456-475.