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Review

Recent Advances in Plant-Based Green Synthesis of Nanoparticles: A Sustainable Approach for Combating Plant-Parasitic Nematodes

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Abstract: Nanotechnology is emerging as an innovative and sustainable agricultural approach that minimizes environmental impacts by developing nanostructured materials to promote plant growth and combat plant-parasitic nematodes (PPNs). Plant-based nanoparticles (NPs) are attracting increasing attention as they are more environmentally friendly, economical and biocompatible compared to traditional chemical and physical synthesis methods. The ability of plants to reduce and stabilize metal ions and form NPs of specific size and morphology through their biochemical content offers great advantages for agricultural applications. Phytochemicals produced by plants enable the biological synthesis of metal and metal oxide NPs by acting as reducing agents and coating agents in NP synthesis. The effects of plant-based NPs in nematode control are based on mechanisms such as the disruption of the nematode cuticle, induction of oxidative stress and interference with parasite metabolism. Several plant species have been investigated for the synthesis of metal and metal oxide nanoparticles such as silver (Ag-NPs), nickel oxide (NiO-NPs), zinc oxide (ZnO-NPs), copper oxide (CuO-NPs) and iron (Fe-NPs). These biologically synthesized NPs show potent biological activity against important PPNs such as *Meloidogyne* spp., *Pratylenchus* spp. and *Heterodera* spp. The integration of plant-derived NPs into agricultural systems has significant potential for plant growth promotion, nematode suppression and soil health improvement. This review highlights their role in reducing environmental impact in agricultural applications by examining the sustainable synthesis processes of plant-based NPs.

Keywords: plant-based nanoparticles; green synthesis; plant-parasitic nematodes (PPNs); nanotechnology; sustainable agriculture

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1. Introduction

Sustainably feeding the global population is a major challenge. By 2030, the world population is expected to reach 8.5 billion, demanding 50% more food. Therefore, increasing agricultural productivity and taking agronomic measures are critical for food security [1]. However, agricultural production is threatened by diseases caused by agents such as fungi, bacteria, viruses and nematodes [2,3]. These diseases reduce crop yields, negatively affect quality and marketability, and threaten farmers' livelihoods. These diseases are spreading

rapidly on a global scale, especially affecting small-scale farmers and increasing food insecurity [4,5].

Plant-parasitic nematodes (PPNs) are important soilborne pathogens, causing root infections in many agricultural crops worldwide. PPNs cause yield losses of approximately USD 100 billion worldwide each year [6,7]. To date, about 4100 species of PPNs have been identified and some of these species, root-knot nematodes (RKNs) and cereal cyst nematodes (CCNs), are major causes of agricultural diseases [8]. Synthetic nematicides are routinely used to control PPNs. However, with growing concerns about the health risks and environmental impacts of these chemicals, it has become necessary to seek alternative means of control [9].

Recently, nanotechnology has attracted considerable interest as a viable option for pest management. Nanoparticles are gaining more interest nowadays as they have some better properties such as being extremely durable, highly chemically reactive and electrically conductive in nature [10]. Nanotechnology is a field that aims to manipulate materials at the nanostructure level using the disciplines of physics, chemistry and biology, and it has made tremendous progress in the last few decades [11]. The dominance of the "NP world" in this field will continue to increase in the future [12–14]. Nanoparticles have proven to be responsible in many fields such as medicine, cosmetics, food science and agriculture [15]. Due to their small dimensions, high surface area and high reactivity, nanoparticles have unique properties compared to bulk materials [16,17].

The rapid growth of the world's population has made it necessary to increase agricultural production. In order to achieve this, the potential of nanotechnology in various areas of agriculture needs to be explored. There are huge opportunities for nanotechnology in many areas such as pests, pathogens, weeds, plant diseases, soil conditions, water sources and improving product quality [18,19]. Nanoparticles have the potential to improve fertilizer efficacy, soil health, plant growth and plant disease control [20]

Traditional nanoparticles have been of great concern to researchers, in contrast to green and sustainable synthesis routes [21]. Nanoparticles can be synthesized by chemical, physical and biological methods. While chemical and physical methods can produce quality nanoparticles, they are disadvantaged by environmental concerns, high expense, ecological risks, toxicity and poor biocompatibility [22,23]. Therefore, environmentally friendly alternative solutions need to be developed for the industrial-scale use of nanoparticles [24].

Biological nanoparticles can be synthesized with the help of reducing agents such as microorganisms (fungi and bacteria) and plant extracts [25]. Plant-based green nanoparticle synthesis is reported to possess the best quality among biological methods and the process has advantages such as simplicity and diversity of plants [26]. Plants offer abundant and easily accessible resources in ecosystems. Their phytochemicals may be utilized to replace toxic, expensive and environmentally unfriendly chemical-reducing agents [27].

Although the antimicrobial activities and mechanisms of green-synthesized nanoparticles have been extensively reviewed in several review articles, more comprehensive reviews are needed on the inhibitory effects of these nanoparticles on PPNs. This review introduces green nanoparticles derived from plants and discusses their potential in managing PPNs. Additionally, some successful experiments are presented with examples and developments in the field are considered. By highlighting the advantages and disadvantages of plant-assisted nanoparticle synthesis, the review aims to present a comprehensive understanding of their role in sustainable agriculture.

2. Overview of Nanoparticle Synthesis

The process of synthesizing NPs is often referred to under two broad categories, namely "top-down" and "bottom-up" synthesis [28]. In top-down synthesis, NPs are

formed from bulk raw materials [29]. Size reduction is achieved by subjecting them to various physical and chemical treatments. In bottom-up synthesis, NPs are formed by chemical reactions of atoms, compounds or smaller particles [30]. In contrast to top-down techniques, the bottom-up process is also known as a "build up" technique as it involves the synthesis of NPs from lower level substances. The method includes processes such as deposition, chemical vapor deposition (CVD) and reduction processes [31]. The core of the bottom-up strategy is the formation of nanoscale molecules or atoms through chemical and biological methods to create complex molecular structures [32]. Using greener solvents and environmentally friendly reducing and stabilizing agents (coatings), green nanotechnology integrates biological systems such as plants, bacteria, fungi, algae and other microorganisms [33–35]. These microorganisms can synthesize nanoparticles intracellularly and extracellularly by reducing metal ions to stable nanoparticles. Biological processes are environmentally friendly, cost-effective and safer than conventional physical and chemical processes. They also allow a high degree of control over the size, surface properties and shape of nanoparticles, enabling them to be tailored for specific applications in fields such as medicine, electronics and environmental remediation [36,37].

3. Green Synthesis of Nanoparticles

Green synthesis is a sub-field of green chemistry that has emerged with the realization of the need for sustainable processes in chemical production. Green chemistry aims to design safer chemical products and processes by reducing or avoiding the formation and application of harmful constituents [38]. In the last few years, with a safety-first design philosophy, environmentally friendly and economical green synthesis pathways for nanoparticles (NPs) have been developed. Biological media such as fungi, bacteria and plant extracts are employed largely in NP synthesis and offer safer, more effective synthesis methods [39,40]. However, plant material, especially leaves, fruits, roots, stems and seeds, have been employed widely in the synthesis of a wide range of nanoparticles [41].

4. Plant-Based Green Synthesis of Nanoparticles

Plant organs or plant extracts are the primary constituents responsible for NP biosynthesis and plant biomolecules could also act as stabilizers, coating and reducing agents [42,43]. Metal elements encompass green biological nanomaterials such as silver, copper, gold, titanium and iron. The metal NPs possess a high potential for use as biosensing tools due to their light scattering-enhanced, plasmon excitation-induced effects. The green synthesis method is cost-effective, non-toxic, environmentally friendly and suitable for the development of biological processes [44] (Figure 1). The plant-mediated synthesis of nanoparticles (NP) can be performed by extracellular and intracellular methods. In extracellular methods, plant extracts or purified phytochemicals are utilized as raw materials used for NP synthesis, while in intracellular methods, NP synthesis occurs in plant cells [45]. The preferred route of green synthesis is the use of plant extracts because it is mostly applied at ambient pressure and temperature, neutral pH levels and within a few minutes [46]. In the process, bioreduction via plant extracts entails the mixing of the plant extract with an aqueous salt solution of the metal [47] (Figure 2).

The synthesis of plant-based NPs is characterized by several techniques (Table 1). UV-vis spectroscopy, Transmission Electron Microscopy (TEM), Fourier Transform Infrared Spectroscopy (FTIR), Dynamic Light Scattering (DLS), Zeta potential, Scanning Electron Microscopy (SEM), Energy-Dispersive X-ray Spectroscopy (EDS or EDX) and X-Ray Diffraction (XRD) are more advanced and famous for their characterizations. The synthesis of different NPs using different plant extracts is listed in Table 1.

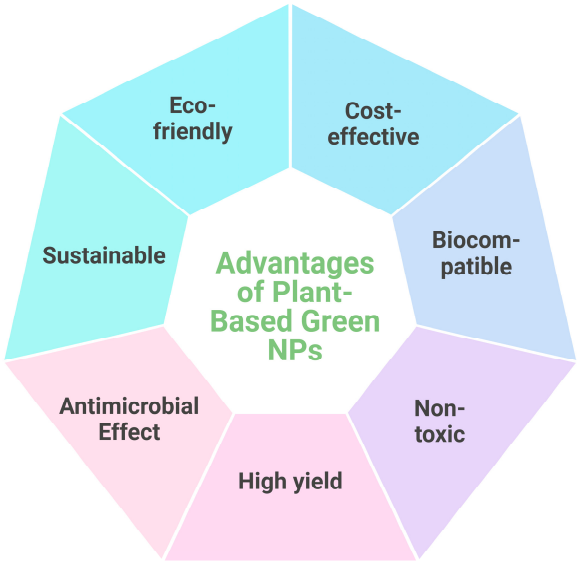


Figure 1. Biological and sustainable advantages of plants in nanoparticle production.

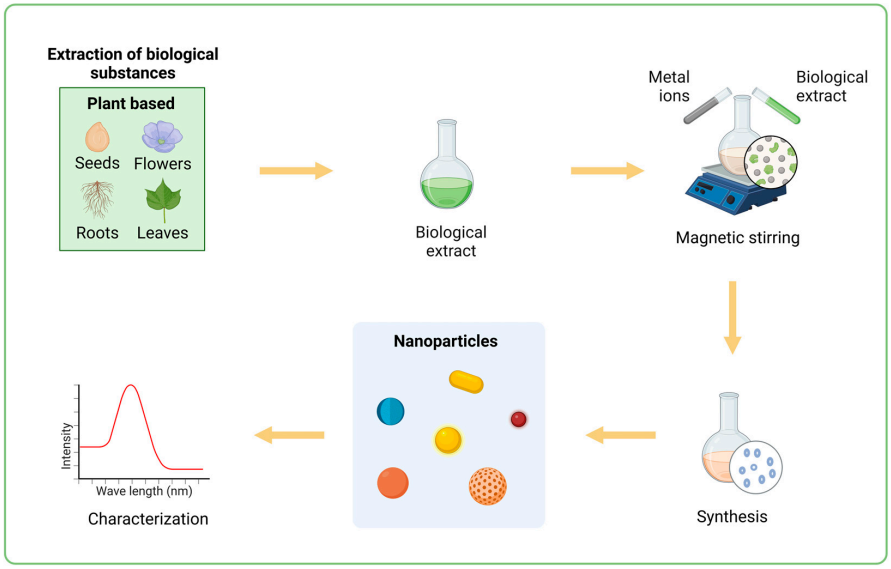


Figure 2. Illustration of the stages in plant-based nanoparticle synthesis process.

Table 1. Plant-based green NPs and their characterization.

Nanoparticle Type	Plant Species Used	Characterization Techniques/Tools	Particle Size Range (nm)	Morphology	Stability and Surface Charge	Reference
Ag-NPs	*Euphorbia tirucalli*	UV–vis spectroscopy, FTIR	20–30	Spherical and cubic	Not mentioned	[48]
Ag-NPs	*Citrus limon* L.	UV–vis spectroscopy, SEM, TEM, XRD, FTIR	16.56–83.09 average size of 38.31	Face-centered cubic (fcc)	Not mentioned	[49]
Ag-NPs	*Acalypha wilkesiana*	UV–vis spectroscopy, SEM, FTIR, XRD	10 to 30	Spherical	Zeta value: −16.1 mV	[50]
Ag-NPs	*Eichhornia crassipes*	TEM	15.71	Spherical	Not mentioned	[51]
Ag-NPs	*Eucalyptus officinalis*	UV–vis spectroscopy, FTIR, SEM	100	Spherical	Not mentioned	[52]
ZnO-NPs	*Salix alba*	UV–vis spectroscopy, SEM, FTIR, XRD	7.14	Irregular shapes	Not mentioned	[53]
Cu-NPs	*Haplophyllum tuberculatum*	SEM	85	Not mentioned	Not mentioned	[54]

Table 1. *Cont.*

Nanoparticle Type	Plant Species Used	Characterization Techniques/Tools	Particle Size Range (nm)	Morphology	Stability and Surface Charge	Reference
MgO-NPs	*Fragaria* × *ananassa*	UV–vis spectroscopy, EDX, TEM, FTIR, XRD	100	Spherical	Zeta potential: −34.5 mV,	[55]
Ag-NPs	*Solanum nigrum*	UV–vis spectroscopy, EDS, TEM, FTIR, XRD	30	Spherical	Not mentioned	[56]
Ag-NPs	*Senna seamia*	UV–vis spectroscopy, EDX, SEM, TEM, FTIR, XRD	05–60	Polydisperse	Not mentioned	[57]
S-NPs	*Rosmarinus officinalis*	UV–vis spectroscopy, SEM, TEM, FTIR	40	Spherical	Not mentioned	[58]
Ag-NPs	*Artemisia judaica*	UV–vis spectroscopy, SEM	50–150	Not mentioned	Not mentioned	[59]
NiO-NPs	*Ocimum sanctum*	UV–vis spectroscopy, FTIR, SEM	15–40	Uniformly	Not mentioned	[60]
Ag-NPs	*Fragaria* × *ananassa*	UV–vis spectroscopy, SEM, TEM, FTIR, XRD	55–70	Rectangular	Not mentioned	[61]
Ag-NPs	*Glycyrrhiza glabra*	UV–vis spectroscopy, EDX, SEM, TEM, FTIR	9–20	Spherical	Zeta potential: −35.7 mV	[62]
Ag-NPs	*Glycine max*	UV–vis spectroscopy, SPR, DLS, FTIR	11	Spherical	Zeta potential: −23 to 25	[63]
Ag-NPs	*Cynanchum dioscoridis*, *Melia azedarach*, *Moringa oleifera*	UV–vis spectroscopy, SEM	30–100	Spherical	Not mentioned	[64]
Cu-NPs, Fe-NPs, Zn-NPs	*Tridax procumbens*	UV–vis spectroscopy, EDX, TEM, FTIR, SAED	2–100	Rod-shaped	Not mentioned	[65]
Fe-NPs	*Camellia sinensis*	TEM, FTIR, XRD	36–55	Spherical	Not mentioned	[66]
Cu-NPs	*Orobanche aegyptiaca*	UV–vis spectroscopy, XRD, TEM, SEM	50	Spherical	Not mentioned	[67]
Ag-NPs	*Cnidoscolus aconitifolius*	UV–vis spectroscopy, FTIR, SEM	2–20	Spherical	Not mentioned	[68]
CuO-NPs	*Jatropha curcas*	UV–vis DRS spectroscopy, FTIR, TEM, XRD	5–15	Spherical, pure	Not mentioned	[69]

5. Applications of Plant-Based Green Synthesis of Nanoparticles Against Plant-Parasitic Nematodes

Plant diseases, especially those caused by PPNs, pose a threat to food security by causing significant yield losses worldwide [70,71]. PPNs threaten agricultural productivity by causing major damage, especially on vegetables, fruits and staple crops [72]. Although synthetic nematicides are often used to control PPNs, environmental concerns and health risks associated with these chemicals have led to the search for alternative and more sustainable methods [9]. The use of nanoparticles in agriculture has attracted considerable interest due to their potential to increase plant resistance to pathogens, promote plant growth, reduce disease severity and improve yields [73]. Among the different types of nanoparticles, silver nanoparticles (Ag-NPs) have shown an especially significant effect against many plant pathogens, including nematodes [74].

Unfortunately, the exact mechanism of action of nanoparticles on nematodes has not yet been fully elucidated. However, the available data suggest that this mechanism is largely similar to the mechanisms of the action on microorganisms [75]. The cuticle of nematodes is negatively charged, like the membranes of bacteria [76], which allows positively charged silver nanoparticles to interact strongly with the cuticle and these interactions damage the cuticle structure. These interactions lead to the weakening of the

cuticle structure and disruption of the reproductive systems, increasing the mortality rate of PPNs [77]. Furthermore, nanoparticles trigger stress responses in plant roots, promoting the production of secondary metabolites that enhance plant defense mechanisms against nematodes. This synergistic effect disrupts the life cycles of nematodes and increases plant resistance [78]. Furthermore, the production of reactive oxygen species triggers oxidative stress conditions, which in turn lead to nucleic acid damage, protein oxidation and degradation. Consequently, these processes can lead to apoptosis (cell death), causing the death of cells in a programmed manner [77]. This mechanism of action through biogenic nanoparticles is shown in Figure 3.

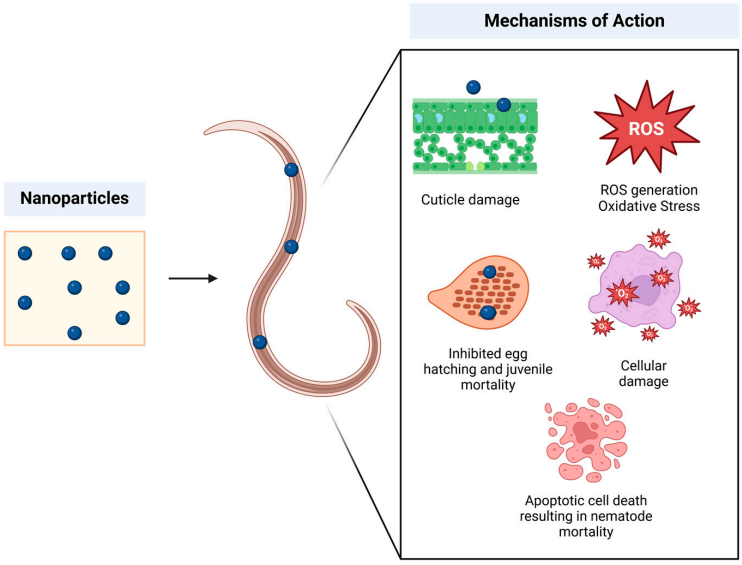


Figure 3. Mechanism of action of plant-mediated green nanoparticles in combating plant-parasitic nematodes.

Table 2 summarizes the most recent research on the use of plant-based green nanoparticles (NPs) against PPNs. Nasr et al. [49] reported that Ag-NPs synthesized with *Citrus limon* L. (lemon) showed higher efficacy against *Meloidogyne javanica*, with 100% mortality of J2 larvae at a concentration of 100 ppm. In addition, disease severity was reduced by 66.67% and the nematode population was reduced by 99.27% under in vitro and in vivo conditions. Kalaiselvi et al. [48] demonstrated the efficacy of Ag-NPs from *Euphorbia tirucalli* against *Meloidogyne incognita*, with 96% to 100% killing of J2 under in vivo and in vitro conditions. Infection was 46.95% inhibited at a concentration of 100 ng/mL and 100% inhibition was expressed at 1000 ng/mL. Further research has demonstrated the efficacy of nanoparticles from various plant materials. Ahmad et al. [53] reported a breakthrough in the synthesis of ZnO NPs from *Salix alba*, which achieved an impressive 92.2% *M. incognita* kill in 48 h in vitro. Soliman et al. [54] reported that copper nanoparticles (Cu-NPs) derived from *Haplophyllum tuberculatum* resulted in 63.59% mortality of *M. incognita*. In contrast, the commercial nematicide Nemaprope®10G exhibited a significantly lower mortality rate of just 6.14%. In another significant study, Rani et al. [62] found that Ag-NPs synthesized from *Glycyrrhiza glabra* completely inhibited the egg hatching of *M. incognita* at a concentration of 10 ppm and achieved 100% nematode mortality at 6 ppm. Oliveira et al. [63] demonstrated that Ag-NPs from *Glycine max* (soybean) inhibited the mobility of *Pratylenchus brachyurus*, with calculated IC50 and IC90 values providing insights into their dose-response relationship. Mahmoud et al. [66] investigated iron nanoparticles (Fe-NPs) synthesized from *Camellia sinensis* (tea) and reported a 22.44% reduction in root galls caused by *M. incognita* under in vivo conditions. Additionally, Fabiyi et al. [65] studied

copper (Cu-NPs), iron (Fe-NPs) and zinc nanoparticles (Zn-NPs) synthesized from *Tridax procumbens* and found significant reductions in nematode populations, egg counts and gall indices at 100 ppm. Akhter et al. [67] reported that Cu-NPs synthesized from *Orobanche aegyptiaca* suppressed the *M. incognita* juvenile emergence by 83% at a concentration of 800 µg/mL, while lower concentrations still exhibited a considerable inhibitory effect. Thiruvenkataswamy et al. [56] validated that Ag-NPs synthesized from *Solanum nigrum* caused 100% mortality of nematodes *M. incognita* in vitro at a concentration of 2.5 µg/mL, and a concentration of 0.5 µg/mL achieved 48% mortality.

Table 2. Application of plant-based green synthesis NPs to combat various plant-parasitic nematodes.

Plant Name	Prepared Nanoparticle Name/Type	Nematode Species	Host Plant	Condition/Method (In Vitro or In Vivo)	Efficacy	References
Euphorbia tirucalli	Ag-NPs	*Meloidogyne incognita*	Tomato	In vitro and In vivo	96–100% J2 mortality in 6 h, 46.95% infectivity reduction at 100 ng/mL and 100% at 1000 ng/mL.	[48]
Citrus limon L.	Ag-NPs	*Meloidogyne javanica*	Faba bean	In vitro and In vivo	100% J2 mortality at 100 ppm, reduced disease severity by 66.67%, nematode populations by 99.27%.	[49]
Acalypha wilkesiana	Ag-NPs	*Meloidogyne incognita*	-	In vitro	53.3% nematode mortality after 48 h at 100 mg/mL.	[50]
Eichhornia crassipes	Ag-NPs	*Meloidogyne javanica*	Swiss chard	In vivo	115.14 egg masses, 2909 juveniles, RF 0.92 with 3 µg/mL Ag-NPs.	[51]
Eucalyptus officinalis	Ag-NPs	*Heterodera sacchari*	Rice	In vivo	11.01 kg seed weight, 10 cysts (carbofuran: 11.20 kg seed weight, 7 cysts).	[52]
Salix alba	ZnO-NPs	*Meloidogyne incognita*	-	In vitro	92.2% mortality at 1000 µg/mL after 48 h.	[53]
Haplophyllum tuberculatum	Cu-NPs	*Meloidogyne incognita*	-	In vitro	Cu-NPs caused 63.59% mortality, Nemaprope®10G showed the lowest mortality at 6.14%.	[54]
Fragaria × *ananassa*	MgO-NPs	*Meloidogyne incognita*	-	In vitro	71 ± 2 juveniles at 24 h, 106 ± 2 at 48 h; 14 dead juveniles at 48 h.	[55]
Solanum nigrum	Ag-NPs	*Meloidogyne incognita*	-	In vitro	100% mortality at 2.5 µg/mL, 48% mortality at 0.5 µg/mL.	[56]
Senna Siemia	Cu-NPs	*Meloidogyne incognita*	Ajwain	In vivo	100 ppm AgNPs reduced gall formation and egg mass production compared to inoculated control.	[57]
Rosmarinus officinalis	S-NPs	*Meloidogyne javanica*	-	In vitro	100% mortality at 30 ppm and 60 ppm after 4 days.	[58]
Fragaria × *ananassa*	Ag-NPs	*Meloidogyne incognita*	-	In vitro	Reduced hatching, 9 dead juveniles compared to 4 in control after 48 h.	[61]
Jatropha curcas	CuO-NPs	*Meloidogyne incognita*	Chickpea	In vitro and In vivo	80% inhibition at 200 ppm, dose-dependent reduction in J2 hatching.	[69]
Glycyrrhiza glabra	Ag-NPs	*Meloidogyne incognita*	-	In vitro	100% egg-hatching inhibition at 10.0 ppm, 100% mortality at 6.0 ppm, LC-50 = 0.805 ± 0.177 ppm.	[62]
Glycine max	Ag-NPs	*Pratylenchus brachyurus*	Soybean	In vitro and In vivo	Inhibited *P. brachyurus* mobility at 25 µmol L^{-1} or higher after 48 h, IC50 and IC90 values calculated.	[63]
Tridax procumbens	Cu-NPs, Fe-NPs and Zn-NPs	*Meloidogyne incognita*	Cabbage	In vivo	Reduced Meloidogyne incognita population, egg count, and gall index at 100 ppm.	[65]
Camellia sinensis	Fe-NPs	*Meloidogyne incognita*	Tomato	In vivo	Reduced root galls by 22.44% at 3 mg/kg, 17.76% at 6 mg/kg.	[66]
Orobanche aegyptiaca	Cu-NPs	*Meloidogyne incognita*	-	In vitro	Inhibited juvenile emergence by 83% at 800 µg/mL, 68%, 53%, 39%, and 26% at lower concentrations.	[67]
Cnidoscolus aconitifolius	Ag-NPs	*Meloidogyne incognita*	Carrot	In vivo	67 soil nematodes ± 0.5, 58 root nematodes ± 1.3 (control: 3107 soil and 928 root nematodes).	[68]

These studies demonstrate the potential of plant-origin nanoparticles as effective, eco-friendly alternatives for controlling PPNs in agriculture. Not only is green synthesis

from plant extracts an environmentally friendly method for pest control, but the application of fewer environmental resources compared to chemical nematicides is another advantage. Lastly, variations in nanoparticle concentrations and their efficacy toward various species of nematodes suggest additional work in optimizing applications for a specific crop and nematode species.

6. Challenges and Limitations

Green synthesis offers many advantages compared to physical and chemical methods. Inorganic nanoparticles obtained from plant extracts offer an environmentally friendly approach because the chemicals used are directly derived from bioactive compounds found in plants [79]. However, there are also some challenges in producing nanoparticles by this method. Their main challenge is low production efficiency. This also depends on the quantity and quality of the bioactive compounds, which vary according to the type of plant used, the part of the plant used, the growing conditions and the time of harvest. For example, some plants can only produce NPs under certain climatic or soil conditions. In addition, plants need to be grown in a controlled environment as light intensity, nutrient levels and soil pH can affect the yield of metabolites required for green synthesis [79,80]. In addition, seasonal and geographical variations are also important. If the same biological source is used at different times or locations, the structure and composition of the compounds may be different. This can affect the properties of the nanoparticles and lead to inconsistencies in the efficiency of production [81]. Such problems may limit the industrial applications of green synthesis. However, research and development to overcome such obstacles can make green synthesis methods more efficient and reliable.

7. Conclusions and Future Perspectives

Plant-based NP synthesis is emerging as a sustainable and environmentally friendly alternative for the control of PPNs. Through their metabolic activities, plants can produce metal and metal oxide NPs with antibacterial and antifungal properties. These nanoparticles provide an effective solution to PPNs by increasing plant resistance and improving soil health. Reducing the use of nematicides reduces environmental impact and enables more sustainable agricultural practices.

However, most applications of this technology are still at the experimental stage and critical issues such as the standardization of nanoparticle production processes, large-scale production and a full understanding of the environmental impacts remain to be addressed. Future research should focus on the optimization of NP production methods and a more detailed assessment of their environmental impact. In particular, the potential impact of nanoparticles on soil health and biodiversity should be further investigated.

Tailoring NPs to different agro-ecosystems and PPN species could increase the effectiveness of the solution. Future research should investigate the efficacy of NPs in different crops and soil types. It should also be investigated how they can be incorporated into Integrated Pest Management (IPM) strategies and how they can improve the effectiveness of these strategies.

In conclusion, plant-based NPs have great potential in the control of PPNs. However, for this technology to be applied in an efficient and environmentally friendly manner, nanoparticle synthesis methods need to be developed, production processes need to be scaled up and environmental impacts need to be fully assessed. Once these challenges are overcome, plant-based NPs could improve the resilience of agricultural systems by providing a sustainable, environmentally friendly and effective solution to control PPNs.

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Abbreviations

The following abbreviations are used in this manuscript:

PPNs	Plant-parasitic nematodes
RKNs	Root-knot nematodes
J2	Second-stage juveniles
NPs	Nanoparticles

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