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Unveiling the Future of Agriculture: Nanoparticles and Omics in Nematode Control

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Abstract: Plant parasitic nematodes (PPNs) are a significant menace to global agricultural productivity, inflicting substantial damage to various crops and vegetables. Root-knot nematodes (RKNs), a notable subgroup of PPNs, infest plant roots, inducing the formation of characteristic galls. While chemical interventions have historically been employed to manage RKN populations, their extensive adverse impacts on human health and the environment underscore the pressing need for alternative strategies. This review delineates a spectrum of control methods for RKNs, encompassing botanicals, fungal and bacterial agents, resistant plant cultivars, and green-synthesized nanoparticles. Notably, nanotechnology represents a burgeoning frontier of scientific research, offering vast potential across diverse domains, including insecticides, pharmaceuticals, electronics, and agriculture. Green-synthesized nanoparticles arising from this technological advancement hold particular promise for agricultural pest management. Furthermore, omics methodologies provide a comprehensive framework for elucidating the intricate biology of RKNs and their intricate interactions with host plants. By harnessing the power of emerging technologies, alongside a deeper understanding of nematode biology afforded by omics techniques, it is feasible to devise holistic strategies for the eradication of this pest.

Keywords: RKN; sustainable; *Meloidogyne*; galls; nanoparticles; omics.

1. Introduction

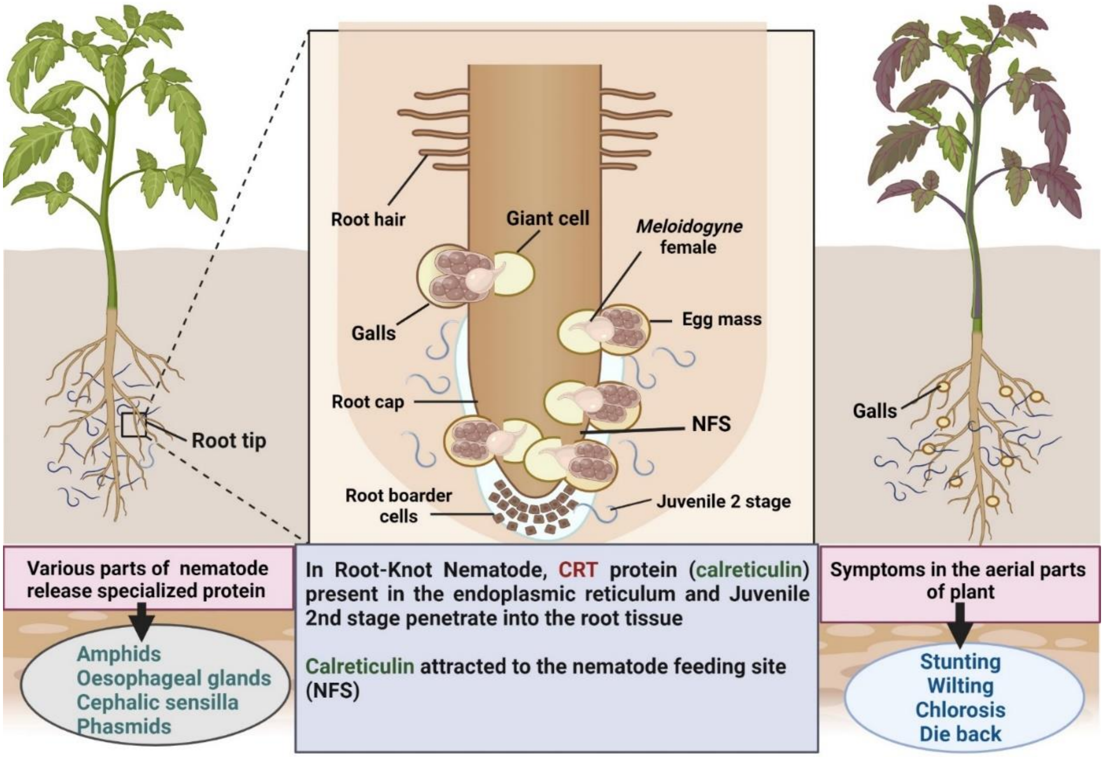
Plant diseases have been identified as a major cause of severe crop production losses worldwide, with serious implications for food security [1]. There are many types of plant-parasitic nematodes (PPNs) in conventional and organic agriculture that attack a variety of plants and are among the most critical and dangerous pests [2]. Approximately 173 billion dollars are lost each year due to PPNs, which damage crop yields and quality worldwide [3]. These PPNs are minuscule roundworms that inhabit soil or plant structures and consume plant tissues, leading to a substantial reduction in crop yield [4]. *Meloidogyne incognita*, *M. hapla*, *M. arenaria*, and *M. javanica* are major root-knot nematode (RKN) species that target a variety of crops [5]. RKN imposes a constraint on tomato cultivation, with its proliferation more pronounced in tropical environments [6]. Tropical conditions promote the rapid growth of RKN populations. Several biotic factors affect tomato production worldwide, including RKN. Tropical and subtropical regions of the world consume brinjal (Solanum melongena L.)

regularly [7]. There were relatively more losses in tomato (Rs. 6035.2 million) and brinjal (Rs. 3499.12 million) among the vegetable crops due to RKN [8]. One of the oldest and most important crops in the world is okra (*Abelmoschus esculentus* L. Moench). Okra plants with RKN suffer stunted growth and nutrient deficiencies [9]. A severe infestation can reduce yield by 10-50%, resulting in significant economic losses. By forming root galls and causing wilting, the RKN *Meloidogyne incognita* (*M. incognita*) poses a major threat to chili (*Capsicum annum*) cultivation [10]. Besides soil, root debris, and plants of the Solanaceae family, these nematodes have been found in other crops of this family as well. In Kenya, the common bean is the most widely grown grain legume, serving as the main protein source for the majority of small-scale farmers, and RKN is the main pest responsible for these losses [11]. *M. graminicola* is a major rice-parasitic nematode, especially in Southeast Asia, where almost 90% of the world's rice is cultivated [12]. In peanuts (legume or oil crop), RKN (*Meloidogyne* spp.) has been considered a limiting factor [13]. Guava (*Psidium guajava*) cultivation can indeed be affected by various species of root-knot nematodes, including different members of the *Meloidogyne* genus [14]. Guava is seriously challenged by PPNs. Globally, sweet potatoes rank seventh behind wheat, rice, maize, potato, barley, and cassava in terms of food production [15].

Among the RKN species, *M. incognita* and *M. enterolobii* (guava root-knot nematode) are the most destructive pests of sweet potatoes [16]. Most polyphagous pest species cause damage to cultivated woody plants like Prunus, grapevine, and coffee, but are mostly infested by RKNs [17]. As the sericulture industry developed, several pests and diseases emerged, including root-knot nematode disease, a major disease affecting Chinese mulberry plantations [18]. About 120 countries worldwide grow tobacco (Nicotiana tabacum L.) as an important economic crop and as a model plant for molecular research [19]. One of the most destructive pathogens affecting tobacco production is the RKN (*M. incognita*), which causes severe losses to the quality and productivity of tobacco plants [20]. RKN (*Meloidogyne* spp.) causes extensive damage to avocado (*Persea americana*), kiwi (*Actinidia chinensis*), fig (*Ficus carica*), papaya (*Carica papaya*), and pineapple (*Ananas comosus*) seedlings, as well as date palms (*Phoenix dactylifera*) [21].

2. Host-pest relation

RKN (*Meloidogyne* spp.) are obligate, sedentary nematodes that cause major crop losses worldwide. Juvenile 2nd stage (J2) hatch from host-plant roots exudates at the apex, primarily in the zone of differentiation and elongation [17]. RKN releases specialized proteins (effector) generated by various parts of the nematode (amphids, hypodermis, dorsal, and sub-ventral oesophageal glands) (Figure 1). There are many roles that effector molecules play in plant parasitism, including enzymes, peptides, metabolites, and biomolecules [22]. As part of complex molecular interactions between the nematode and the host plant, they invade root systems, suppress immune defenses, and sustain permanent feeding structures [23]. RKNs are engaged in intimate relationships with their host plants, involving complex morphological and physiological alterations of host cells into specialized cells called Giant cells [24]. Genes in RKN are responsible for generating proteins associated with parasitism, which are subsequently released by the nematodes and directly contribute to their ability to parasitize plants [25]. In order to break down the structural plant cell walls, nematodes release a mixture of enzymes that digest cell walls in order to weaken the cell walls [26]. Various enzymes involved in cell wall breakdown are calreticulin, cellulase, chorismate mutase, pectate lyase, polygalacturonase, and xylanase [27]. It is thought that several proteins participate in the induction and maintenance of nematode feeding site (NFS) expression in oesophageal glands by nematode secretory extensions of gland cells [28]. In addition to controlling the cell cycle, calreticulin, a protein found in *M incognita*, regulates cell signaling and metabolic pathways [29]. Proteomic analysis of the secretions from newly hatched *M. incognita* (Juvenile) has revealed the presence of Mi-CRT, a calreticulin protein [29]. As PPNs infect the plant, they activate a complex host defense response that regulates their growth and aggression. Oxylipins, lipid-based signaling molecules, play a crucial role in this intricate system, serving as essential regulators of both plant development and the immune response [30]. During invasion and migration, *Meloidogyne* secretes numerous effectors that support the construction and maintenance of feeding sites. In the plant's defense mechanism, oxylipins could be considered significant signaling molecules that form a crucial foundation for understanding nematode parasitism.



In Root-Knot Nematode, CRT protein (calreticulin) present in the endoplasmic reticulum and Juvenile 2nd stage penetrate into the root tissue

Calreticulin attracted to the nematode feeding site (NFS)

Figure 1. Root-knot Nematodes release specialized proteins (effectors) from amphids, hypodermis, and dorsal and sub-ventral oesophageal glands. The Calreticulin protein is attracted to the feeding site in the plant. RKN infection results in wilting, chlorosis, dieback, and stunting of plants. Created with BioRender.com.

3. Management control strategies of root-knot nematodes

Various control methods are used against RKN, including chemical, botanical, fungal, and bacterial controls. Biological control has been shown to be ineffective in most studies, making it unsuitable as a sole agent of pest control. As a result, integrating biological control with other methods could serve as an excellent model for nematode control and achieve the desired results in the long run (Figure 2).

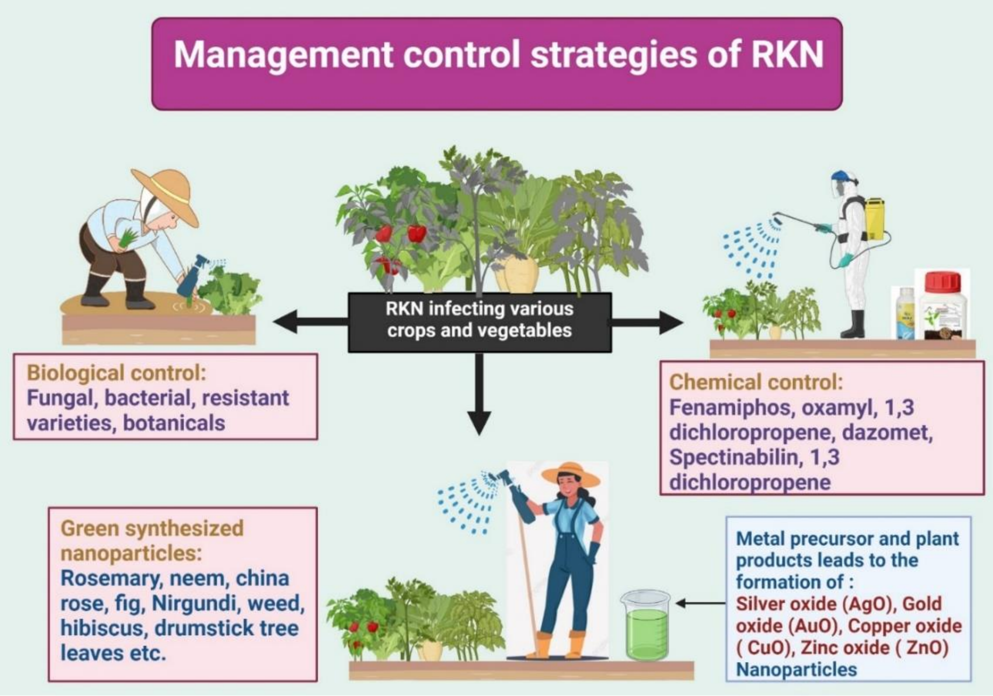


Figure 2. Management strategies of Root-Knot Nematodes are chemical control, biological control, and nanoparticle control. Biological control involves the use of fungal, bacterial, and resistant varieties. Chemical control involves the use of chemical pesticides like Dichloropropene. A new emerging control method is the use of metal-based green synthesized nanoparticles (AgO, AuO, CuO, ZnO), which can be used to control RKNs. Created with BioRender.com.

3.1. Chemical control of root-knot nematodes.

Chemical methods to prevent nematode infection involve applying various formulations to kill *Meloidogyne* species. Fenamiphos, oxamyl, 1,3-dichloropropene (1,3-D), dazomet, etc., are used as nematicides, but once the infection is already in plant tissue, these chemicals are incapable of controlling nematode populations [31]. Macrocyclic lactones, organophosphates, and carbamates are used for the prevention of RKN [32]. Chemical nematicide control is the most effective method, but due to safety and environmental concerns, these chemicals are being phased out [33]. The widespread use of pesticides in agriculture causes a slew of short- and long-term health issues. Every year, tens of thousands of individuals die as a result of their impacts. Pesticide use must be kept to a minimum in future agricultural practices. Meanwhile, pesticides that cause the most human harm and environmental disruption should be regulated [34]. In addition to being toxic to animals and humans, these chemicals disrupt the food chain and pollute the environment. Spectinabilin is a more effective nematicide than commonly used nematode drugs such as abamectin and phosphine thiazole [35]. It has been repeatedly noted that 1,3-dichloropropene (1,3-D) is one of the most effective fumigants and nematode nematicides, and that it positively affects crop yields [36]. The environmental concerns raised by synthetic nematicides have led to integrated management strategies that combine non-chemical control strategies, such as organic amendments and biocontrol agents.

3.2. Biological control of root-knot nematodes.

3.2.1. Fungal control of root-knot nematodes.

In nematode biology, chitin is present in the fungal wall and plays an imperative role. Nematophagous fungi are egg parasites that cause the embryo to become immobilized, leading to its death [37]. To control nematode spread, the biotic and abiotic properties of the soil are important factors that promote pathogen growth [37]. *Rhizobacteria* and *Trichoderma* can be excellent biocontrol agents [38]. Arbuscular mycorrhizal fungi (AMF) are obligate root symbionts mainly found in vascular plants. AMFs are mainly used as bio-fertilizers, capable of symbiotic interactions with 90% of crops [39]. Hydroxyapatite nanoparticles and mycorrhizal fungi inhibit nematode gall formation and growth. Nanoparticle-based formulations are now used as novel biofertilizers in agricultural practices due to their ease of absorption and deposition under stress conditions [40]. The entomopathogenic fungus *Metarhizium anisopliae* is also used for the control of RKN and insects [41]. The most prevalent fungal species associated with Meloidogyne suppression in sustainable vegetable production systems was Pochonia chlamydosporia [42]. *Bacillus velezensis* strain YS-AT-DS1 (isolated from tidal soil) enhanced tomato growth and significantly reduced the infection rate of juveniles of RKN [43]. *Trichoderma* and *Rhizobacteria* are excellent biocontrol agents. The biological and abiotic properties of soil are important factors in regulating nematode spread [44]. *Meloidogyne javanica*, a plant-parasitic nematode, was biocidal and killed by Lecanicillium sp. Scanning electron microscopy and proteomics techniques confirmed this [45]. Biological control of *M. javanica* by *Pasteuria penetrans* and *Trichoderma harzianum* on tomato plants results in a significant reduction in root gall index and number of eggs [46].

3.2.2. Bacterial control.

Paecilomyces lilacinus and *Verticillium chlamydosporium* control M. hapla by suppressing root gall formation, egg masses, egg hatching, and J2 of RKN [47]. *X. bovienii* bacterial supernatant shows a successful control level for *M. incognita* and *M. arenaria* [48]. *Pseudomonas* and *Bacillus* isolates, when interacting with the rhizosphere, were used in the management of RKN [49]. Various lactic acid bacteria strains (LAB) were used against the *Meloidogyne* species, in which *Lactobacillus brevis* WiKim0069 gives the best results against *M. incognita*, *M. arenaria*, and *M. hapla species* (inhibits the egg hatching) [50]. *Pseudomonas fluorescens* (increase plant growth, biocontrol, and adaptation to stress) controls *M. javanica* on tomato plants [51]. The kiwifruit vine harbored a diverse array of endophytic bacteria, including Bacillus, Pseudomonas, Chryseobacterium, Microbacterium, Pantoea, Streptomyces, Variovorax, and Exiguobacterium, with antagonistic activity against M. incognita, resulting in reduced numbers of galls and egg masses [52]. Antagonistic bacterial strain *B. arboris* J211 (isolated from rhizosphere soil) acts against the *M. incognita* nematode population both *in vitro* and *in vivo* [53]. *In vitro* studies of *Bacillus* isolates showed great results on the second juvenile stage of *M. enterolobii* [54]. Bacterial isolates also showed an effect on egg mass, J2 in soil, and plant growth parameters. *Pseudomonas fluorescens* inhibited *M. incognita* egg hatching [55]. *Bacillus subtilis* acts as a biocontrol agent against root knot nematode (*M. incognita*) [56].

3.2.3. Resistant crop varieties.

A variety resistant to Meloidogyne species has genes that confer resistance, reducing production costs and improving the environment [57]. Species identification and an effective surveillance strategy are necessary to produce resistant varieties. The cost of resistant genotypes will be higher, but it can be a better, eco-friendly technique [58]. Artificial inoculations and molecular markers linked to the Mi gene were used to screen 25 indeterminate tomato germplasm lines for resistance to root-knot nematode, *M. incognita* [59]. In general, resistant tomato plants with the Mi-1 gene and cowpea plants with the Rk gene suppress nematode reproduction and reduce root galling [60]. The *Coffea canephora* clones BRS 3210, C12, BRS 2299, BRS 2314, BRS 3137, and BRS 1216 were resistant to *M. incognita, indicating the potential for selecting* genotypes resistant to root nematodes in coffee breeding programs [61]. It is important to develop nematode-resistant varieties based on nematode-resistant germplasm. Two accessions of *Solanum incanum* (IC260115 and IC253963A) showed resistance against *M. incognita* [62].

3.2.4. Botanical control.

Effective botanicals increase the productivity of plants (crops) and reduce pests, nematodes, and various pathogens. Botanicals are less toxic than pure compounds, have the capacity to degrade, are derived from renewable sources, and are not harmful to the environment [63]. Coarsely grounded neem seeds control the root-knot nematode infestation in tobacco plants [64]. Neem-based treatments can be effectively used against nematodes [65]. *Cannabis sativa* and *Zanthoxylum alatum* can be used to control root-knot nematodes [64] successfully. The use of Lantana grass, Mexican poppy, and Ashwagandha controls root nematode infection in bottle gourd and also increases growth parameters [66]. *Parthenium argentatum* is a weed used in the control of *M. graminicola* species of nematodes [67]. Neem extract shows a high mortality rate, inhibits RKN colony growth, and can be directly applied to the juvenile stage of RKN [68]. *Phyllanthus amarus* and *Leucas cephalotes* inhibit egg hatching and result in the mortality of second-stage juveniles of *M. incognita* [69]. An annual or biennial herb, Datura is a poisonous flowering plant belonging to the Solanaceae family, as well as scopolamine and hyoscyamine. Atropine is among its structurally diverse alkaloids. In RKN management, Datura plays a significant role by affecting nematode egg hatching, larvae mortality, root galling, and promoting plant growth [70]. A study of *Thymus citriodorus* on *M incognita* and *M javanica* in soil micromes, as well as on free-living nematodes, showed a strong effect on their control [71]. Two nematicidal compounds (sesquiterpenoid acids, artemisinic acid, and dihydroartemisinic acid) extracted from *Artemisia annua* acted against the second juvenile stage of root-knot nematodes [72]. The antioxidant activity of buckwheat (*Fagopyrum esculentum* Moench) prevents root-knot nematode infection [73]. *M. Chitwood* can be controlled by aqueous *Solanum linnaeanum* extracts and *Solanum sisymbriifolium* containing nematicidal phytochemicals [74]. Asteraceae plant (*Carlina acaulis* L) produces an essential oil (EO) that is insecticidal and has a limited impact on aquatic and terrestrial organisms [75]. *Ipomoea carnea* was effective against root-knot nematode (M. incognita) infecting carrot, inhibiting egg hatching and improving carrot growth [76]. Various neem-based products are useful for nematode control [77].

4. Utilization of nanoparticles to control root-knot nematodes

Environmentally friendly and sustainable pest management methods have gained increasing interest in recent years [78]. Bio-insecticides have subsequently led to a resurgence of pests, increased resistance, and a decline in beneficial insects. Research has been redirected to develop an eco-friendly, sustainable control strategy due to adverse effects on the ecosystem, agricultural production, and human health. Researchers have recently shown interest in nanomaterials as nano-pesticides due to their useful characteristics, such as stiffness, crystalline nature, and high surface-to-volume ratio [79]. Researchers have synthesized various nanoparticles and reported their insecticidal properties [80]. There are nanomaterials that can stabilize soil and immobilize pesticides to reduce their movement and bioavailability, such as nanoclays [81]. The use of nanotechnology in agriculture is an emerging field with the potential to provide solutions to a range of agricultural issues [82]. In agriculture, nanotechnology is increasingly applied to enhance plant productivity, boost stress resistance, and minimize chemical inputs. Nonetheless, the unregulated release of nanoparticles into the environment raises concerns about potential toxic effects on plants. However, Nanotechnology safety is a major concern when applied in agriculture. These concerns are addressed through various safety measures like safer design, standardized tests, updated regulations, continuous research, and sustainable use of nanomaterials [83]. So, to avoid environmental pollution, the synthesis of nanoparticles via biological precursors has shown remarkable outcomes.

Two approaches have been used in the formation of nanoparticles: “top-down” and “bottom-up”. In the “top-down” approach, the bulk materials were converted into small particles with the use of various physical methods (ball milling, ultrasonic machine, laser ablation), and “bottom-up” approach involves the synthesis of nanoparticles using chemical (metal salt as a precursor) and biological methods (Figure 3) (a plant extract with metal salt precursor) [84]. Green synthesis of nanoparticles has been achieved using plant extracts. For example, *Eucalyptus oleosa* plant extract was prepared and mixed with metal precursor ($AgNO_3$ for silver oxide nanoparticles) [85]. Plant extract helped reduce silver ions and formed stable nanoparticles.

Silver nanoparticles synthesized from two algal species (*Colpomenia sinuosa* and *Corallina mediterranea*) can be used as an alternative to chemical nematicides [86]. Green-synthesized silver nanoparticles from Senna siamea were tested against Meloidogyne incognita, and the results revealed that these AgONPs could be an efficient, safe, cost-effective, and affordable nematicide [87]. The first report of green-synthesized nanoparticles from Acalypha wilkesiana against root-knot nematode (Meloidogyne incognita) showed strong nematicidal activity [3]. Biologically synthesized silver nanoparticles obtained from Moringa oleifera leaf extract treatment reduced the juvenile population in the soil, the number of galls, and the egg masses of *M. incognita* [88]. Silver nanoparticles synthesized from *Conyza dioscoridis*, *Melia azedarach*, and *Moringa oleifera* show great activity against *Meloidogyne incognita* [89]. *In vivo*, the study of *Euphorbia tirucalli*, which synthesized silver oxide nanoparticles on tomato plants, used the root-dip method, resulting in healthier growth parameters and a reduced juvenile population of RKN [90].

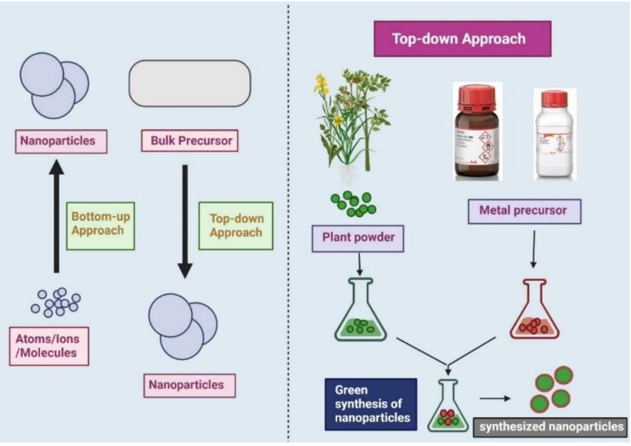


Figure 3. In the bottom-up approach, small atoms /ions aggregate to form nanoparticles. A top-down approach is used, in which large materials break down into nanoscale particles. For the green synthesis of nanoparticles, metal precursor and stabilizing agent (plant products) were used. Created with BioRender.com.

Lower concentration and short-term exposure to green-synthesized silver oxide nanoparticles (Glycyrrhiza glabra) assess their nematicidal potential against *Meloidogyne incognita* [91]. The GC-MS analysis of AgONPs revealed that certain metabolites have increased. Copper oxide nanoparticles were shown to have antagonistic actions on *M. incognita* synthesized with the help of *Jatropha curcas* leaf [92]. *In vitro* and *in vivo* studies of silver boron nanoparticles showed anti-nematode activity against RKN. Sulfur nanoparticles from *Rosmarinus officinalis* leaf extract showed a cytotoxic effect on the J2 stage and egg hatching of *M. javanica* [93]. In the future, sulfur nanoparticles are expected to have broader applications in agriculture for controlling nematode infestations in many crops. Silver nanoparticles synthesized from *Ficus sycomorus* could be a better recommendation for the management of PPNs [94]. Various nanomaterials (silver, zinc, copper, titanium, gold, etc.) are also used in arthropod pest management [79]. Green-synthesized nanoparticles are the best alternative for controlling nematodes because they have specific properties, such as small size, large surface area, high chemical reactivity, and electrical conductivity [92]. All green-synthesized nanoparticles used against RKN are listed in Table 1.

Table 1. Green synthesized nanoparticles used against root-knot nematodes.

S.No.	Plants	Plant parts	Nanoparticles	References
1	*Utrica urens*	Leaves	Silver	[95]
2	*Artemisia Judaica*	Leaves	Silver	[96]
3	*Conyza dioscordis, Melia azedarach* and *Moringa oleifera*	Shoots	Silver	[89]
4	*Zingiber officinale*	Rhizomes	Silver	[97]
5	*Euphorbia tirucalli*	Stems	Silver	[98]
6	*Cnidoscolus aconitifolius*	Leaves	Silver	[99]
7	*Acalypha wilkesiana*	Leaves	Silver	[3]
8	*Lantana camara* and *Lonyza dioscordis*	Leaves	Silver	[100]
9	*Jatropha curcas*	Leaves	Copper	[92]
10	*Colpomenia samosa* and *Corallina mediterranea*	Algal extract	Silver	[101]

5. Omics approaches

Omics technologies provide a comprehensive understanding of pests' biological systems and their interactions with the environment [102,103]. The study of root-knot nematode (RKN) species can significantly benefit from omics technologies, such as genomics, transcriptomics, proteomics, and metabolomics. These techniques uncover how nanoparticles interact with biomolecules, influencing cell function, communication, and adaptation to environmental changes [104,105] (Figure 4). During RKN parasitism, various morphophysiological and molecular events occur, and these omics approaches will provide valuable insights into the mutually beneficial interactions between plants and nematodes [106]. In nanotoxicology, Omics data, while closely related to living systems, often lack comprehensiveness [107]. The economic study of applied nanoparticles explores the various impacts on the entire biological system of plants [108]. Only a few articles focused on the effects of nanoparticles on host-pest interactions. A review examines the interactions of silicon nanoparticles (SiNPs) from an omics perspective, aiming to encourage dialogue within the silicon research community about their potential role in plant physiology, particularly given the existing uncertainties in this area [109]. In the future, omics studies of nematode anatomy will reveal which proteins are targeted by nanomaterials.

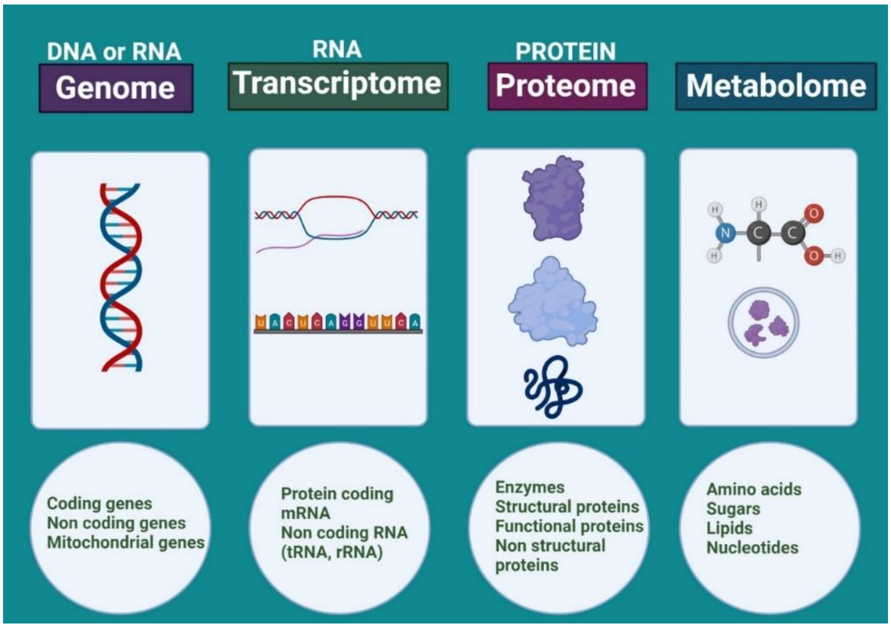


Figure 4. Depicting omics-driven strategies. Genomics: DNA/RNA and various important genes, including coding, non-coding, and mitochondrial genes, can be identified by this technique. Transcriptomics is used to predict genes and their expression levels. Proteomics is used to identify proteins that may be structural, non-structural, or functional. Metabolomics: deals with metabolic compounds such as amino acids, sugars, lipids, and nucleotides. Created with BioRender.com.

5.1. Transcriptomics.

Gene transcription and defense responses to various environmental stresses are dependent on transcription factors. Under nematode infection, the molecular basis of its interaction with *M. incognita* prompted us to perform a comparative transcriptome analysis [110]. During nematode parasitism, RKN-sensitive and resistant sweet potato cultivars differ in their expression of important functional genes [111]. There are several candidate genes, including hormone-signaling-related transcription factors and pathogenesis-related genes, that may contribute to protecting sweet potato roots against RKN infection. *M. enterolobii* (mulberry RKN), resulting in strong virulence, transcriptome sequencing technology is used for understanding the interactions between resistant and susceptible mulberry varieties [18].

Plant hormone (Auxin) has been reported in the early development of nematode-feeding sites [112]. The abnormal development of giant cells is hindered by low auxin and cell cycle expression levels, as well as by high levels of cell wall proteins, which impede the development of *M. incognita* [113]. Only a limited number of plants exhibit resistance to *M. incognita*. There has been a shortage of research dedicated to identifying the essential resistance genes. Consequently, advancements in the development of *M.* incognita-resistant plant varieties have not been as substantial as desired [114]. Depending on the pathosystem, zinc (Zn) accumulation and deficiency affect pest and disease responses differently. Plants with high Zn concentrations help trigger defense signaling pathways and enhance structural defenses. Transcriptomics data resources suggest a molecular potential framework for Zn-interaction in RKN [115]. Researchers have used various approaches to study transcriptomic changes during host–RKN interactions, including RNA blotting, differential cDNA library screening, EST sequencing, microarrays, and, more recently, NGS [116]. Addressing the challenges posed by M. incognita resistance in crops requires a multidisciplinary approach that integrates genetics, plant breeding, and agronomic practices to develop more resistant varieties and sustainable nematode management strategies.

5.2. Proteomics.

The interaction at the molecular level between PPNs and their host begins at a distance, initiated by changes in the surface of infective J2 in response to compounds released by plant roots. The proteomics approach was used to determine the amino acid sequences of those antigens, which showed similarity to several proteins, including signal recognition particle protein (galactose-binding lectin, zinc finger motif, neurotransmitter-gated ion channel, and transmembrane protein), in the nematode genomic database [117]. *M incognita* and *M. graminicola* (J2) whole-body homogenates showed cross-reactivity with polyclonal and monoclonal antibodies raised against several nematode species [118]. The functions of the identified nematode genes can be determined by RNA interference and by assessing their importance for nematode survival, development, or parasitism. In the breeding program to develop root-knot-resistant tomato varieties, these proteins may be promising candidates for identifying resistant genotypes against the root-knot nematode [119]. For quantitative differential proteomics studies, stable isotopes have been metabolically incorporated into a variety of systems using isotopically enriched growth media [120]. Proteomics research in labs primarily focuses on understanding the interactions between plants and parasitic RKN (*Meloidogyne* spp.) [121]. PPNs communicate with plants through proteins secreted through their styles. Soluble proteins from oesophageal gland cells of female *M. incognita* and their proteomic analysis reveal the functions of these proteins [122].

5.3. Metabolomics.

Using metabolomics, breeders can identify biochemical markers that play an important role in determining plant resistance to pests and diseases [123]. The resistance of plants to various pathogens produces several biologically active chemicals and secondary metabolites. Peroxidases contribute to tomato plant resistance by producing toxins and inhibiting nematode development [124]. A tomato plant that is resistant to nematode attack produces a variety of biochemical compounds that are associated with nematode defense mechanisms. Plant development programs can use these metabolites to identify candidate traits. Root and leaf showed similar metabolites that are important for nematode resistance, namely, glucosamine and caffeic acid [125]. Metabolites associated with tomato plants' defense mechanisms against nematodes are not only produced locally in the infected area but also throughout the plant's non-infected tissues.

The nematodes are capable of regulating the expression of genes that control metabolite synthesis. Genes involved in high metabolic activity, such as sucrose transporters, starch synthases, myo-inositol oxygenases, myo-inositol phosphate oxygenases, and sucrose UDP-glucose dehydrogenases (UGDs), were upregulated [126]. Plant-nematode interactions can be inferred from comprehensive metabolic profiling of nematode-infected plants.

6. Conclusion

RKN are difficult to control and manage due to their polyphagous nature. An integrated management approach must be promoted that combines various control strategies for local RKN problems with local agricultural practices. Nanotechnology is an emerging field, and hence green-synthesized nanoparticles may prove to be the safest and most eco-friendly method to combat the damage caused by RKN. There are, however, still some studies to be done to isolate specific secondary metabolites and produce them in a nanoform that is safe, effective, environmentally friendly, and has low side effects in mammals. More studies are needed on the nematode's feeding sites and the molecular mechanism of feeding. Also, it is likely that molecular control of nematodes will ultimately be better integrated with other pest management measures, such as omics studies, to maximize crop production in the future. Omics approaches hold immense promise for the future of nematode control by providing a deeper understanding of nematode biology and offering innovative, sustainable, and targeted solutions to mitigate their impact on agriculture. The adoption of innovative strategies like omics and nanosciences can contribute to sustainable agriculture by mitigating the impact of Root-knot nematodes and promoting long-term food security.

Author Contributions

Conceptualization, S.K.; methodology, S.K. and K.C.; validation, D.S. and K.T.; formal analysis, A.R., K.R. P.K., and J.Y.; investigations, K.C., R.K., and D.S.; writing original draft preparation, K.C.; writing review and editing, S.K. and D.S. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

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Conflicts of Interest

The authors declare that they have no conflict of interest.

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