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Eco-friendly management of root-knot nematodes (*Meloidogyne* spp.): biological and botanical control strategies

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Abstract: *Root-knot nematodes (RKNs, Meloidogyne spp.) are major agricultural pests, infecting over 5,000 plant species and causing significant economic damage by forming galls and interfering with nutrient flow. Due to the environmental and health risks associated with chemical nematicides, there is an increasing demand for environmentally sound management measures. This review explores sustainable alternatives, focusing on biological and botanical control strategies. Biological control utilizes natural antagonists such as bacteria (Bacillus, Pseudomonas, Pasteuria penetrans) and fungi (Trichoderma, Purpureocillium lilacinum), which suppress nematodes through mechanisms like direct killing, parasitism, and inducing plant resistance. These agents not only regulate RKN populations but also promote plant growth and systemic resistance, supporting a safer agro-ecosystem. Botanical* *control involves using plant-derived nematicides like neem seed cake and extracts from plants such as Melia azedarach and Brassica macrocarpa. Key bioactive metabolites, including alkaloids, terpenoids, and phenolics, contribute to nematode control by exhibiting direct nematicidal activity and bolstering plant defense reactions. Essential oils and allelopathic cover crops are also highlighted as eco-friendly tactics. The integration of biological and botanical methods, often combined with organic amendments and crop rotation, offers a holistic and multi-faceted approach to nematode management, aiming for increased efficacy, reduced chemical reliance, and prolonged agricultural sustainability. Despite the potential, constraints like variability in field efficacy, economic barriers, and the complexity of developing resistant cultivars limit widespread adoption. Future directions include the application of omics technologies and nanotechnology to support sustainable management.*

Keywords *Root-knot nematodes (Meloidogyne spp.), Biological control, Botanical control, Biocontrol agents, Bacillus, Trichoderma, Neem, Allelopathy, Integrated Pest Management (IPM), Sustainable agriculture.*

1. Introduction

Root-knot nematodes Meloidogyne spp., being a genus of the family Heteroderidae, is one of the most economically important agricultural pests, infecting more than 5,000 plant species and resulting in considerable economic damage worldwide (Youssef Banora, 2024). Their effect is particularly strong because they can invade plant roots, resulting in the formation of galls and interference with the nutrient flow thus reducing the yield and quality of the host plants. The demand for environmentally sound management measures has become more pressing due to the negative effects linked to chemical nematicides. (A. Khan et al., 2023; Mondal et al., 2021). Although these chemicals are functional to control nematodes, they involve large-scale risk on the environment, humans, and non-target soil organisms. Environmental friendly measures, including the application of biocontrol agents or natural products could provide a sustainable solution to populations that can regulate a nematode population without adverse effects (Sharma et al., 2018).

Biocontrol tactics rely on natural inhibitors, such as fungi and bacteria, to inhibit nematode activity. Fungi are use various baiting-trapping devices to catch and kill nematodes, while the formation of antibiotic compounds which prevent development of the nematodes occurs in some bacteria (A. Khan et al., 2023). Plant-derived nematicides including that of Melia azedarach and Brassica macrocarpa have been proven effective toward nematode suppression and can stimulate soil biological activity, thereby promoting plant growth without the harm associated with chemical candidates (Argento et al., 2019; N. Ntalli et al., 2017). Also, environmentally friendly management strategies also contribute to lowering nematode populations and lessening stress to crops like rice without harming the environment (Mondal et al., 2021). These practices are consistent with the aims of sustainable agriculture to minimize chemical inputs, support healthier crops and maintain ecological balance (Shang et al., 2024).

2. Biological Control

Bacteria such as Bacillus, Pseudomonas and Pasteuria penetrans are beneficial antagonists of root knot nematodes which are phyto-pathogenic to several crops. Bacillus spp have been proved, as effective from various points of view. They secrete nematicidal compounds, which can directly kill or paralyse the nematodes. Moreover, Bacillus spp. induce resistance in plants, thus making the same resistant to nematode attack. They can also degrade the nematode cuticle, thus preventing infections by nematodes Vasantha-Srinivasan et al., 2025; Zuckerman et al., 1993). Various Bacillus such as B. halotolerans, B. kochii and B. oceanisediminis from different works presented great nematicidal capacity, even for greenhouse and in field that are the main attraction sites to control the population of nematode by increasing the crop yield (Liu et al., 2020). Bacterium buthingiemSs has also been found to greatly alleviate the root-knot nematode-caused plant damage in a broad spectrum of crops (Zuckerman et al., 1993).

Pseudomonas, including P. aeruginosa were also found to be effective biocontrol agents of Meloidogyne (root-knot nematode). They operate in a mode similar to that of Bacillus, generating chemicals that are harmful to nematodes and induce plants immune response toward these pests (Liu et al., 2020). Pasteuria penetrans is a facultative parasite with root-knot nematodes and it is famous for its role in reducing nematode population densities by limiting their fecundity. The spores of P. penetrans adhere to the nematode cuticle and grow in its body, then kill and reduce the populations of it. Because this bacterium can reduce nematode populations when present in the soil or applied at high levels, it may also decrease root damage and improve plant health. Nevertheless, the mass production and application of P. penetrans is difficult because of its intricate life cycle and obligatory parasitism (Bhuiyan et al., 2017; Charles et al., 2005; Phani et al., 2017).

Both *Trichoderma* and *Purpureocillium lilacinum* may be good in the fight against nematodes, as they apparently exert multiple effects on these devious little pests, helping to guard valuable crops. Trichoderma genuses is the good bio-control agents that use several different mechanisms to prevent nematodes. These fungi are able to parasitize nematodes through direct attachment and penetration of their body with lytic enzymes (Poveda et al., 2020). They also secrete nematicidal secondary metabolites that suppress nematode growth and development. Also, Trichoderma increases the plant resistance to nematodes by stimulating systemic resistance in the plant. This is done through activation of hormonal defense pathways such as those regulated by salicylic and jasmonic acids resulting into reinforcement of the plant's innate immune response to nematode assault (Yao et al., 2023).

Purpureocillium lilacinum (previously Paecilomyces lilacinus) has the ability to infect nematodes, especially in the stationary phase, like eggs or juveniles. It does so by using it to penetrate the nematode's cuticle, enabling the fungus to interfere with the life cycle2 of the nematodes and thereby reduce their number in soil (A. Khan et al., 2006). This direct parasitic action is coupled with the synthesis of nematicidal toxins which inhibit nematode growth and decrease their capacity to damage their host plant (Morton et al., 2004). Both fungi also promote overall environmental integrity of agricultural systems by circumventing dependence on chemical nematicides, many of which carry environmental hazards and health risks. For example, Trichoderma can serve as a natural nematicide and also increases plant growth and nutrient efficiency, so it is used to engineer for sustainable agriculture (Pinto et al., 2024). Likewise, Purpureocillium lilacinum is used as an ecofriendly and cost-effective choice to control nematodes populations that are in line with the practices of integrated pest management for preserving of ecological balance and soil health (Moosavi & Zare, 2020).

The diversity of direct parasitism and induced plant resistance by the fungi underline their potential biocontrol efficiency as providing sustainable means to control nematodes and support overall resilience in agricultural ecosystems (Sikora et al., 2007; Topalović et al., 2020). Endophytes, PGPR and mycorrhizae prime plant resistance against root-knot nematodes by different mechanisms, which activate the host for more extensive defense in biological control situations. Endophyte that invades plant internal tissues employs a combination of mechanisms to defend plants from nematode. These fungi are involved in plant health through favoring some interactions and inhibiting others. They signal to the plant as a resistance through gene expression, metabolism of fungi derived metabolite compounds, and hormone signaling molecules (Siddiqui 2005). Endophytic fungi can synthesize secondary metabolites and enzymes which induce the plant defense pathways such as antibiosis response leading to reducing pathogenic nematodes activity (Poveda et al., 2020).

PGPR are well characterized for their ability to influence plant growth and serve as biocontrol agents against a variety of pathogens such as nematodes. They stimulate plant growth and immunity via hormones, nutrient uptake, and changes in the native microbial community to a more favorable microflora. (Kong et al., 2022). PGPR trigger the systemic resistance in plants and are thus armoring them against nematodes. They act indirectly by activating an immune response of the roots and promoting microbial communities antagonistic to nematode populations (Siddiqui, 2005). Mycorrhizal fungi, namely arbuscular mycorrhizal fungi (AMF), are mutualistic symbionts of plant roots and play a role in defending plants against nematodes. AMF increase resource aprovechamiento, such as nutrient and water uptake making the plant's health more robust and resistant. They also induce systemic resistance by also eliciting plant defense mechanisms and possibly generating diverse metabolites that inhibit the growth of pathogens (including nematodes) directly or indirectly (M. Singh et al., 2024). Moreover, AMF can associate other beneficial soil microorganisms and increase the biocontrol activity (Siddiqui 2005). As a representative of beneficial fungi, species from the genus Trichoderma induce plant immune responses i.e. induced systemic resistance (ISR), which enhance nematode resistance as well as defense against other pathogens in plants. The production of enzymes and secondary metabolites by the fungi lead to the breakdown of nematode structures and are highly competitive with nematodes for space and resources (Al-Ani, 2018).

Table 2.1 Biological Control Agents and Mechanisms

Agent Category	**Specific Examples**	**Mechanism of Action**
Bacteria	*Bacillus* spp. (*B. halotolerans*, *B. kochii*, *B.*	Secrete nematicidal compounds; degrade the nematode cuticle; induce

	oceanisediminis), *Pseudomonas* spp., *Pasteuria penetrans*	plant resistance (ISR); *P. penetrans* spores adhere to and parasitize the nematode body, reducing fecundity
Fungi	*Trichoderma* spp., *Purpureocillium lilacinum* (formerly *Paecilomyces lilacinus*)	Parasitize nematodes (direct attachment and penetration with lytic enzymes); secrete nematicidal secondary metabolites; stimulate plant systemic resistance by activating hormonal defense pathways (salicylic and jasmonic acids)
Associated Microorganisms	Endophytes, Plant Growth-Promoting Rhizobacteria (**PGPR**), Arbuscular Mycorrhizal Fungi (**AMF**)	Induce plant resistance (e.g., antibiosis, systemic resistance); synthesize secondary metabolites; promote plant growth and nutrient uptake, leading to greater plant health and resilience

3. Botanical Control

Neem seed cake with sesame oil are effective in the management of root-knot nematodes (Meloidogyne spp.). In an experiment, neem seed cake and sesame oil-based biostimulants applied to soil treated significantly decreased nematode eggs and galls in root of tomato plants. They also enhanced the growth of tomato vs. untreated controls (D'Addabbo et al., 2019). Neem is a well-recognized botanical nematicide that can be included in sustainable management programs for nematodes, with potential for use in organic and integrated crop management. Essential oils and allelopathic cover crops are fundamental in botanical pest control tactics, representing more environmentally friendly than synthetic pesticides applied for the management of agricultural pests (Baker et al., 2022). Essential oils are extracts derived from plants, traditionally known for powerful insecticidal activity. They are known for their bioinsecticide properties which are safe for the environment and low risk to humans and non-target organisms. EOs, such as neem ones, exert pest control effects by acting as repellents and growth regulators (Devrnja et al., 2022). Neem, for instance, is known for the bioactive substance azadirachtin offering antiviral, antiseptic and insect-repelling effects. These properties also make neem a plant of great importance in sustainable agriculture, lessening dependency on synthetic pesticides (Perveen, 2024). However, problems of rapid loss and differences in performance depending on the geographical location need to be overcome to broaden the use of botanical pesticides (Damalas & Koutroubas, 2020).

Allelopathic Cover Crops Allelopathy is the biological phenomenon when plants produce chemicals that are capable of affecting other organisms by inhibiting them from growing, surviving, or reproducing. (Sturm et al., 2018). Allelopathic cover crops are also sown to deal with weeds, insects and plant diseases in the most natural way possible. These plants release allelochemicals that suppress the growth potential competitors in their soil, including weeds. In this way, they offer an eco-friendly approach for pest control without causing the adverse effects on ecology from synthetic herbicides (Farooq et al., 2011). Furthermore, the use of allelopathic cover crops can improve integrated weed management programs and reduce the selection pressure towards herbicide resistant weeds (Scavo & Mauromicale, 2020). Both essential oils and allelopathic cover crops are elements of integrated pest management (IPM) and organic farming, which enhance biodiversity and sustainable agriculture while maintaining crop yield or environmental health. They are considered potential approaches to improve natural pest control and to reduce the reliance on synthetic chemical pesticides (Opender Koul & Suresh Walia, 2009; Reiff et al., 2021). Despite these advances, regulatory provisions and necessity for standardization and quality control are obstacles that limit the application of such botanicals in pest management practices (Damalas & Koutroubas, 2020).

Table 3.1 Botanical Control Strategies and Bioactive Metabolites

Strategy/Source	Key Component	Mode of Action/Significance
Plant-Derived Products	Neem seed cake, Sesame oil, *Melia azedarach*, *Brassica macrocarpa*	Decrease nematode eggs and galls; enhance plant growth; offer nematicidal and insect-repelling effects (azadirachtin from Neem)

Essential Oils (EOs)	Carvacrol, Thymol, Nerolidol	Act as repellents and growth regulators; exhibit potent, often dose-dependent, nematicidal activity; environmentally safe
Allelopathic Cover Crops	Allelochemicals	Release chemicals that suppress competing organisms like weeds and nematodes; disrupt the growth, survival, or reproduction of pests
Key Metabolites	**Alkaloids** (from *W. indica*), **Terpenoids** (Monoterpenoids, Sesquiterpenoids), **Phenolics**	Exhibit non-specific toxicity; strong nematocidal activities; induced in plants upon pathogenesis to suppress pathogen growth and provide defense

Alkaloids, terpenoids and phenolics are bioactive metabolites that contribute to the botanical control of nematodes, providing environmentally friendly alternatives to chemical nematicides. These metabolites have varied modes of action to fight against nematode infections and protect the plant. (Desmedt et al 2020). Alkaloids, including those containing nitrogen, are a mechanism used by the plant to combat nematodes and other pests. They serve as reservoirs of nitrogen and have non-specific toxicity that may make them unpalatable to predators (Ali et al., 2019). There are some sort of alkaloids that have strong nematocidal activities, and include those extracted from W. indica for use in pot as well as field studies (Jang et al., 2019). Their pharmacological actions, which are typically used in medicine also demonstrate their efficacy in pathogen resistance (Awuchi, 2019).

Monoterpenoids and sesquiterpenoids, including terpenoids, are well-recognized potent phytochemicals with proven nematicidal activity. Compounds such as carvacrol, thymol and nerolidol have powerful nematicidal activity that frequently involves dose-dependent responses (Abdel-Rahman et al., 2013). They are key constituents of the essential oils of many plants exhibiting higher nematicidal properties; so, it may be used as natural nematicide (Awuchi, 2019). Phenolics are also a major group of secondary metabolites involved in the defense reactions of plants. These are generally induced in case of pathogenesis and impart resistance against nematode attack. Such compounds can suppress the growth of pathogens and are widely used in plant defense mechanisms (Ohri & Pannu, 2010). Phenolic compounds contribute to the maintenance of plant health through their antioxidative activity and have ethnomedicinal relevance (Shoker, 2020). Significance of these findings: Alkaloids, terpenoids and phenolics play a pivotal role in the defense mechanism of plants and provide an environmentally safe mean to check nematode population causing minimal hazard due to reduction in the use of chemical nematicides and ensuring sustainability in agricultural production (Chitwood, 2002).

4. Integrated Approaches

Integrating biological and botanical nematode control offers a holistic and environmentally benign pest management strategy by harnessing the benefits of both to develop more sustainable pest management systems. Biological control employs living organisms such as fungi or bacteria that are natural enemies of nematodes. These biocontrol agents may be able to control nematodes by different actions, including trapping, enzyme production, nutrient competition and induction of systemic resistance in host plants (Bhat et al., 2023; Moosavi & Zare, 2020; Thoden et al., 2011). In contrast, botanical control is the use of plant-based substances and work as natural pesticides with less risk for human health and environment in compare to chemical pesticides (Damalas & Koutroubas 2020). Combining these methods may extend nematode management by providing a multi-faceted protection system, decreasing reliance on chemical nematicides and prolonging agricultural sustainability via maintaining soil fertility and mitigating loss of biodiversity (Abd-Elgawad & Askary, 2018). A combination of biocontrol agents based on fungi and bacteria are often compatible with organic amendments and may be used with botanical pesticides to act synergistically in improving efficacy (Damalas & Koutroubas, 2020; Rosskopf et al., 2020). This mixture can enable the use of bioactive compounds from plants to migrate soil in a manner that is conducive for costimulating biocontrol organisms and the consequent suppression of nematode populations (Damalas & Koutroubas, 2020).

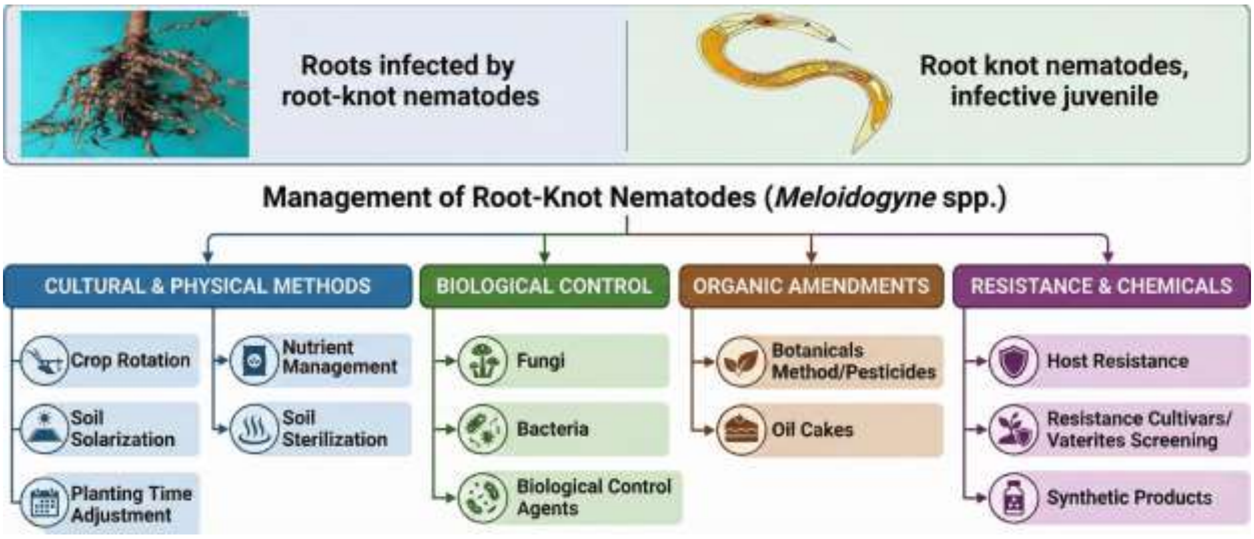
Organic amendments and crop rotation play a critical role in supporting integrated eco-friendly management. Firstly, organic amendments are essential components of an integrated nematode management approach that improves soil health and resilience. (Devi et al., 2020). For instance, different composts or green manures have been linked to improved soil quality and changes in soil microbial community composition, and reduced populations of plant-parasitic nematodes. (Tóthné Bogdányi et al., 2021). Due to their potential, organic amendments have the capacity to support the growth of non-pathogenic nematodes or other non-nematode pathogenic organisms, which lowers the environment's susceptibility to plant-parasitic nematodes and increases crop production. Concerning plant parasites, crop rotations, especially those with non-host or resistant cultivars, disrupt the nematode's lifecycle since they cannot locate its indigenous hosts. (Lopes et al., 2019). The strategy is expected to decrease nematode pressure and reduce soil pathogen populations in the long run, contributing to adequate field fertility and cultivation. When combined with organic amendments, plant nutrition can be used to improve soil composition by increasing microbial diversity and the prevalence and functions of beneficial fungi and bacteria. (Lopes et al., 2029). Although integrated management systems may offer a long-term solution to root-knot nematodes, it is not yet evident whether they can adequately suppress the primary factors responsible for the infections. Although I cannot provide the full paper, I hope this brief summary will still be beneficial. (Sikora et al., 2023).

From the field perspective, widespread application of ecofriendly RKN management strategies is restricted by various constraints. A key difficulty lies in ensuring successful implementation of biological control agents in current agricultural systems. Biological control, though effective has a variable persistence in the field because control of nematodes by living organisms (viz., fungi and bacteria) are antagonistic to them and must be actively managed, including favorable environmental conditions as well as knowledge-intensive application scenarios for effectiveness (Bhat et al., 2023; A. Khan et al., 2023).

Environmental factors including soil type, temperature and moisture content that can influence the efficiency of biocontrol agents are a further obstacle. Such variation can give non uniform control results and standardization between different agricultural surroundings is an arduous task (Vashisth et al., 2024). There are substantial economic barriers as well. However, green tactics such as biocontrol provide a long-term sustainable strategy though they are usually expensive up front and more technically challenging than chemical nematicides. The transitional costs, and potential perception of complexity, establishing these new activities can deter farmers from adopting them, in the abscence of support/input incentives (N. G. Ntalli & Caboni, 2012).

Finally, one of the problems is the complexity related with the technical and scientific part for obtaining plant resistance. Molecular breeding of resistant cultivars is a difficult task which is lagging behind to incorporate and durability in resistance against RKNs. The absence of strong-resistant cultivars is a major barrier to the clear deployment at large scale of non-chemical strategies (Kaloshian & Teixeira, 2019). Finally, the presence of soil pest such as RKN can exacerbate efforts to manage a disease due to their varied means of survival and capacity to develop into a disease complex with other pathogens. It requires eco-friendly as well as threshold-based control technologies including IPM, which is still an active research & development focus (Vasantha-Srinivasan et al., 2025; Vashisth et al., 2024). To apply environmentally friendly production techniques across all industries, standardization, formulation improvements and new technologies such as omics and nanotechnology have high potential. In this article, we consider how these latter approaches provide support for sustainable management. (Majumdar et al., 2021).

Figure 4.1 Integrated Management Strategies for Root-Knot Nematodes (*Meloidogyne spp.*)



Conclusion

The environmentally friendly biological and botanical methods are sustainable options for controlling root-knot nematodes because of their implications in sustainable agriculture and environment. Biological control using antagonistic microorganisms like bacteria, and fungi has proven to be an efficient tool in the management of RKN (Azeem et al., 2020). These biocontrol agents not only regulate the parasitic nematodes but also promote plant growth and trigger systemic resistance against a wide range of biotic stresses. This thereby facilitates a safer agro-ecosystem at the cost of the absence of a collateral damage to non-target organisms and maintaining microbial diversity and nutrient cycling (Bhat et al., 2023; Vasantha-Srinivasan et al., 2025).

Botanical tactics are those implemented by plant-derived compounds which are naturally part of plant-environment interface. These compounds are Nematode management options that can be included in pest mgmt programs. They are considered as sustainable because they have been evolved in biodiversity-rich areas, Mediterranean Basin, one of the richest nematicidal botanicals additionally, botanical alternatives are not toxic like the synthesis nematicides therefore they can be a viable option for environment friendly agriculture (Dsouza et al., 2025). Moreover, application of microbial antagonists such Bacillus spp., Trichoderma spp., provides good control against nematode along with plant health. Bacillus sp., nematicidal compounds, induces systemic resistance in host plants and contributes to soil health through increasing microbial diversity. For example, Trichoderma citrinoviride not only decreases nematode numbers but also enhances plant growth, making it an excellent candidate for sustainable and organic crop production (Vasantha-Srinivasan et al., 2025).

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