



Controlling Root-knot Nematodes (*Meloidogyne* spp.) using Garlic and Neem Extracts: A Review

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ABSTRACT

Root-knot nematodes (RKNs) are among the most significant causes of economic losses in many crops. Given the environmental and health risks associated with chemical nematicides, plant extracts have emerged as safe and sustainable alternatives. This review examines the efficacy of garlic (*Allium sativum*) and neem (*Azadirachta indica*) extracts in controlling root-knot nematodes. Studies have shown that allicin in garlic and azadirachtin in neem possess effective nematicidal effects by inhibiting egg hatching, increasing larval mortality and reducing root penetration and reproduction. The results also showed that these extracts reduce nematode populations and root-knot formation and improve plant growth and productivity under laboratory and field conditions. Available evidence suggests that garlic and neem represent promising, environmentally friendly alternatives that can be integrated into integrated management programs for root-knot nematodes.

Key words: Allicin, *Allium sativum*, *Azadirachta indica*, Azadirachtin, Botanical nematicides, *Meloidogyne* spp., Root-knot nematodes.

Root-knot nematodes are serious plant pathogens that cause considerable economic losses by inducing root gall development, altering the plant's vascular system and extracting essential nutrients from the plant host. The extreme damage caused by these persistent plant parasites can lead to stunted growth, reduced yield, wilting, root deformation, leaf discoloration and deterioration in quality (even to the point of complete crop loss). Root-knot nematode (*Meloidogyne* spp.) infestation can also reduce plants' resistance to abiotic and biotic elements (Jones *et al.*, 2013). They are obligate parasites of woody plants and herbaceous monocotyledonous and dicotyledonous plants. This genus includes about 100 species, while the four principal species are: *Meloidogyne incognita*, *M. javanica*, *M. arenaria* and *M. hapla* (Lunt *et al.*, 2014).

Chemical pesticides are currently widely used to control parasitic plant nematodes. Despite their effectiveness, they pose risks due to residues in plants and adverse effects on production and the environment, leading to the banning of some compounds (Desaeger *et al.*, 2020). Bioproducts of plant origin are considered promising sources for overcoming the problem of root-knot nematodes, as some of their products can be used directly as nematicides or indirectly to manufacture improved compounds that are effective, environmentally safe and low-cost (Khan *et al.*, 2022). Alternative solutions, such as plant extracts, offer an opportunity for successful control without harming humans, plants, or the environment (Jardim *et al.*, 2020).

To control Root-knot nematodes (RKNs), various plant extracts have been used as effective strategies for managing RKNs. When used with fertilizers and biopesticides, these extracts are economical, easy to apply, environmentally friendly and capable of improving soil health. Garlic, (*Allium sativum*), a member of the Alliaceae

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family, contains diallyl polysulfide, an active compound that targets cellular mechanisms. This effect, particularly observed in roots, may contribute to the development of resistance to RKNs. Top of Form Garlic-based products have been studied as environmentally friendly nematicides and their active compounds (diallyl polysulfides) are available on the market as formulated nematicides (Eder *et al.*, 2021). Garlic extract has also been found to have nematicidal effects and inhibit egg hatching, thereby reducing nematode damage, including egg masses, gall formation and juvenile hatching on plant roots and reducing the number of juveniles in the soil. Investigations have been conducted to determine the effectiveness of products with different garlic formulations in controlling root-knot nematode (Jardim *et al.*, 2020).

Neem cake is the residue left after pressing neem seeds to extract oil and is considered a valuable source of organic fertilizer. The role of this type of fertilizer is not limited to nourishing plants; it also helps control root-knot nematodes. Furthermore, neem cake can be used as an inhibitor of many types of pathogenic fungi (Shah *et al.*, 2008).

In addition, neem leaf powder can be used as a nematicide to control nematodes as an alternative to synthetic nematicides (Ebong *et al.*, 2008). Neem (*Azadirachta indica*), which belongs to the Meliaceae family, is considered one of the most valuable plant sources of nematicidal substances. Its active compounds, mainly alannin, azadirachtin, nimbin and related limonoids, indicate potent antifeedant, repellent, growth-inhibiting and nematicidal impacts (Sambo *et al.*, 2024). This review aims to provide a thorough assessment of the efficacy of garlic and neem products in controlling root-knot nematodes, while highlighting their bioactive compounds, modes of action and effects on reducing nematode development and enhancing plant health.

Life cycle of *Meloidogyne* spp.

The life cycle of RKNs begins when the female lays (300-500) eggs on the roots of susceptible plants, covering them with a gelatinous substance secreted from anal glands that protects them from unfavorable conditions and microbial agents (Moens *et al.*, 2009). When conditions are favorable, embryos develop inside the eggs and juveniles develop as first-stage juveniles (J1) inside the egg, then molt to second-stage juveniles (J2), which hatch and search for a suitable host. It then penetrates the root, usually behind the root cap, to begin the infection process. Entry is achieved by pushing an extensible stylet into plant cells, thereby releasing cell-wall-degrading enzymes likely produced by dorsal pharyngeal glands (Karsen and Moens, 2006). The J2 moves between cells through the cortical region toward the vascular tissues, where it establishes a specialized feeding site known as giant cells. The nematode stimulates the redifferentiation of a single cell into a large, multinucleated giant cell through its secretions. After the giant cells are formed, the J2 molts into the third-stage juvenile (J3) and then molts into the fourth-stage juvenile (J4). Both the J3 and J4 settle within

the roots, lack stylet functionality and develop within the cuticle of the previous stage; thereafter, the life cycle diverges and the J4 molts into a female or male (Fig 1) (Al-Juhaishi *et al.*, 2026). Adult females are sedentary, pearly white, pear-shaped or round, 0.5-1.0 mm long and 300-700 μ m wide. While males become worm-like and cease feeding, migrating to the soil, they measure 1.2-1.5 mm long and 30-36 μ m wide. Males are typically observed in parthenogenetic reproduction when conditions are unsuitable for female development, such as during food scarcity. The life cycle is completed once the adult female lays eggs. The short life cycle, lasting 3 to 4 weeks, enables it to reproduce rapidly as long as a suitable host is present. (Moens *et al.*, 2009).

Mechanism of root-knot nematode infection

Nematode infection of roots begins after eggs hatch in the soil, releasing second-stage (J2) juveniles, which are the primary infective stage. These juveniles move actively through the soil in search of a suitable host plant, then penetrate the roots, most often in the root elongation zone behind the root cap. After penetration, the juveniles migrate between cells toward the inner tissues and eventually settle in the vascular cylinder, where they begin secreting bioactive compounds that help create specialized feeding sites that support their growth and development within the root (Moens *et al.*, 2009). At this site, they establish persistent feeding sites and undergo three molts to reach adulthood. Female nematodes remain sedentary and produce large egg masses, as shown in Fig 2B, whereas males exit the host plant. Root-knot nematodes infest root tissues using mechanisms similar to those of plant pathogenic fungi and bacteria. One key mechanism is the production of cell wall-degrading enzymes (Habteweld *et al.*, 2024). The infestation leads to root gall formation (Fig 2A), which impairs the plant's ability to absorb and transport nutrients and water. This results in pronounced

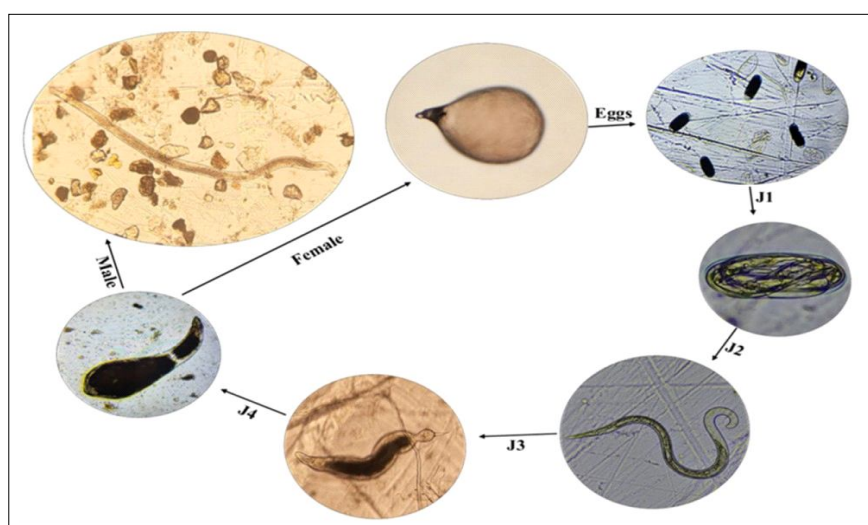


Fig 1: Root-knot nematode life cycle (Source: Al-Juhaishi *et al.*, 2026).

physiological stress and greater susceptibility to wilting. During feeding site establishment, nematodes secrete various effector proteins through their stylet into host cells. These effectors change plant cellular processes, suppress host defenses and trigger the development of specialized multinucleated feeding structures known as giant cells. These giant cells act as metabolic reservoirs, providing a constant supply of nutrients essential for nematode growth and reproduction. As the infection progresses, the affected root system exhibits reduced efficiency in water and nutrient uptake, leading to stunted growth, yellowing and substantial yield losses (Habteweld *et al.*, 2024).

The economic damage caused by root-knot nematodes

Root-knot nematodes (RKNs) cause an estimated \$157 billion in annual losses worldwide (Youssef *et al.*, 2013). However, in most countries, the impact of these nematodes is significantly underestimated. The total annual losses caused by this pathogen are likely to be much higher than estimated. Several factors have contributed to the scarcity of information on the global economic impacts of these nematodes. First, there is a general lack of awareness of this pathogen's impact on crop production, leading to its neglect. Second, the lack of information is attributed to a severe shortage of resources (human and financial) required to launch the large-scale projects necessary to

fully assess the impacts of RKNs (De Waele and Elsen, 2007). Finally, the long-term use of nematicides has led to the underestimation of the impact of root-knot nematodes. However, as options for using nematicides dwindle, problems with root-knot nematodes are likely to resurface. Although information on the impact of root-knot nematodes on crop production in Iraq is generally limited, there is growing evidence that problems with them on many farms across the country pose a serious threat to crop production. The rejection of low-quality crops exacerbates the shortage of healthy and clean propagation material both locally and globally and exposes growing crops to the risk of secondary infection by other organisms, particularly soil-borne pathogens, which are also problems associated with root-knot nematode infection. For example, interactions between *Meloidogyne* spp. and pathogens such as *Fusarium* spp. are well documented, while many other interactions may exist that have not been sufficiently studied (Mongae *et al.*, 2013). The presence of these populations of *Meloidogyne* nematodes poses a serious threat to global agricultural production, as most farmers lack detailed information about the root-knot nematodes present on their farms (Onkendi and Moleleki, 2013). The importance of root-knot nematodes extends beyond their role as independent plant pathogens; they are also associated with fungal, bacterial and viral diseases, as they weaken the host plant's resistance to other organisms.

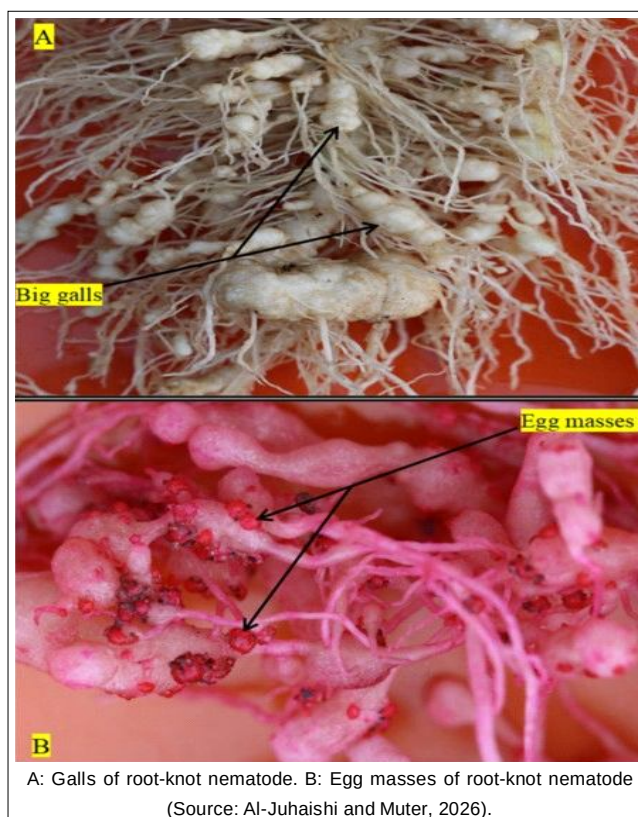


Fig 2: Symptoms of root-knot nematode below ground.

The importance of *Allium sativum*

Garlic (*Allium sativum*) is characterized by its compact bulbs, each consisting of several small cloves covered by a white skin (Li *et al.*, 2022). Its products, including garlic oil extracts, essential oils, garlic powder and aged garlic extract, exhibit significant therapeutic effects. Garlic is known for having few side effects because it is derived from natural ingredients and is considered a common dietary plant (Tsai, 2019). The nematicidal impacts of garlic often involve ethanolic or aqueous garlic extracts, which are poisonous to various species of plant-pathogenic nematodes (Anwar *et al.*, 2017). Therefore, it is of economic importance due to its nutritional properties and health benefits. Garlic extract and its essential oils are known to exhibit potent antioxidant, antifungal, antibacterial and antinematode activity. Garlic essential oils are considered promising botanical nematicides. When properly prepared, their efficacy may exceed that of well-known synthetic chemicals such as dazomet and carbofuran (Jardim *et al.*, 2020). These essential oils are rich in volatile and non-volatile sulfur compounds that are toxic to nematodes. The main compound is the organosulfur compound allicin, which breaks down into highly toxic sulfur compounds. These compounds include, among others, diallyl disulfide, diallyl sulfide, dithiane, diallyl trisulfide and ajoene (Eder *et al.*, 2021). It is worth noting that soil or field treatments exhibit a sustained preventive effect, significantly reducing root knot formation and nematode reproduction without showing any phytotoxicity (Jardim *et al.*, 2020). Extracts from chives (*Allium tuberosum*), which contain organic sulfides, carboxylic acids, ketones and glycosides, demonstrated efficacy against *Meloidogyne incognita* and significantly reduced the formation of root galls on tomatoes and cucumbers (Huang *et al.*, 2016). Garlic is a common spice with wide-ranging applications in both nutrition and medicine and is characterized by its content of bioactive compounds that confer numerous health benefits. Garlic contains active sulfur compounds such as allicin and ajoene, which numerous studies have shown to be effective as antioxidants, anti-inflammatories and antimicrobial agents, in addition to their role in boosting immunity and preventing many diseases.

Garlic phytochemical and bioactive compounds

Garlic contains reasonable amounts of nutrients such as selenium, calcium, magnesium, manganese, iron and vitamins A, B and C, as well as phosphorus, potassium, zinc, sodium and sulfur (Agarwal, 1996). It also contains a range of bioactive compounds, including phenols, polysaccharides, enzymes, linalool, saponins, phellandrene, tannins, ajoene, geraniol, alliin and allicin. These compounds have attracted significant scientific interest due to their biological effects. It has been reported that diallyl disulfide impairs fungal membrane functions, while simultaneously encouraging host plant resistance by stimulating the production of lignin and hydrogen peroxide, two key defense

responses against pathogen invasion (Yang *et al.*, 2021). The high sulfur content of diallyl disulfide is involved in oxidative stress and synergetically acts with other metabolites of sulfur to enhance garlic's efficacy as a fungicide (Zaini *et al.*, 2020). Garlic contains approximately 184 types of active secondary metabolites. Approximately 90% of these metabolites include (70) sulfur-containing organic compounds, (29) saponins, (16) flavonoids, (12) amino acids, (10) phenyl prostanoids and (7) alkaloids, as well as (3) compounds, selenium products and fatty acids (Ahmed *et al.*, 2022). However, Ajoene is one of the key compounds in garlic; it affects the integrity of the fungal cell membrane and inhibits the growth of fungal hyphae, making it an effective component in processed garlic extracts (Tedeschi *et al.*, 2007). Alliin is also an essential compound for the formation of allicin, although it has no direct biological activity; its quantity varies depending on the type of garlic, which affects its antifungal efficacy (Mandal *et al.*, 2019).

Role of garlic in managing root-knot nematodes

Garlic is considered a promising plant for controlling root-knot nematodes, as it contains biologically active sulfur compounds with nematicidal properties. Numerous studies have shown that garlic extracts reduce egg hatching and increase juvenile mortality, leading to a decrease in nematode populations and a reduction in the severity of plant infestation. This efficacy is primarily attributed to compounds such as allicin and allyl disulfides, which affect the cell membranes and vital enzymes of nematodes, thereby leading to paralysis of the juveniles and a decrease in their ability to move, feed and reproduce (Soliman *et al.*, 2023). As restrictions on chemical pesticides increase, garlic is considered a natural and environmentally friendly option for use in integrated pest management programs against root-knot nematodes. Tibugari *et al.* (2012) reported that aqueous extracts of garlic, marigold and castor bean reduced the severity of infestation, the number of root galls and the reproduction of the nematode *Meloidogyne javanica* in tomatoes, indicating their effectiveness in biological control, although the appropriate concentrations still need to be determined to achieve optimal results. El-Nagdi and Youssef (2013) reported that garlic and castor bean extracts reduced the severity of root-knot nematode infection and improved tomato plant growth compared to chemical treatment under greenhouse conditions. AbdelRazek *et al.* (2024) reported that garlic stalk extracts demonstrated clear efficacy against the root-knot nematode. The ethanol extract achieved a 100% mortality rate of second-stage juveniles at concentrations of 50% and 75% 72 hours after treatment, while the mortality rates for the fermented extract ranged between 72% and 94% and the aqueous extract showed lower efficacy with mortality rates ranging between 64% and 86%. These results indicate the high potential of garlic extracts, particularly ethanol extracts, to inhibit the development of

second-stage juveniles. A study by Javed *et al.* (2026) showed that an aqueous garlic extract is remarkably effective in reducing the development and reproduction of the root-knot nematode *Meloidogyne incognita* on tomato plants. The use of the extract led to increased juvenile mortality and reduced egg hatching, resulting in lower nematode populations and reduced infection severity. Therefore, application of garlic extract to the soil proved more effective than root dipping, reducing root knots and nematode reproduction, making it a natural option for root-knot nematode integrated pest management. Alarcón-Aguay *et al.* (2026) demonstrated that garlic extract was the most effective treatment against root-knot nematodes in greenhouse tomatoes, reducing both the infestation severity and the number of nematodes in the roots, thereby confirming its role as a natural and sustainable control option. However, some of the active garlic compounds tested against root-knot nematodes are summarized in Table 1.

Mechanisms of the garlic inhibition of the root-knot nematode

The nematicidal effect of garlic (*Allium sativum*) is attributed to its content of active sulfur compounds such as allicin and its derivatives, which are among the most important factors responsible for its biological toxicity against root-knot nematodes. These compounds cause widespread disruption of the nematodes' vital functions, including effects on cell membranes, metabolic processes and the ability to survive and reproduce (Mwamula *et al.*, 2022). The most important mechanism by which sulfur compounds exert their impact is by impairing the integrity of cell membranes, thereby increasing their permeability and causing a loss of water and ion balance within the juvenile's body (Fig 3). This leads to reduced juvenile movement and survival, especially in the second-stage juveniles, which are most

susceptible to this effect (Dababat *et al.*, 2025). Additionally, garlic compounds affect cellular energy production in nematodes by disrupting mitochondrial function and reducing adenosine triphosphate (ATP) production, thereby impairing juveniles' motility and their capacity to penetrate roots and develop feeding sites (Fig 3). Therefore, the active compounds in garlic also affect nematode eggs; they can penetrate the eggshell and disrupt embryonic development (Fig 3), leading to a decreased hatching rate and a reduction in the number of juveniles in the soil. Furthermore, garlic extracts may enhance plant defenses, such as by activating defense pathways associated with defense enzymes and phenolic compounds, thus limiting of ability of nematodes to create giant cells within the root system (Degroote *et al.*, 2024).

The importance of *Azadirachta indica*

The Meliaceae family has attracted considerable attention due to the abundance of limonoid triterpenes in the aerial and root parts of its members, particularly *Azadirachta indica* and *Melia azedarach*. The neem tree (*Azadirachta indica*) is a tropical evergreen tree native to India and Burma. It is also cultivated throughout most of West Africa and Southeast Asia. Most parts of the neem plant have been traditionally used as antivirals, antiseptics, antipyretics, anti-ulcer agents and antifungal agents. The neem plant has a unique ability to absorb calcium; thus, it is capable of neutralizing soil acidity. All parts of the neem plant possess fungicidal, insecticidal and nematicidal properties; among all parts of the plant, the leaves and seeds are most commonly used as insecticides (Roshan and Verma, 2015). The neem tree has been the subject of extensive studies to date due to azadirachtin, a tetranortriterpenoid limonoid that has undergone testing. Neem is typically used in the form of crude plant extracts, oil cakes, seed coatings and root-dipping agents, as well as coatings for fertilizers

Table 1: A list of garlic active compounds, rate and concentration tested for root-knot nematode nematicidal activity.

Garlic part	Active compound	Type of extracts/ treatment	Rate and concentration	Targeted nematode	References
Bulbs	Diallyl disulfide and diallyl trisulfide	Essential oil	LC50/48h values were 134.4 and 36.2	<i>Meloidogyne incognita</i>	Jardim <i>et al.</i> (2020)
Cloves	-	Aqueous	µg/mL Concentrations of 100%, 50% and 25%	<i>Meloidogyne spp.</i>	Kouamé <i>et al.</i> (2021)
Cloves	Allicin and polysulfides	Crushed garlic	LC90 and LC50/96 h range of 1.5 and 0.8 mg/mL	<i>Meloidogyne incognita</i>	Eder <i>et al.</i> (2021)
Cloves	-	Methanolic, ethanolic and aqueous	Rates of 2, 4 and 6 ml/plant	<i>Meloidogyne incognita</i>	Soliman <i>et al.</i> (2023)
Stalk	Phenolics and total flavonoids	Aqueous, fermented and ethanolic	Concentrations of 75% and 50%	<i>Meloidogyne incognita</i>	AbdelRazek <i>et al.</i> (2024)
Bulb	-	Nanoemulsion garlic oil and emulsion garlic oil	Rates of 10 ml/plant	<i>Meloidogyne incognita</i>	Osman <i>et al.</i> (2025)

such as urea, or the use of whole plants as soil enhancers (McSorley, 2011). Along with azadirachtin, neem contains between 100 and 300 limonoids and other substances that exhibit antinematode and insecticidal properties, such as feeding inhibition, repellency and inhibition of hatching and growth (Aarthy *et al.*, 2018). The neem tree is considered one of the most important plant resources in sustainable agriculture, as it is highly effective against parasitic nematodes, plant pathogens and insect pests. The various parts of the neem plant have been used since ancient times due to their great importance. Primary neem products, such as neem oil and extracts from its leaves, seeds and roots, as well as byproducts like neem cake, possess insecticidal characteristics and are used as biological insecticides, fungicides and organic fertilizers (Acharya *et al.* 2017).

Neem phytochemical and bioactive compounds

Neem is recognized as one of the richest sources of bioactive phytochemicals among medicinal plants. Therefore, limonoids such as azadirachtin, salannin, nimbin, nimbolide and gedunin are considered the principal bioactive constituents responsible for the antagonistic effects of neem against plant-parasitic nematodes and insect pests by inhibiting feeding, hatching, growth and reproduction. Furthermore, compounds such as polysaccharides, amino acids, flavonoids, dihydrochalcones, coumarins, tannins, sulfurous and aliphatic substances constitute part of the chemical composition of neem. (Aarthy *et al.*, 2018). Azadirachtin is the main biologically active component of the neem tree and is the primary active ingredient in almost all commercial neem-based bioinsecticides. Chemo-structurally, azadirachtin is a

highly oxygenated tetranoterpenoid limonoid ($C_{35}H_{44}O_{16}$) that occurs naturally in several structural isomers and enantiomers, known as azadirachtins A through K. The most abundant and biologically active form found in neem seeds is azadirachtin A. Several studies have shown that azadirachtin A has potent insecticidal, feeding-inhibitory, growth-regulating and repellent properties across a broad range of agricultural pests (Su *et al.*, 2023). Due to its high activity and comparatively low ecological effects, azadirachtin has become one of the most widely used plant compounds in the formulation of commercial bio-insecticides and IPM programs. Further, azadirachtin demonstrates efficacy against a range of plant pathogens and pests, including fungi, nematodes, viruses and parasites.

Role of neem in managing root-knot nematodes

Neem has emerged as one of the most important sustainable botanical alternatives for controlling root-knot nematodes (RKNs). This is due to its content of active compounds, such as nimbidin, azadirachtin, nimbin and others, which reduce egg hatching, impair juvenile mobility and limit their ability to penetrate roots, thereby reducing the severity of infestation and the formation of root galls (d'Errico *et al.*, 2023). Javed *et al.* (2007) reported that aqueous extracts of neem leaves and neem cake, as well as azadirachtin extracted from neem seeds, resulted in a significant reduction in the number of females and egg masses of the *Meloidogyne javanica*. The effectiveness of these substances in limiting nematode reproduction and RKNs persisted for up to 16 weeks after treatment. Saravanan *et al.* (2021) indicated that the use of neem cake at a rate of 100 g/plant, particularly when combined with biological control agents, resulted in a significant

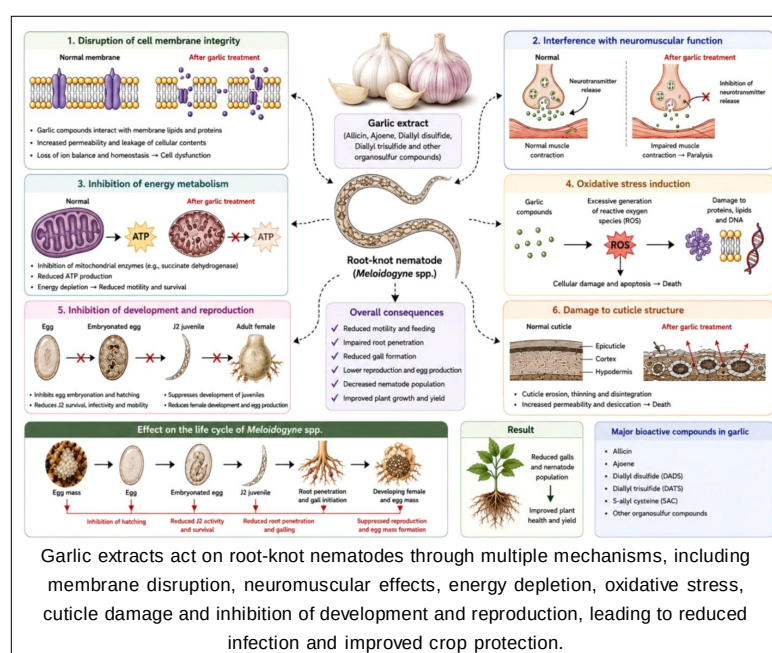


Fig 3: Mode of action of garlic extracts on root-knot nematodes.

reduction in the population density of *M. incognita* and reduced gall formation, as well as improved banana plant growth, underscoring the importance of neem cake in integrated nematode management programs. A study by d'Errico *et al.* (2023) found that a nematicide based on azadirachtin, the primary active compound in the neem tree, successfully reduced infection by *M. incognita* and increased the yield of short-cycle lettuce. In long-cycle tomato crops, however, azadirachtin was unable to effectively control infestation, although it did achieve a significant increase in yield. The results indicate that azadirachtin is a promising alternative to chemical pesticides for short-cycle crops, whereas combining it with other control methods is preferable for long-cycle crops. Hahn *et al.* (2025) reported that extracts from the neem tree exhibited nematicidal activity against *M. javanica*, with an EC50 concentration of 0.40-0.44% for egg hatching, while the EC50 for second-stage juvenile mortality ranged from 13.3% to 13.9%. Similarly, the use of a 1% concentration of the extracts reduced the nematode reproduction rate to a degree comparable to that of the nematicide abamectin, neem extracts demonstrated a clear nematicidal effect against the eggs and second-stage juveniles of the root-knot nematode, as they contributed to reducing nematode reproduction and lowering their population density on tomato plants, confirming their potential as an effective and environmentally friendly method for controlling *M. javanica*. Kankam and Sowley (2016) demonstrated that various neem products, including leaf powder, seed powder and neem cake at a rate of 20 g/pot, reduced the populations of root-knot nematodes in chili peppers. Neem leaf powder was the most effective, achieving the greatest reduction in nematode density and

the number of root galls, suggesting its potential as a safe botanical alternative to conventional nematicides. However, some of the active compounds and concentrations in neem that have been tested against root-knot nematodes are summarized in Table 2.

Mechanisms of the neem inhibition of the root-knot nematode

Neem extracts have a direct effect on eggs and second-stage (J2) juveniles, reducing egg hatching rates and causing paralysis and death in juveniles, which leads to a significant decrease in nematode density in the soil and roots (Abbasi *et al.*, 2005; Nile *et al.*, 2018). Neem compounds also affect juveniles' behavior, reducing their ability to recognize or move toward plant root exudates, which leads to lower rates of root penetration and nodule formation (López-Pérez *et al.*, 2011). Once the nematodes have entered the root, the nematicides disrupt the formation of giant cells responsible for feeding the nematodes, thereby reducing their reproduction and decreasing the number of eggs formed within the plant tissues (Abbas *et al.*, 2023). In addition, neem helps boost plant resistance by stimulating the activity of defense enzymes such as phenylalanine ammonia-lyase (PAL), peroxidase (POX) and polyphenol oxidase (PPO), thereby enhancing plant immunity and reducing the severity of infection (Nile *et al.*, 2018). Furthermore, the use of neem cake and organic amendments leads to changes in soil properties, such as an increase in pH and the release of ammonia during decomposition, in addition to promoting beneficial microorganisms, thereby creating an environment unsuitable for the growth and reproduction of nematodes. Neem extracts directly affect the eggs of root-knot nematodes

Table 2: A list of neem active compounds, rate and concentration tested for root-knot nematode nematicidal activity.

Neem part	Active compound	Type of extracts/ treatment	Rate and concentration	Targeted nematode	References
Seed	Azadirachtin	Commercial seed extract containing	Concentrations of 50%, 25%, 10%, 5%, 1%, 0.5%, <i>M. incognita</i>	<i>Meloidogyne</i> <i>javanica</i> and	Gravanis <i>et al.</i> (2011)
Neem cake	1% azadirachtin	0.25%, 0.1% and 0.05% Ethanollic	Concentrations of 100%, 20%, 10%, 5% and 2.5%	<i>Meloidogyne</i> spp.	Hieu <i>et al.</i> (2014)
Leaves	-	Ground neem leaves	Rates of 30, 20, 10 and 5 g/kg soil	<i>Meloidogyne</i> <i>incognita</i>	Yadav <i>et al.</i> (2018)
Aerial parts	-	Aqueous and alcoholic	Concentrations of 80, 60 and 40%	<i>Meloidogyne</i> <i>incognita</i>	Nile <i>et al.</i> (2018)
Seed	Alkaloids, flavonoids, saponins and terpenes	Aqueous and methanolic	Concentrations of 300, 200, 150, 100 and 50 mg/ml	<i>Meloidogyne</i> spp.	Sambo <i>et al.</i> (2024)
Leaves	Flavonoid, alkaloid, saponin, steroid, phenol, tannin, terpenoid and anthraquinones	Aqueous and Ethanollic	Concentrations of 200, 100, 50 and 25 mg/m	<i>Meloidogyne</i> spp.	Zawiyya (2025)

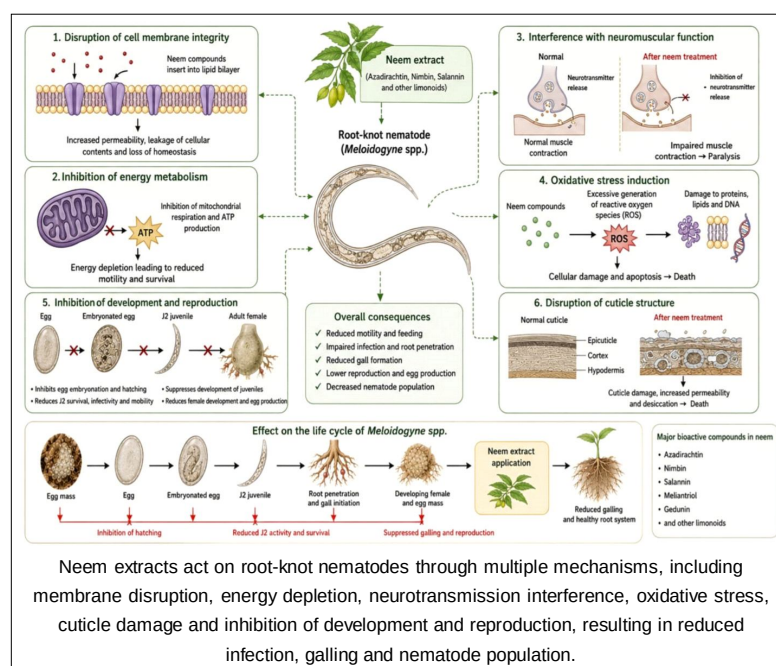


Fig 4: Mode of action of neem extracts on root-knot nematodes.

by inhibiting embryogenesis within the egg. These compounds significantly reduce the hatching rate by disrupting vital processes within the egg, such as cellular respiration and membrane permeability (Fig 4). Studies have shown that neem treatment leads to a significant reduction in juvenile mortality and egg hatching rates, which may reach 70-100% depending on the concentration and type of extract, with the presence of non-viable eggs observed as a result of the direct toxic effect of the active compounds (Abbasi *et al.*, 2005; López-Pérez *et al.*, 2011; Nile *et al.*, 2018). It is believed that phenolic compounds and limonoids weaken the egg's protein membrane, thereby preventing normal embryonic development. Second-stage juveniles (J2) are the most sensitive to neem compounds, as exposure to them leads to clear physiological and behavioral effects, including paralysis, loss of mobility and immediate death. Neem compounds disrupt the juvenile's neuromuscular system, inhibiting its ability to move and seek out plant roots (Fig 4). In addition to its direct lethal effect, neem affects juvenile behavior by reducing their ability to respond to plant root exudates. This results in impaired chemotaxis and a lower rate of juvenile arrival at the roots, thereby reducing penetration rates and root gall formation. Results have shown that neem-treated plants contain significantly fewer root knots compared to untreated plants, indicating that neem disrupts early stages of infection (Zawiyya, 2025; López-Pérez *et al.*, 2011). Neem extract derived from *Azadirachta indica* has a multi-mechanism effect on the root-knot nematodes (*Meloidogyne* spp.), including inhibition of egg hatching, direct killing of J2 and disruption of host-seeking behavior, resulting in a significant reduction in infection and damage.

CONCLUSION

Root-knot nematodes (*Meloidogyne* spp.) are considered one of the most dangerous plant-parasitic nematodes, causing significant economic losses in many crops worldwide. With increasing restrictions on the use of chemical nematicides due to their negative impacts on human health and the environment, plant extracts have emerged as promising and safe alternatives within integrated pest management programs. Both garlic and neem are among the most promising plant extracts for controlling RKNs due to the bioactive compounds that directly affect egg hatching, juvenile mortality and the nematodes' ability to penetrate roots and reproduce within them. Their effects also stimulate plant defenses and improve the root environment, which results in reduced nematode density, less severe infestation and improved plant growth and productivity. However, further studies are still needed to standardize extraction and application methods, determine optimal concentrations and the most effective compounds and evaluate their long-term performance under various field conditions to ensure their maximum benefit in sustainable agriculture.

Conflict of interest

The author declare that there are no competing interests.

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