OPEN ACCESS Plant Protection, 10 (03) 2026. 589-600 DOI:10.33804/pp.010.03.5426

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Available Online at EScience Press
Plant Protection
ISSN: 2617-1287 (Online), 2617-1279 (Print)
http://esciencepress.net/journals/PP

Research Article

Therapeutic Potential of Neem (*Azadirachta indica*) and Hemp (*Cannabis sativa*) soil amendments for the Sustainable Management of Root-Knot Nematodes (*Meloidogyne incognita*) in Tomato

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ARTICLE INFO

Article history
Received: 17th January, 2026
Revised: 10th May, 2026
Accepted: 13th May, 2026

Keywords
Neem amendment
Hemp amendment
Root-knot nematode
Meloidogyne incognita
Sustainable nematode management

ABSTRACT

Root-knot nematodes (*Meloidogyne incognita*) are destructive pathogens that severely reduce tomato growth and yield. This study evaluated the efficacy of neem (*Azadirachta indica*) and hemp (*Cannabis sativa*) soil amendments, applied individually and in combination, for suppressing *M. incognita* and improving tomato performance under greenhouse and field conditions. All amendments significantly ($P < 0.05$) reduced nematode infestation compared with the inoculated control. Neem consistently exhibited greater nematicidal activity than hemp, with efficacy increasing in a concentration-dependent manner. Under greenhouse conditions, neem at 75% was the most effective individual treatment, reducing the galling index from 6 to 1 and decreasing juvenile density, egg masses, and galls to 42 J2 per 100 g soil, 29 egg masses, and 17 galls per root system, respectively. Similarly, under field conditions, neem at 75% reduced the galling index to 1.66 while suppressing juvenile density, egg masses, and galls to 48 J2 per 100 g soil, 34.33 egg masses, and 22 galls per root system, respectively. The combined application of neem and hemp (50% + 50%) also markedly suppressed nematode infestation and consistently produced the greatest improvements in tomato growth and yield, recording the highest plant height, shoot weight, flower production, stem diameter, and fruit weight under both greenhouse and field conditions. Hemp at 75% was particularly effective in increasing fruit number and root length. Overall, both amendments effectively mitigated *M. incognita* damage. Neem at 75% provided the greatest nematode suppression, whereas the combined neem-hemp treatment maximized tomato growth and productivity, demonstrating its potential for sustainable integrated nematode management.

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Introduction

Tomato (*Lycopersicon esculentum* L.; currently recognized as *Solanum lycopersicum* L.), a member of the family Solanaceae, is one of the most economically important vegetable crops worldwide because of its high nutritional value, industrial applications, and contribution to global food security. It is an excellent source of vitamins A and C, minerals, carotenoids, flavonoids, and the antioxidant lycopene, making it an indispensable component of the human diet. The crop is believed to have originated in South America and performs optimally under temperatures ranging from 25 to 29°C. Globally, tomato is the leading processing vegetable and is cultivated across diverse agro-climatic regions. In Pakistan, it is grown in all major agro-ecological zones over approximately 63,203 ha, with an average productivity of only 9.51 t ha^{-1}, considerably lower than the yields reported from China (57.71 t ha^{-1}), India (25.98 t ha^{-1}), and the United States (86.55 t ha^{-1}) (FAO, 2017). This substantial yield gap is largely attributed to the cultivation of low-yielding cultivars and the increasing pressure of abiotic stresses and destructive plant pathogens, particularly soil-borne diseases and plant-parasitic nematodes (Mukhtar, 2018; Azeem et al., 2021, 2025; Gondal et al., 2024; Mehak et al., 2026).

Among the biotic constraints limiting tomato production, root-knot nematodes (RKNs) (*Meloidogyne* spp.) are regarded as one of the most devastating groups of plant-parasitic nematodes worldwide (Kayani et al., 2017; Kayani and Mukhtar, 2018; Khan et al., 2019; Mukhtar and Hussain, 2019; Mukhtar and Kayani, 2019, 2020; Yaseen et al., 2023). They infect more than 5,500 plant species, including numerous vegetable, fruit, ornamental, and field crops, resulting in severe economic losses estimated at billions of US dollars annually. In Pakistan, root-knot nematodes are among the principal constraints to tomato production (Tariq-Khan, 2018; Hussain and Mukhtar, 2019; Tariq-Khan et al., 2024, 2025). Their widespread occurrence has also been documented in the diverse agro-ecological regions of Azad Jammu and Kashmir (AJK), particularly in Muzaffarabad, where they represent a major threat to vegetable cultivation (Tariq-Khan et al., 2017, 2020a, 2020b, 2020c, 2; Saeed and Mukhtar, 2024; Khan et al., 2025). Owing to its favorable climatic conditions, AJK is recognized as an important hotspot for the diversity and distribution of tropical *Meloidogyne* species.

Among the economically important RKN species, *Meloidogyne incognita* is the most prevalent and destructive in tropical and subtropical agricultural systems (Hussain et al., 2016; Mukhtar et al., 2017a, b; Kayani et al., 2018; Mukhtar and Kayani, 2019, 2020; Haq et al., 2022). This sedentary endoparasitic nematode invades young roots as second-stage juveniles (J2), establishes permanent feeding sites known as giant cells, and induces the formation of characteristic root galls. These physiological modifications disrupt water and nutrient transport, impair root architecture, reduce photosynthetic efficiency, and predispose plants to secondary infections by soil-borne fungi and bacteria (Asghar et al., 2020). The broad host range, rapid reproductive capacity, short life cycle, and remarkable adaptability of *M. incognita* enable it to persist under diverse environmental conditions, making its management particularly challenging. In addition, climate change and intensive cropping systems are expected to further increase its prevalence and economic significance in vegetable production systems.

Tomato is particularly susceptible to *M. incognita* because of its succulent and highly penetrable root system, which facilitates nematode invasion, establishment, and reproduction. Disease severity is often aggravated under tropical and subtropical conditions characterized by elevated soil temperatures, intensive irrigation, continuous monocropping, and excessive fertilizer inputs (Sasser and Carter, 1982; Tariq-Khan et al., 2017). Yield reductions attributable to root-knot nematodes have been estimated at approximately 29% worldwide (Sasser, 1979), whereas losses in Pakistan range from 38% in Khyber Pakhtunkhwa (Naz et al., 2013) to as high as 80-100% under severe infestations (Wanjohi et al., 2018). Recent surveys in the hilly regions of Azad Jammu and Kashmir have further revealed mixed infestations of multiple *Meloidogyne* species, with nematode incidence recorded in 15.3% of surveyed fields (Tariq-Khan et al., 2025), highlighting the increasing complexity of nematode management in the region.

Root-knot nematode infection is characterized by the formation of conspicuous root galls that interfere with normal root function and substantially reduce the plant's ability to absorb water and nutrients. Consequently, infected plants exhibit chlorosis, stunted growth, premature wilting, reduced fruit yield, poor fruit quality, and shortened productive lifespan. Furthermore, nematode-induced root damage facilitates the establishment of secondary pathogens, resulting in disease complexes that exacerbate crop losses (Yaseen et al., 2024, 2025). Although integrated management strategies involving cultural, biological, host resistance, and chemical approaches have been developed, chemical nematicides remain the most widely adopted management option because of their rapid efficacy. Nevertheless, increasing concerns regarding environmental contamination, non-target toxicity, human health risks, and stringent regulatory restrictions have substantially limited their use (Onkendi et al., 2014). Moreover, prolonged and indiscriminate application of synthetic nematicides has accelerated the development of resistance while reducing their long-term effectiveness, particularly under intensive vegetable production systems (Engindeniz and Cosar, 2013).

The growing emphasis on sustainable agriculture has therefore intensified the search for environmentally benign alternatives capable of suppressing plant-parasitic nematodes while maintaining soil health and crop productivity (Nazir et al., 2019; Mukhtar et al., 2021; Saeed et al., 2023). Botanical pesticides have emerged as attractive candidates because they are biodegradable, renewable, relatively safe to non-target organisms, and comprise complex mixtures of bioactive compounds that reduce the likelihood of resistance development. Plant-derived metabolites exhibit nematicidal, nematostatic, ovicidal, repellent, and anti-feedant activities through multiple mechanisms, including disruption of egg hatching, juvenile mobility, host recognition, feeding site establishment, development, and reproduction. In addition, several botanical products enhance soil microbial diversity and stimulate plant defense responses, thereby contributing to integrated nematode management (Kankam et al., 2015; Afzal and Mukhtar, 2024; Saeed et al., 2021, 2026).

Among medicinal plants with considerable biopesticidal potential, neem (*Azadirachta indica*) and hemp (*Cannabis sativa*) have attracted increasing scientific interest because of their rich phytochemical composition and broad-spectrum biological activities. Neem contains numerous biologically active constituents, including azadirachtin, nimbin, salannin, gedunin, limonoids, and other triterpenoids, which possess well-documented insecticidal, antifungal, antibacterial, and nematicidal properties. These compounds interfere with nematode hatching, mobility, feeding, growth, and reproduction while simultaneously improving soil health through enhanced microbial activity (Youssef and Lashein, 2013). Likewise, *C. sativa* contains a diverse array of secondary metabolites, including cannabinoids, terpenoids, flavonoids, phenolic compounds, and alkaloids, many of which exhibit antimicrobial and anthelmintic activities. Previous studies have demonstrated that hemp-derived products can suppress insect pests, plant pathogens, weeds, and plant-parasitic nematodes (Kayani et al., 2012, 2013). Hemp grows naturally throughout northern Pakistan and Azad Jammu and Kashmir, making it an abundant, inexpensive, and locally available resource for developing sustainable nematode management strategies. Despite these promising attributes, comparatively little information is available regarding the nematicidal efficacy of soil amendments of hemp, particularly in comparison with neem under greenhouse pot and field conditions.

Therefore, the present study was conducted to evaluate the therapeutic potential of soil amendments of neem and hemp for the sustainable management of *M. incognita* infecting tomato. Specifically, the study assessed their effects on nematode suppression under laboratory and field conditions and investigated their influence on plant growth and physiological performance. The findings are expected to provide an environmentally sustainable and economically viable alternative to synthetic nematicides, contributing to the development of integrated nematode management strategies for sustainable tomato production.

Materials and Methods

Experimental site and general conditions

The study was conducted under controlled greenhouse conditions and in field micro-plots to evaluate the nematicidal efficacy of neem and hemp amendments against *M. incognita*. The greenhouse experiment was carried out under natural photoperiod conditions at 25-30°C, while the field experiment was established in a naturally ventilated research farm with a history of root-knot nematode infestation. Standard agronomic practices were maintained throughout the experimental period, except for pest and nematode control measures, which were withheld to ensure uniform nematode pressure.

Preparation of nematode inoculum

A pure culture of *M. incognita* was established from infected tomato roots collected during a field survey. Egg masses were hand-picked and incubated in modified Baermann funnels at 27 ± 2°C to obtain freshly hatched second-stage juveniles. The inoculum suspension was calibrated under a stereomicroscope, and the concentration was adjusted to 2000 J2 per plant for both pot and field experiments.

Preparation of neem and hemp amendments

Dried leaf powders of neem and hemp were prepared by shade-drying healthy plant material at room temperature (25 ± 2°C) until constant weight was achieved. The materials were then ground using an electric grinder and passed through a 1 mm sieve to ensure uniform particle size. Stock formulations were prepared and applied at graded concentrations (25%, 50%, and 75%) either singly or in combination (50% neem + 50% hemp, w/w basis).

Greenhouse pot experiment

The greenhouse experiment was conducted in plastic pots (30 cm height × 25 cm diameter), each filled with 5 kg of sterilized sandy loam soil (autoclaved at 121°C for 1 h on two consecutive days). Soil physicochemical properties were analyzed prior to experimentation to ensure uniformity across treatments.

Experimental design and treatments

The experiment was arranged in a completely randomized design (CRD) with eight treatments, each replicated five times:

T1 = Negative control (non-inoculated, non-treated)

T2 = Positive control (inoculated with 2000 J2 *M. incognita*)

T3 = Neem amendment (25%)

T4 = Neem amendment (50%)

T5 = Neem amendment (75%)

T6 = Hemp amendment (25%)

T7 = Hemp amendment (50%)

T6 = Hemp amendment (75%)

T9 = Combined amendment (Neem + Hemp, 50% + 50%)

Each pot received 2000 freshly hatched J2 suspended in 10 mL water, applied in two holes around the root zone at 3-4 cm depth. Amendments were incorporated into the soil 7 days prior to nematode inoculation to allow decomposition and release of bioactive compounds.

Field micro-plot experiment

The field experiment was conducted in micro-plots measuring 2 m × 2 m, with row spacing of 50 cm and plant spacing of 40 cm. Each plot contained 10 tomato plants (cv. Roma). Plots were separated by 1 m buffer zones to prevent cross-contamination of nematodes and amendments.

Experimental design and treatments

A randomized complete block design (RCBD) was used, following the same treatment structure as the pot experiment. Each micro-plot was uniformly inoculated at transplanting by applying 2,000 second-stage juveniles per plant equivalent into the planting holes.

Organic amendments (neem and hemp powders) were incorporated into soil two weeks before transplanting at the designated concentrations and thoroughly mixed to a depth of 15-20 cm.

Data collection and nematode assessment

Nematode infestation was assessed 60 days after inoculation in both pot and field experiments using the following parameters:

1. Galling index (0-10 scale) (Bridge and Page, 1980).
2. Number of J2 per 100 g soil
3. Galls per root system
4. Egg masses per root system

Roots were gently washed and stained where necessary for clear visualization of egg masses. Soil samples were homogenized prior to nematode extraction.

Plant growth and yield parameters

The following growth parameters were recorded at harvest:

1. Plant height (cm)
2. Shoot fresh weight (g)
3. Root fresh weight (g)
4. Root length (cm)
5. Stem diameter (cm)
6. Number of flowers per plant
7. Number of fruits per plant
8. Fruit weight per plant (g)

All measurements were taken from five randomly selected plants per replicate and averaged for statistical analysis.

Statistical analysis

All data were subjected to statistical analysis using analysis of variance (ANOVA) appropriate for CRD (greenhouse experiment) and RCBD (field experiment) (Steel et al., 1997). Treatment means were separated using the Least Significant Difference (LSD) test at $P \leq 0.05$. Prior to analysis, percentage and count data were checked for normality and homogeneity of variance and transformed where necessary. Statistical analyses were performed using Statistix 8.1. Interaction effects among treatments were considered where applicable, and results were presented as mean ± standard error. Correlation analysis between nematode population parameters and plant growth attributes was also performed to determine treatment efficiency relationships.

Results

Nematicidal efficacy of neem and hemp under greenhouse pot experiment

The application of neem and hemp amendments significantly ($P < 0.05$) reduced root-knot nematode infestation compared with the positive control across all assessed parameters (Table 1). The untreated inoculated plants exhibited the highest galling index (6), juvenile population (281 J2/100 g soil), egg masses (127 per root system), and galls (101 per root system), whereas the negative control remained free of nematode infestation.

Among the individual amendments, neem exhibited greater nematicidal efficacy than hemp, with effectiveness increasing in a concentration-dependent manner. Neem applied at 75% was the most effective individual treatment, reducing the galling index to 1 and suppressing juvenile density, egg masses, and galls to 42 J2/100 g soil, 29 egg masses, and 17 galls per root system, respectively. Hemp also significantly decreased nematode infestation, with the 75% concentration producing greater reductions than the lower concentrations, although its efficacy remained inferior to that of neem.

The combined application of neem and hemp (50% + 50%) provided superior suppression compared with most individual treatments, reducing the galling index to 2 and limiting juvenile density, egg masses, and galls to 79 J2/100 g soil, 44 egg masses, and 26 galls per root system, respectively. Overall, neem, particularly at 75%, was the most effective treatment for suppressing root-knot nematode infestation under greenhouse pot experiment, while the combined amendment also demonstrated strong nematode-suppressive potential.

Table 1. Effect of hemp and neem amendments on *M. incognita* infestation under greenhouse pot experiment.

Treatments	Galling index	Numbers of J2/ 100 g soil	Egg masses/ root system	Galls/ root system
Negative control	0f	0h	0h	0i
Positive control RKN J2 (2000)	6a	281a	127a	101a
Neem 25%	4bc	179b	88b	50b
Neem 50%	4bc	138cd	75d	41d
Neem 75%	1ef	42g	29g	17h
Hemp 25%	5ab	168c	77bc	47c
Hemp 50%	4bc	124d	72cd	42e
Hemp 75%	3cd	115e	55e	35f
Neem + Hemp 50% +50%	2de	79f	44f	26fg

Means in a column followed by the same letters are not significantly different at P < 0.05 by Least Significant Difference Test.

Growth and yield responses of tomato to neem and hemp amendments under greenhouse pot experiment

M. incognita infestation significantly ($P < 0.05$) reduced tomato growth and yield attributes compared with the uninoculated control (Table 2). Soil amendment with neem and hemp individually or in combination markedly improved all measured growth and yield parameters, with treatment efficacy generally increasing with application rate.

The combined application of neem and hemp (50% + 50%) produced the greatest improvement in plant performance, recording the highest plant height (98.8 cm), shoot weight (34.9 g), flowers per plant (46), fruit weight per plant (3138.3 g), and stem diameter (0.265 cm), all of which were significantly higher than the nematode-inoculated control. The combination treatment also maintained high fruit production (28.33 fruits plant^{-1}) and root length (10.07 cm). Among the individual amendments, 75% neem significantly enhanced plant height, shoot weight, stem diameter, and root weight, whereas 75% hemp was the most effective in increasing fruit number (28.33 fruits plant^{-1}), fruit weight (3092.3 g plant^{-1}), and root length (10.8 cm). Overall, both amendments substantially alleviated the adverse effects of *M. incognita* on tomato growth and productivity, with the combined treatment exhibiting the greatest overall efficacy.

Field Suppression of *M. incognita* by neem and hemp amendments

The application of neem and hemp amendments significantly ($P < 0.05$) suppressed *M. incognita* infestation under field conditions compared with the inoculated control (Table 3). The positive control exhibited the highest nematode infestation, with a galling index of 6.33, 288 J2 per 100 g soil, 132 egg masses, and 107 galls per root system, whereas no nematode infection was detected in the negative control.

Among the individual amendments, neem demonstrated greater nematicidal efficacy than hemp, with suppression increasing in a concentration-dependent manner. Neem applied at 75% was the most effective treatment, reducing the galling index to 1.66 and decreasing juvenile density, egg masses, and galls to 48 J2 per 100 g soil, 34.33 egg masses, and 22 galls per root system, respectively. Hemp also significantly reduced nematode infestation, with the 75% concentration outperforming the lower concentrations, although its efficacy remained lower than that of neem. The combined application of neem and hemp (50% + 50%) also provided substantial nematode suppression, reducing the galling index to 3.33 and limiting juvenile density, egg masses, and galls to 84 J2 per 100 g soil, 49.6 egg masses, and 32 galls per root system, respectively. Overall, neem at 75% was the most effective treatment for suppressing *M. incognita* under field conditions, while the combined amendment exhibited greater efficacy than most individual hemp treatments.

Table 3. Effect of hemp and neem amendments on *M. incognita* infestation under field experiment.

Treatments	Galling index	Numbers of J2/ 100 g soil	Egg masses/ root system	Galls/ root system
Negative control	0f	0i	0h	0h
Positive control RKN J2 (2000)	6.33ab	288a	132a	107a
Neem 25%	5bc	184.5b	93.667b	56b
Neem 50%	4cd	144.7d	79.33cd	46.6d
Neem 75%	1.66e	48h	34.33g	22g
Hemp 25%	7a	173c	83c	53bc
Hemp 50%	5.66ab	130e	77.667d	47.7cd
Hemp 75%	3.66cd	120.6f	59.667e	40.3e
Neem + Hemp 50% +50%	3.333d	84g	49.6f	32f

Means in a column followed by the same letters are not significantly different at P< 0.05 by Least Significant Difference Test.

Effects of hemp and neem amendments on tomato growth under field conditions

M. incognita inoculation significantly reduced all measured growth and yield-related traits of tomato compared with the non-inoculated control (Table 4). Soil amendment with neem, hemp, and their combination markedly improved plant performance under nematode infestation, although the magnitude of response varied among treatments. The combined application of neem + hemp (50% + 50%) produced the greatest improvement in plant height (95.5 cm), shoot weight (31.87 g), and flower production (43.33 flowers plant^{-1}), while maintaining the highest fruit weight (2963.0 g plant^{-1}), which was statistically comparable to hemp at 50% and 75%. Hemp at 75% resulted in the highest number of fruits per plant (27.0) and, together with neem at 50%, produced the longest roots (9.69 and 9.33 cm, respectively). Neem at 75% significantly increased stem diameter (0.239 cm), comparable to the combined treatment (0.235 cm) and neem at 50% (0.233 cm). Root weight was highest under neem at 75% (35.0 g), whereas the positive control exhibited the poorest overall performance. Overall, the combined neem + hemp treatment was the most effective in mitigating the adverse effects of *M. incognita* and enhancing tomato growth and productivity under field conditions.

Discussion

Tomato is one of the most widely cultivated vegetable crops globally and plays a vital role in human nutrition and agribusiness. However, its productivity is severely constrained by multiple biotic and abiotic stresses, particularly in ecologically fragile regions such as Azad Jammu and Kashmir, where soil erosion, nutrient depletion, and plant-parasitic nematodes collectively limit yield potential. Among these constraints, root-knot nematodes, primarily *M. incognita*, are recognized as one of the most destructive soil-borne pathogens of tomato, causing substantial yield losses across tropical and temperate agro-ecosystems (Tariq-Khan et al., 2017; Tariq-Khan et al., 2020a).

Table 2. Effect of hemp and neem amendments on growth and yield parameters of tomato cv. Roma under greenhouse pot experiment treated with *M. incognita*.

Treatments	Plant height (cm)	Shoot weight (g)	No. of fruits per plant	No. of flowers per plant	Fruit weight per plant (g)	Stem diameter (cm)	Root weight (g)	Root length (cm)
Negative control	80.15e	31.81bc	26bc	43.167ab	2955b	0.244c	31.03bc	8.4cd
Positive control RKN J2 (2000)	75.6f	26.8d	24.66c	39.667c	2590.3d	0.235c	32.2b	6.3e
Neem 25%	88.85c	32.22bc	25.33c	40.5bc	2771c	0.2426c	28.5d	7.8d
Neem 50%	86.9d	33.19ab	25.33c	41.2bc	2708.3cd	0.26ab	29d	10.03ad
Neem 75%	91.4b	34.2a	27ab	43.16ab	2785.67c	0.269a	33.2a	9.13bc
Hemp 25%	89.6bc	31.16c	26bc	46.22a	2563.67d	0.247bc	29.4d	7.7d
Hemp 50%	90.15bc	33.5ab	27.33ab	41.33bc	3084.67ab	0.2446c	30.6c	10.4a
Hemp 75%	90.85b	31.9bc	28.33a	42.83b	3092.3ab	0.2623ab	31.03c	10.8a
Neem + Hemp 50% +50%	98.8a	34.9a	28.33a	46a	3138.3a	0.2646a	31.36bc	10.07ab

Means in a column followed by the same latters are not significantly different at P < 0.05 by Least Significant Difference Test.

Table 4. Effect of hemp and neem amendments on growth and yield parameters of tomato cv. Roma under field conditions inoculated with *M. incognita.*

Treatments	Plant height (cm)	Shoot weight (g)	No. of fruits per plant	No. of flowers per plant	Fruit weight per plant (g)	Stem diameter (cm)	Root weight (g)	Root length (cm)
Negative control	77.550e	28.717cd	24.000cd	40.667abc	2846.0ab	0.2147c	33.133c	6.8500bc
Positive control RKN J2 (2000)	72.567f	23.733e	23.000d	37.167d	2446.7c	0.2057c	34.367ab	6.0667c
Neem 25%	85.717cd	29.090bcd	23.333cd	38.000 cd	2614.7c	0.2127 c	30.633e	6.8500bc
Neem 50%	83.9d	30.077abcd	24.333bcd	38.667cd	2591.7c	0.2333a	31.200e	9.3333a
Neem 75%	88.46b	31.100ab	25.000abcd	40.667abc	2636.3bc	0.2390a	35.000a	7.9433abc
Hemp 25%	86.83bc	28.300d	24.000cd	43.667a	2446.0c	0.2170bc	31.533de	6.6567bc
Hemp 50%	87.06bc	30.637abc	25.333abc	38.833cd	2963.0a	0.2147c	2.600cd	7.3000abc
Hemp 75%	87.5b	28.817cd	27.000a	40.333bc	2932.0a	0.2323ab	32.967c	9.6900a
Neem + Hemp 50% +50%	95.5a	31.867a	26.333ab	43.333ab	2963.0a	0.2347a	33.367bc	8.8100ab

Means in a column followed by the same latters are not significantly different at P < 0.05 by Least Significant Difference Test.

The present study demonstrated that both neem and hemp amendments significantly suppressed nematode infestation under greenhouse, and field conditions, with a clear concentration-dependent response. The highest suppression was consistently observed with neem at 75%, followed by the combined treatment (neem + hemp, 50% + 50%), while hemp alone showed comparatively moderate efficacy. These findings are consistent with earlier reports indicating that botanicals possess strong nematicidal potential and can significantly reduce gall formation, juvenile populations, and egg mass production in RKN-infested crops (Siddiqui and Alam, 1988; Akhtar, 2000; Mukhtar et al., 2013a, b, c).

The superior performance of neem observed in the present study may be attributed to its rich array of bioactive compounds, particularly limonoids such as azadirachtin, which exert multiple modes of action including antifeedant, ovicidal, and nematostatic effects. Neem-derived compounds are known to interfere with nematode behavior, suppress egg hatching, and reduce juvenile infectivity, thereby limiting penetration into host roots (Devakumar et al., 1985; Akhtar, 2000). Moreover, decomposition products of neem such as phenolics, fatty acids, and volatile organic compounds may further contribute to soil suppressiveness by altering nematode survival and enhancing microbial antagonism in the rhizosphere (Schmutterer, 1990; Bridge, 1996).

Similarly, hemp exhibited significant nematicidal activity, although its effect was comparatively lower than neem. The bioactivity of hemp can be linked to its diverse secondary metabolites, including cannabinoids, terpenoids, flavonoids, and phenolic compounds, many of which have been reported to possess antimicrobial and pesticidal properties (Andre et al., 2016). These compounds may disrupt nematode metabolism, impair egg viability, and reduce infective juvenile activity. Previous studies have also demonstrated the suppressive potential of plant-derived extracts against soil-borne pathogens, supporting the current findings (Elbadri et al., 2008; Ntalli et al., 2009).

The combined application of neem and hemp consistently showed enhanced nematode suppression compared with hemp alone and, in several cases, approached the efficacy of neem. This synergistic effect may be attributed to the complementary action of different bioactive compounds, which together may enhance nematode mortality while simultaneously improving soil microbial activity. Organic amendments are known to stimulate beneficial microbial populations, leading to increased competition and antagonism against plant-parasitic nematodes (Alabouvette et al., 1996). Such shifts in soil microbial dynamics likely contribute to the suppressive environment observed in treated soils.

In addition to nematode suppression, both amendments significantly improved tomato growth and yield parameters under nematode pressure. The improvement in plant height, biomass, fruit number, and fruit weight, particularly under the combined treatment, reflects reduced root damage and improved nutrient uptake efficiency. Similar enhancements in plant growth following organic amendments have been previously reported in vegetables and field crops, where improved soil fertility and microbial activity contributed to better plant performance (Salawu, 1992; Akhtar and Malik, 2000).

Interestingly, root weight showed a positive association with nematode infection in untreated plants, likely due to gall formation induced by nematode feeding sites, which cause abnormal cell proliferation (hyperplasia and hypertrophy). Such anatomical modifications have been widely documented in RKN-host interactions and are directly associated with yield reduction. In contrast, reduced galling under botanical treatments corresponded with healthier root architecture and improved physiological function.

The observed increase in yield components under neem and hemp amendments may also be linked to enhanced nutrient availability and improved soil biochemical activity. Organic inputs can stimulate mineralization processes and increase the availability of essential nutrients such as nitrogen, phosphorus, and potassium. Furthermore, improved mycorrhizal associations under organic amendments may contribute to better nutrient uptake and plant vigor, ultimately enhancing fruit production (Natarajan et al., 2006).

Although neem demonstrated strong nematicidal activity, slight reductions in certain growth parameters at higher concentrations suggest potential phytostimulatory or phytotoxic balance effects, as previously reported for concentrated botanical extracts. Nevertheless, overall plant performance remained significantly superior to the untreated infected control, confirming the agronomic potential of these amendments.

Importantly, the present findings highlight that botanical amendments not only act directly against nematodes but also indirectly enhance plant resilience through improved soil health, microbial activity, and nutrient cycling. Similar dual-action effects have been reported in earlier studies where plant-derived products simultaneously suppressed nematodes and improved crop productivity under both controlled and field conditions (Bridge, 1996; Akhtar, 2000).

Conclusions

In conclusion, neem and hemp, particularly when applied in combination, offer an effective, eco-friendly, and sustainable alternative to synthetic nematicides for the management of *M. incognita* in tomato. Their integration into nematode management strategies could reduce chemical dependency while improving soil health and crop productivity, especially under temperate agro-ecological conditions.

Authors' Contributions

MTK and RA conceived and designed the study. HMR, IA, BM, and RA conducted the experiments and collected and analyzed the data. MTK and IA drafted the manuscript, while RA and MTK critically reviewed and revised it. All authors read and approved the final version of the manuscript.

Research Funding

This research did not receive any grant from funding agencies.

Conflict of Interest

The authors declare no conflict of interest.

Sustainable Development Goals Targeted

SDG 2: Zero Hunger
SDG 12: Responsible Consumption and Production
SDG 15: Life on Land

Policy Addressed

This study supports agricultural, environmental, and bioresource policies by demonstrating that combined neem and hemp soil amendments enhance tomato yield and suppress Meloidogyne incognita. The findings promote sustainable, chemical-free nematode management, support climate-resilient agriculture, and provide scientific evidence for the regulated commercialization of locally available Cannabis sativa as a cost-effective botanical resource for smallholder farming.

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