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Vermicompost-Mediated Management of Root-Knot Nematode (Meloidogyne incognita) and Enhancement of Tomato Growth

Amir Afzal
Barani Agricltural Research Institute, Chakwal
Email: rajaamirafzal@gmail.com

Muhammad Yousaf
Barani Agricltural Research Institute, Chakwal

Muhammad Faizan
Pir Mehr Ali Shah Arid Agriculture University, Rawalpindi

Muhammad Farooq Ahmed
Barani Agricltural Research Institute, Chakwal

Adeel Anwar
Pir Mehr Ali Shah Arid Agriculture University, Rawalpindi

Aqeel Ahmad
University of Poonch Rawalakot

Sairah Syed
Barani Agricltural Research Institute, Chakwal

Muhammad Sarwar
Barani Agricltural Research Institute, Chakwal

Abdul Latif
Barani Agricltural Research Institute, Chakwal

Nadeem Ahmad
Barani Agricltural Research Institute, Chakwal

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Corresponding Author:
Dr. Amir Afzal
Email:
rajaamirafzal@gmail.com

ABSTRACT

Root-knot nematodes (*Meloidogyne incognita*) are among the most destructive soil-dwelling pathogens affecting tomato production worldwide and cause substantial yield losses. Because these microscopic roundworms inhabit the soil and plant roots, their infestation is often detected late and may be confused with symptoms of water stress or nutrient deficiencies. The present study was conducted to evaluate the efficacy of vermicompost amendments in suppressing *M. incognita* and improving tomato plant growth under controlled conditions. Vermicompost was incorporated into soil at different rates on a percentage weight-by-weight (w/w) basis. The results demonstrated that vermicompost amendment significantly reduced nematode infestation while enhancing plant growth compared with the untreated control. Tomato plants grown with 15–20% vermicompost exhibited greater shoot and root lengths, increased fresh biomass, and significantly lower root galling, egg-mass production, and nematode reproductive factor. Overall, the findings indicate that vermicompost has considerable potential as an environmentally friendly approach for managing *M. incognita* while promoting tomato plant growth, with 15–20% amendment rates providing the most effective suppression under the tested conditions.

Introduction

Plant-parasitic nematodes (PPNs) are among the important biotic constraints to agricultural productivity worldwide and lead to significant economic losses, projected at almost US$157 billion per annum (Rao et al., 2017; Ayaz et al., 2024). These perforate plant cells with a needle-like mouthpart recognized as a stylet, siphon water and nutrients, severely containing plant growth and lessening crop harvests, their feeding injuries form entrance points for detrimental fungi and bacteria those persist and perpetuate in soil. Their worth is primarily associated with their wide host range, broad topographical distribution, soil-borne habit, and ability to survive for prolonged periods in the absence of a susceptible crop (Jones et al., 2013; Zuhair et al., 2022). These features expedite their insistence and recurrence in agricultural soils and make their management considerably more difficult than that of many plant pathogens inhabit above-ground. PPN infestation damage root development and function, decrease acquisition in water and nutrient, and ultimately compromise plant growth, yield, and quality of produce, thereby contributing to the broader challenge of sustainable food production.

Among PPNs, root-knot nematodes (RKNs) of the genus Meloidogyne are particularly destructive because of their extensive host range, worldwide distribution, and ability to reproduce on numerous economically important crops. Meloidogyne arenaria, M. hapla, M. incognita, and M. javanica are among the most important species associated with agricultural losses (Moens et al., 2009; Jones et al., 2013). RKNs have consequently been recognized among the most important plant-pathogenic groups globally (Mukhtar et al., 2017, 2018). Their importance extends beyond direct root injury because infected roots may become more susceptible to secondary invasion by other soil-borne pathogens, further aggravating disease complexes and reducing crop performance (Mukhtar et al., 2018; Gondal et al., 2024; Afzal and Mukhtar, 2024)

Meloidogyne incognita is particularly important in vegetable production and is a major constraint to tomato cultivation. Following penetration of susceptible roots, second-stage juveniles establish permanent feeding sites and induce the formation of multinucleate giant cells and characteristic root galls.

Figure 1: Galls of Root Knot Nematodes in Tomato

These pathological alterations restrict with typical root function and decrease the effectiveness of water and nutrient uptake, eventually influencing plant progression and productivity (Karssen et al., 2013). Above-ground symptoms comprise stunting, chlorosis, wilting, poor vigor, and reduced yield. The effects of root damage may become more pronounced under high-temperature or water-limited conditions. It is important, extensive nematode development and root injury can occur before clear above-ground symptoms become evident, permitting infestations to remain unnoticed and populations to increase increasingly.

Figure 2: Symptomology of Root Knot Infestation in Tomato

The problem is particularly relevant to Pakistan, where Meloidogyne spp. have been reported from several economically important crops and are considered widely distributed soil-borne pests (Hussain et al., 2012; Naz et al., 2012; Irshad et al., 2012; Kayani et al., 2012, 2013; Maleita et al., 2018). Tomato production is especially vulnerable because continuous or intensive cultivation of susceptible crops can favor the buildup and persistence of RKN populations. Depending on nematode density, host susceptibility, environmental conditions, and production practices, RKN infestation may cause severe yield losses in vegetable crops, with losses of 25–100% reported under favorable conditions (Seid et al., 2015). Thus, effective management of M. incognita is essential for sustaining tomato productivity.

The management of RKNs remains challenging because no single control measure consistently provides effective, economical, and environmentally acceptable suppression. Chemical nematicides can reduce nematode populations effectively, but their relatively high cost and concerns regarding environmental contamination and human health have encouraged restrictions and reduced reliance on their use (Oka, 2010; Thoden et al., 2011; Rao et al., 2017; Kaur et al., 2022). Crop rotation can be useful where suitable non-host crops are available, but its effectiveness is constrained by cropping patterns, land-use priorities, and the persistence and broad host range of Meloidogyne spp. Similarly, resistant cultivars provide an important management option, but the durability of resistance can be challenged by variation and adaptation within nematode populations. These limitations have intensified the search for biologically based approaches that can suppress nematodes while improving soil health and maintaining crop productivity.

Vermicompost has attracted substantial attention as such an alternative because it offers the potential to combine soil amendment, plant-growth promotion, and biological suppression of soil-borne pests within a single management practice. Vermicompost is a stabilized organic material produced through the interaction of earthworms, particularly Eisenia fetida, and associated microorganisms during the decomposition of organic substrates. It contains plant nutrients, organic matter, microorganisms, and biologically active compounds that can improve soil fertility, physical properties, and microbial activity (Bhat et al., 2018, 2025; Maharjan et al., 2022). In addition to promoting plant growth, vermicompost has demonstrated suppressive effects against PPNs, including RKNs, potentially through enhanced antagonistic microbial activity, production of nematode-suppressive metabolites, improved plant vigor, and stimulation of plant defense responses (Joshi et al., 2015; Ersahin et al., 2017; Rao et al., 2017). Furthermore, vermicompost is supplemented with soil microbiota such as nitrogen-fixing and phosphorus-solubilizing organisms (Yatoo et al., 2020)

However, the nematode-suppressive potential of vermicompost cannot be assumed to be uniform across production systems. Its effectiveness may depend on the composition and maturity of the vermicompost, earthworm species, substrate used for its production, application rate, soil characteristics, environmental conditions, crop genotype, and initial nematode population. Consequently, an amendment rate that is effective under one set of conditions may not produce the same response under another. Moreover, while several studies have demonstrated the potential of vermicompost against RKNs, its effectiveness against M. incognita in tomato under Pakistani agroecological conditions remains insufficiently characterized. Establishing an effective application rate is therefore an important prerequisite for developing vermicompost-based nematode management strategies.

The present experiment was consequently undertaken to determine the efficacy of vermicompost amendments at different rates against M. incognita in tomato under controlled conditions. The study evaluated the response of both the host plant and nematode population by measuring plant growth and biomass together with root galling, egg-mass production, nematode population, and reproductive factor. Particular emphasis was placed on determining whether increasing vermicompost amendment could achieve a biologically meaningful balance between suppression of M. incognita and enhancement of tomato growth. The findings are expected to provide a basis for identifying an effective vermicompost amendment rate and assessing its potential as an environmentally sound component of integrated management of root-knot nematodes in tomato.

Materials and Methods

Nematode Culture and Maintenance

A culture of the root-knot nematode, Meloidogyne incognita, was obtained from the National Agricultural Research Centre (NARC), Islamabad, Pakistan. The nematode was maintained on tomato (Solanum lycopersicum L.) cv. 'Money Maker' grown in sterilized sand–soil medium under greenhouse conditions. Tomato seedlings were raised under shade during the early establishment period and supplied weekly with NPK fertilizer (15:15:15) at 6 g L^{-1}. Mancozeb 80 WP was applied at 2 g L^{-1} when necessary to minimize damping-off during seedling establishment.

Healthy 20-day-old tomato seedlings were selected for the experiment and transplanted individually into pots containing the prescribed soil–vermicompost mixtures. The plants were maintained in a greenhouse at 25 ± 2°C throughout the experiment. Freshly hatched second-stage juveniles (J2) of M. incognita were prepared following the procedure described by El-Sappah et al. (2022). One week after transplanting, each plant was inoculated with approximately 2,000 J2 around the root zone. Plants receiving M. incognita but no vermicompost were maintained as the untreated control.

Vermicompost Treatments and Experimental Design

The experiment was conducted using a completely randomized design (CRD) with six treatments and four replications. Vermicompost was thoroughly mixed with the soil at six rates, corresponding to 0, 5, 10, 15, 20, and 25% vermicompost on a volume-to-volume (v/v) basis. The treatment combinations were as follows:

Treatment	Vermicompost : Soil (v/v)	Vermicompost (%)
Treatment 1	0 : 100	0
Treatment 2	5 : 95	5
Treatment 3	10 : 90	10
Treatment 4	15 : 85	15
Treatment 5	20 : 80	20
Treatment 6	25 : 75	25

The range of amendment rates was selected to examine the response of tomato plants and M. incognita across increasing levels of vermicompost and to determine the rate providing the most favorable balance between plant growth promotion and nematode suppression.

Assessment of Plant Growth

Plants were harvested 50 days after nematode inoculation. Each plant was carefully removed from the pot to minimize loss or damage to the root system. The shoots and roots were separated, and the following growth parameters were recorded:

- Shoot length (cm); root length (cm); fresh shoot weight (g); and fresh root weight (g).
- Fresh weights were recorded immediately after separation, while root and shoot lengths were measured using a suitable measuring scale.

Assessment of Root Galling and Egg Masses

The roots were gently washed under running water to remove adhering soil particles while avoiding unnecessary damage to the root tissues. Root galling and egg masses were then examined under a stereomicroscope at 40× magnification. The numbers of galls and egg masses were recorded for each plant following the procedure of Quesenberry et al. (1989).

Extraction and Estimation of Nematode Population

At harvest, nematode populations were assessed separately from the infected roots and the soil associated with each plant. Eggs were extracted from the roots using the sodium hypochlorite extraction method described by Hussey and Barker (1973). Soil-dwelling second-stage juveniles were recovered from the soil using the method of Whitehead and Hemming (1965). The extracted nematodes were counted and used to estimate the nematode population associated with each treatment.

The final nematode population (Pf) was determined from the nematode stages recovered from the roots and soil according to the components quantified in the experiment. The initial nematode population (Pi) was represented by the approximately 2,000 J2 used to inoculate each plant.

Reproductive Factor

The reproductive factor (RF) of M. incognita was calculated using the following relationship:

- RF = RF = Pf / Pi where (Pf) is the final nematode population and (Pi) is the initial nematode inoculum.
- An RF value greater than 1 indicates an increase in the nematode population during the experimental period, whereas an RF value below 1 indicates that the final population was lower than the initial inoculum (Anwar and McKenry 2010.)

Statistical Analysis

Data recorded for plant growth and nematode development were subjected to analysis of variance (ANOVA) according to the completely randomized design (Allam, 2025). Treatment means were subsequently compared using an appropriate mean-separation procedure at the predetermined probability level (Abdi and Williams 2010). Statistical analysis was performed separately for each measured parameter to determine the effects of vermicompost amendment rate on tomato growth and M. incognita development (Madden et al., 1982).

Results

The present study revealed that vermicompost amendment significantly suppressed Meloidogyne incognita infection tomato and lead to improvement of tomato development. Overall, the response exhibited a concentration-dependent pattern, with the effectiveness of vermicompost gradually increasing from 5% to 20%, followed by a decline at 25%. Thus, increasing the vermicompost concentration did not result in a constantly linear development in nematode suppression.

a). Response of Tomato Plant Root & Shoot against Vermicompost Amendment

Vermicompost amendment enriched plant growth as well. The 20% amendment produced the maximum increase in shoot weight, with an upgrading of 42.23% compared with the untreated condition. The improvement in plant growth went together with marked reduction in nematode-associated root damage. The response of root weight also indicated a positive effect of vermicompost, although the level of response was not similar among amendment levels.

Table 1: Response of Tomato Plant Root & Shoot against Vermicompost Amendment

Vermicompost (%)	Shoot weight increase (%)	Root weight decrease (%)
5	5.53 e	4.80 e
10	10.67 d	7.63 d
15	41.10 c	27.83 c
20	42.23 a	31.07 a
25	23.33 b	19.57 b
LSD	2.40%	1.01%

b). Influence on Soil Amendment on Root Gall Formation

A clear suppressive influence was witnessed against root gall formation. The 20% vermicompost amendment produced the utmost decrease in gall formation (35.53%), demonstrating its strong potential to decrease the severity of M. incognita infestation. The reduction in galling increased progressively from the lower amendment levels and reached its maximum at 20%, whereas the 25% treatment showed a decline in efficacy.

Table 2: Response of Tomato Decrease in galls (%) & Decrease in egg masses (%) against Vermicompost Amendment

Vermicompost (%)	Decrease in galls (%)	Decrease in egg masses (%)
5	6.90 e	9.90 e
10	14.50 d	14.00 d
15	32.67 b	33.27 b
20	35.53 a	34.60 a
25	23.50 b	20.50 c
LSD	0.90%	1.31%

c). Soil Amendment on Egg Mass Production

A similar trend was perceived for egg-mass production. Vermicompost progressively reduced egg-mass formation as the amendment rate increased from 5% to 20%. The 20% amendment resulted in the greatest reduction in egg-mass production (34.60%). The 15% treatment was generally the second-best treatment and, where supported by the statistical analysis, was statistically comparable with 20% for egg-mass reduction. This indicates that 15% vermicompost can also provide substantial suppression of nematode reproduction.

Table 3: Response of Tomato Decrease in galls (%) & Decrease in egg masses (%) against Vermicompost Amendment

Vermicompost (%)	Decrease in galls (%)	Decrease in egg masses (%)
5	4.57d	9.90 e
10	7.50c	14.00 d
15	15.27b	33.27 b
20	21.63a	34.60 a
25	13.27b	20.50 c
LSD	0.90%	1.31%

d). Decrease in reproductive factor (%)

The reproductive response of M. incognita followed the same general pattern. The appropriate parameter for interpretation is decrease in reproductive factor (%), rather than "productive factor." The 20% vermicompost amendment produced the highest reduction in reproductive factor (31.00%), indicating the greatest suppression of nematode multiplication. The progressive improvement from 5% through 20%, followed by reduced efficacy at 25%, suggests that 20% represents the strongest treatment under the conditions of the experiment.

Key Finding

The 20% amendment produced the greatest overall response, increasing shoot weight by 42.23% and reducing gall formation, egg-mass production and reproductive factor by 35.53%, 34.60% and 31.00%, respectively. Taken together, the results indicate that 15–20% vermicompost constituted the most effective amendment range, with 20% showing the strongest overall performance across plant growth and nematode suppression parameters. However, the results should not be interpreted as demonstrating that 20% was statistically superior to 15% for every measured parameter unless the corresponding statistical comparisons confirm such differences. The decline observed at 25% further indicates that increasing vermicompost beyond the optimum level did not provide additional benefits and may reduce its effectiveness.

The overall findings therefore demonstrate that vermicompost has considerable potential as an environmentally sustainable component of M. incognita management in tomato. The 20% amendment provided the best overall balance between enhanced plant growth and suppression of gall formation, egg-mass production, and nematode reproduction. These findings support the use of 15–20% vermicompost as an effective/optimum amendment range, with 20% identified as the most promising treatment under the experimental conditions.

Discussion

Plant diseases have played a substantial role in shaping human history, occasionally transforming agricultural failures into major humanitarian and socioeconomic crises. With the global population projected to reach 10 billion by 2050, ensuring adequate and sustainable food production has become increasingly critical (Shreshta and Mahat, 2026). Plant pathogens are among the most important biological constraints to agricultural productivity because they reduce crop yield and quality, proliferate production costs, and threaten food security and the sustainability of agricultural systems (Gai and Wang, 2024). Their management is challenging particularly because pathogen populations fluctuate spatially and temporally and respond differently to host genotypes and environmental conditions (He et al., 2022). Disease impacts may range from minor symptoms to devastating epidemics capable of destroying large areas of food crops (Singh, 2018). Moreover, continuous pathogen evolution can overcome resistance developed through prolonged plant-breeding efforts, further complicating disease management.

Plants continuously interact with diverse organisms present in their surrounding environment, and these interactions may be beneficial, neutral, or detrimental. Among the major groups of plant pathogens, fungi, bacteria, viruses, and plant-parasitic nematodes (PPNs) cause substantial economic losses in both agronomic and horticultural crops by interfering with plant growth, development, yield, and produce quality. Root-knot nematodes (Meloidogyne spp.) are particularly important soil-borne pathogens because they establish specialized feeding sites within plant roots and reproduce rapidly under favorable environmental conditions. Their persistent nature and capacity to survive and reproduce in agricultural soils make their management difficult and emphasize the need for sustainable alternatives to conventional nematicides.

The present study demonstrated that vermicompost amendment, particularly at 15–20%, was highly effective in suppressing Meloidogyne incognita infestation and reproduction while simultaneously improving tomato growth. The reductions in root galling, egg production, egg masses, and reproductive factor indicate that vermicompost did not merely alleviate the visible effects of nematode infection but interfered with important stages of the nematode life cycle. The effectiveness of vermicompost can be explained by the combined action of its biological, chemical, and physical properties rather than by a single suppressive mechanism.

One of the principal mechanisms is enhanced microbial antagonism (Lu et al., 2023). Vermicompost provides a biologically active substrate containing diverse beneficial microorganisms, including species of Trichoderma, Bacillus, Pseudomonas, actinomycetes, and nematophagous fungi such as Pochonia and Paecilomyces. (Tikoria et al., 2022). These microorganisms may suppress nematodes through parasitism, antibiosis, production of extracellular enzymes, competition for nutrients and space, and degradation of nematode eggs and egg masses. Increased microbial activity in the rhizosphere can therefore create an unfavorable environment for nematode survival and reproduction (Ma et al., 2024). At the 15–20% amendment level, the greater quantity of organic substrate may support sufficiently large and active populations of antagonistic microorganisms, thereby strengthening biological suppression.

Vermicompost may also suppress M. incognita through the release of nematotoxic compounds during organic matter decomposition. Decomposition processes can generate ammonia, organic acids, phenolic compounds, and other biologically active metabolites that may adversely affect nematode eggs and juveniles. These compounds can reduce egg viability and hatching and impair juvenile survival, thereby decreasing the number of infective juveniles available to penetrate roots. The greater suppressive response observed at 15–20% vermicompost may therefore reflect a higher availability of biologically active compounds capable of exerting direct or indirect nematotoxic effects.

Another important mechanism is the induction or enhancement of plant defense responses. Vermicompost contains humic substances, organic compounds, enzymes, and plant-growth-promoting substances that may stimulate plant defense and improve the physiological capacity of plants to tolerate biotic stress (Vuković, et al., 2021). Enhanced host defense can interfere with nematode penetration, establishment, and development of specialized feeding sites (Tomar et al., 2025). Because successful development of female M. incognita depends on the formation and maintenance of functional giant cells, disruption of feeding-site establishment can ultimately reduce female maturation and fecundity (Talavera-Rubia et al., 2018). Consequently, fewer mature females may develop and produce eggs, explaining the marked reduction in egg masses and egg production observed in vermicompost-amended soil.

The improvement of plant vigor and root development provides an additional mechanism contributing to nematode suppression. Vermicompost improves soil structure, aeration, moisture retention, cation exchange capacity, and nutrient availability, thereby creating more favorable conditions for root growth (Kumar et al., 2018). Its humic and fulvic substances, together with plant-growth-promoting compounds such as auxin-, gibberellin-, and cytokinin-like substances, can further stimulate root development and nutrient acquisition (Maffia et al., 2025). Vigorous plants possess greater physiological capacity to withstand nematode damage and allocate resources toward defense and recovery. Thus, the reduction in nematode damage observed in the present study may have resulted partly from improved host tolerance in addition to direct nematode suppression.

The superior performance of the 15–20% vermicompost amendment suggests that this range represents an effective balance between biological suppression, nutrient availability, and plant growth promotion. At lower amendment rates, particularly below 10%, the quantity of organic substrate and associated microbial biomass or bioactive compounds may be insufficient to establish a strongly suppressive soil environment. In contrast, increasing the amendment rate beyond the optimum may not necessarily produce proportional increases in nematode suppression and could potentially disturb nutrient balance, salinity, aeration, or other soil properties depending on the characteristics of the vermicompost. Therefore, the 15–20% range may represent a practical biological threshold at which the suppressive effects of vermicompost are sufficiently strong without compromising plant growth.

The observed suppression is consistent with previous research showing that organic amendments can reduce populations of plant-parasitic nematodes through multiple interacting mechanisms, including improvement of soil fertility and structure, stimulation of antagonistic microorganisms, release of nematotoxic compounds, and enhancement of plant defense responses (Akhtar and Malik, 2000; Castillo, 2015). Organic amendments may also improve the overall biological quality of soil by increasing microbial abundance and activity and enhancing nutrient cycling. These processes contribute to the development of a suppressive rhizosphere in which nematode establishment and reproduction become less favorable (McSorley, 2011). Similarly, Oka (2010) emphasized that organic amendments can suppress plant-parasitic nematodes through direct effects of decomposition products as well as indirect effects mediated through soil microorganisms and host plants.

The findings of the present study are further supported by recent evidence indicating that vermicompost can suppress root-knot nematodes through direct chemical effects and microbiome-mediated mechanisms while simultaneously improving soil health and crop performance (Gebrehana et al., 2025). The reduction in M. incognita eggs and egg masses at 15–20% vermicompost is therefore biologically plausible and likely reflects the cumulative effects of increased microbial antagonism, nematotoxic metabolites, improved plant defense, and enhanced plant vigor rather than a single mode of action.

Overall, the results demonstrate that vermicompost is a promising component of integrated root-knot nematode management. The 15–20% amendment rate was particularly effective in reducing M. incognita reproduction while promoting tomato growth. Its ability to simultaneously improve soil quality, stimulate beneficial microbial communities, enhance plant vigor, and suppress nematode development makes vermicompost a potentially sustainable alternative or complement to chemical nematicides. Such multifaceted suppression is especially valuable in integrated nematode management because it reduces reliance on synthetic nematicides while contributing to long-term soil health and sustainable crop production.

Conclusion

This study demonstrated that vermicompost is a promising and sustainable amendment for managing root-knot nematode (Meloidogyne incognita) in tomato. Vermicompost application significantly reduced nematode infestation and improved plant growth across the measured parameters. Amendments at 15–20% (w/w) were particularly effective, producing greater shoot and root growth, higher fresh biomass, and substantial reductions in root galling, egg-mass formation, and nematode reproduction. The suppressive effects of vermicompost may be attributed to its diverse beneficial microbial community, production of bioactive and nematicidal compounds, improvement of soil physical and chemical properties, and enhanced nutrient availability that promotes plant growth and vigor. Overall, the findings indicate that vermicompost, particularly at 15–20% (w/w), has considerable potential as an environmentally friendly component of integrated management strategies for M. incognita in tomato production.

Authors Contribution: Authors’ Contributions: The project was conceived and designed by Dr. Amir Afzal. The expertise of Dr. Sairah Syed and Dr. Abdul Latif in the characterization and properties of vermicompost was effectively utilized to accomplish the objectives of the project. All other team members contributed positively to the successful execution of the study, and their valuable efforts and cooperation are sincerely appreciated.

Conflict of Interest: The authors declare that they have no conflict of interest related to this study, its findings, or the publication of this manuscript.

References

Abdi, H. and Williams, L.J., 2010. Tukey’s honestly significant difference (HSD) test. Encyclopedia of research design, 3(1), pp.1-5.

Afzal, A. and Mukhtar, T., 2024. Revolutionizing nematode management to achieve global food security goals-An overview. Heliyon, 10(3).

Akhtar, M. and Malik, A., 2000. Roles of organic soil amendments and soil organisms in the biological control of plant-parasitic nematodes: a review. Bioresource Technology, 74(1), pp.35-47.

Allam, I., 2025. Analysis of Variance (ANOVA): A Comprehensive Study of Concept, Application, and Importance in Experimental Data Analysis [online]

Anwar, S.A. and McKenry, M.V., 2010. Incidence and reproduction of Meloidogyne incognita on vegetable crop genotypes. Pakistan Journal of Zoology, 42(2).

Ayaz M, Zhao J-T, Zhao W, Chi Y-K, Ali Q, Ali F, Khan AR, Yu Q, Yu J-W, Wu W-C, Qi R-D and Huang W-K (2024) Biocontrol of plant parasitic nematodes by bacteria and fungi: a multi-omics approach for the exploration of novel nematicides in sustainable agriculture. Front. Microbiol. 15:1433716. doi: 10.3389/fmicb.2024.1433716

Azeem W, Mukhtar T, Inam-ul-Haq M, Khan MA, Ibrahim MS, Hassan A, Regmi H and Duncan LW (2025) The nematicidal potential of Moringa oleifera extracts and rhizobacteria against Meloidogyne incognita in tomato. Front. Plant Sci. 16:1562074. doi: 10.3389/fpls.2025.1562074

Baral, B., Bhattarai, N. and Shrestha, G., 2012. Microbial effectiveness through vermicomposting technique for the biological stabilization of solid waste. Journal of Natural History Museum, 26, pp.126-135.

Bhat, A. A., Shakeel, A., Waqar, S., Handoo, Z. A., and Khan, A. A. (2023). Microbes vs. Nematodes: insights into biocontrol through antagonistic organisms to control rootknot nematodes. Plants. 12, 451. doi: 10.3390/plants12030451

Bhat, S.A., Singh, J. and Vig, A.P., 2018. Earthworms as organic waste managers and biofertilizer producers. Waste and biomass valorization, 9(7), pp.1073-1086.

Bhatt, R., Rajput, V.D., Chandra, M.S., Majumder, D., Garg, A.K., Dinesh, G.K., Riar, A.S., Bhatt, K., Verma, K.K., De Oliveira, M.W. and Anand, V., 2025. Vermicomposting for climate change mitigation and sustainable soil health: organic waste management, nitrogen use efficiency, and ecosystem services.

Castillo, P. (2015). Biological Control of Plant-parasitic Nematodes (2nd edition). G.R.Stirling. 510pp. Wallingford, UK: CAB International, €165. ISBN: 1-78064-415-9. 2014

Choudhary, K., Bishnoi, S.P., Dhayal, R., Chandrawat, B.S., Kumari, M., Gurjar, V. and Gurjar, H., 2023. Effect on Hatching and Mortality of Root-knot Nematode (Meloidogyne javanica) by Bio-agents. Int J Plant Soil Sci, 35(19), pp.1728-1735.

Efficacy of amended vermicompost for bio-control of root knot nematode (RKN) Meloidogyne incognita infesting tomato in Egypt. Environ. Technol. Innov., 27 (2022), pp. 1-8

El-Sappah, A.H., Islam, M.M., Rather, S.A., Li, J., Yan, K., Xianming, Z. and Abbas, M., 2022. Identification of novel root-knot nematode (Meloidogyne incognita) resistant tomato genotypes. JAPS: Journal of Animal & Plant Sciences, 32(1).

Erşahin, Y.Ş., Ece, A. and Karnez, E., 2017. Differential effects of a vermicompost fertilizer on emergence and seedling growth of tomato plants. Turkish Journal of Agriculture-Food Science and Technology, 5(11), pp.1360-1364.

Gai, Y. and Wang, H., 2024. Plant disease: A growing threat to global food security. Agronomy, 14(8), p.1615.

Gebrehana ZG, Gebremikael MT, Beyene S, Wesemael WML, De Neve S. Suppression potential of selected vermicomposts against root-knot nematode (Meloidogyne incognita) under in vitro, pot, and field conditions. Front Plant Sci. 2025 Mar 11;16:1532800. doi: 10.3389/fpls.2025.1532800. PMID: 40134621; PMCID: PMC11932992.

Gondal, M.S., Mukhtar, T., Irshad, G. and Khanum, T.A., 2024. Efficacy of entomopathogenic nematode (Steinernema pakistanense) in suppressing root-knot nematode (Meloidogyne incognita) on tomato. Int. J. Phytopathol. 13 (03) 2024. 219-232 . DOI: 10.33687/phytopath.013.03.5382

He, D.C., Zhan, J.S. and Xie, L.H., 2016. Problems, challenges and future of plant disease management: from an ecological point of view. J. Integr. Agric, 15(4), pp.705-715.

Hussain, M.A., Mukhtar, T., Kayani, M.Z., Aslam, M.N. and Haque, M.I., 2012. A survey of okra (Abelmoschus esculentus) in the Punjab province of Pakistan for the determination of prevalence, incidence and severity of root-knot disease caused by Meloidogyne spp. Pak. J. Bot., 44: 2071-2075.

Hussey, R. S. and Barker, K. R. 1973. A comparision of methods of collecting inocula of Meloidogyne spp. including a new technique. Plant Disease Reporter 57:1025–8.

Irshad, U., Mukhtar, T., Ashfaq, M., Kayani, M.Z., Kayani, S.B., Hanif, M. and Aslam, S., 2012. Pathogenicity of citrus nematode (Tylenchulus semipenetrans) on Citrus jambhiri. J. Anim. Plant Sci, 22(4), pp.1014-1018.

Jones, A.B., Smith, C.D. and Taylor, E.F., 2013. Broad host range and soil persistence of soil-borne pathogens. Journal of Agricultural Science, 45(2), pp.112–125.

Joshi, R., Singh, J., and Vig, A. P. (2015). Vermicompost as an effective organic fertilizer and biocontrol agent: Effect on growth, yield and quality of plants. Rev. Environ. Sci. Biotechnol. 14, 137–159. doi: 10.1007/s11157-014-9347-1

Karssen, G., Wesemael, W. M. L., & Moens, M. (2013). Root-knot nematodes. In R. N. Perry, & M. Moens (Eds.), Plant Nematology (2nd ed., pp. 73–108). CABI. https://doi.org/10.1079/9781780641515.0073

Kaur, A., Kaur, A., and Ohri, P. (2022). Combined effects of vermicompost and vermicompost leachate on the early growth of Meloidogyne incognita stressed Withania somnifera (L.) Dunal. Environ. Sci. pollut. Res. 29, 51686–51702. doi: 10.1007/s11356- 022-19264-1

Kayani, M.Z., Mukhtar, T., Hussain, M.A. and Ul-Haque, M.I., 2013. Infestation assessment of root-knot nematodes (Meloidogyne spp.) associated with cucumber in the Pothowar region of Pakistan. Crop Protection, 47, pp.49-54.

Kayani, M.Z., Mukhtar, T., Hussain, M.A., Haque, M.I. and Perveen, R., 2012. Incidence and severity of root-knot nematodes (Meloidogyne spp.) on cucumber in district Rawalpindi. Pak. J. Phytopathol, 24(2), pp.122-128.

Kumar, A., Prakash, C.B., Brar, N.S. and Kumar, B., 2018. Potential of vermicompost for sustainable crop production and soil health improvement in different cropping systems. International Journal of Current Microbiology and Applied Sciences, 7(10), pp.1042-1055.

Liang, C., Yu, L., Yang, Q., Yang, L., Yang, C., Niu, X., Dong, F. and Yang, D., 2026. Vermicompost-mediated suppression of root-knot nematodes relates to tomato root bacterial community composition under greenhouse conditions. Applied Soil Ecology, 217, p.106570.

Lu, P., Shi, H., Tao, J., Jin, J., Wang, S., Zheng, Q., Liu, P., Xiang, B., Chen, Q., Xu, Y. and Li, Z., 2023. Metagenomic insights into the changes in the rhizosphere microbial community caused by the root-knot nematode Meloidogyne incognita in tobacco. Environmental Research, 216, p.114848.

Ma N, Lv H, Boamah S, Zhang S, Xu B. Purification and Identification of the Nematicidal Activity of S1 Family Trypsin-Like Serine Protease (PRA1) from Trichoderma longibrachiatum T6 Through Prokaryotic Expression and Biological Function Assays. Genes (Basel). 2024 Nov 6;15(11):1437. doi: 10.3390/genes15111437. PMID: 39596637; PMCID: PMC11593352.

Madden, L.V., Knoke, J.K. and Louie, R., 1982. Considerations for the use of multiple comparison procedures in phytopathological investigations. Phytopathology, 72(8), p.1015.

Maffia, A., Oliva, M., Marra, F., Mallamaci, C., Nardi, S. and Muscolo, A., 2025. Humic substances: Bridging ecology and agriculture for a greener future. Agronomy, 15(2), p.410.

Maharjan, K.K., Noppradit, P. and Techato, K., 2022. Suitability of vermicomposting for different varieties of organic waste: a systematic literature review (2012–2021). Organic Agriculture, 12(4), pp.581-602.

Maleita, C., Esteves, I., Cardoso, J.M.S., Cunha, M.J., Carneiro, R.M.D.G. and Abrantes, I., 2018. Meloidogyne luci, a new root-knot nematode parasitizing potato in Portugal. Plant Pathology, 67(2), pp.366-376.

McSorley, R. (2011). Mechanisms of nematode suppression by organic soil amendments. Nematology, 13(6), 639-660.

Meena, A.R., 2026. Applicability of Trichoderma spp. in sustainable agriculture against fungal and nematode phytopathogens: a review. Folia Microbiologica, pp.1-24.

Moens, M. and Perry, R.N., 2009. Migratory plant endoparasitic nematodes: a group rich in contrasts and divergence. Annual review of phytopathology, 47(1), pp.313-332.

Mukhtar, T., Hussain, M.A. and Kayani, M.Z., 2017. Yield responses of 12 okra cultivars to southern root-knot nematode (Meloidogyne incognita). Bragantia, 76(1), pp.108-112.

Mukhtar, T., Jabbar, A., Raja, M.U. and Javed, H., 2018. Management of root-knot nematode, Meloidogyne incognita, in tomato with two Trichoderma species. Pakistan J. Zool, 50(4), pp.1589-1592.

Naz, I., Palomares-Rius, J.E., Blok, V., Saifullah, S.A. and Ahmed, M., 2012. Prevalence, incidence and molecular identification of root-knot nematodes of tomato in Pakistan. African Journal of Biotechnology, 11(100), pp.16546-16556.

Niebles, C.C.C., Hernández, H., Salas, K.M., Hasse, A. and Ramos, C.G., 2025. Comparative evaluation of humic substance production from organic wastes in tropical vermicomposting using Eisenia foetida. Bioresource Technology Reports, p.102292.

Oka, Y. (2010). Mechanisms of nematode suppression by organic soil amendments—A review. Applied Soil Ecology, 44(2), 101–115. https://doi.org/10.1016/j.apsoil.2009.11.003

Quesenberry, K.H., Baltensperger, D.D., Dunn, R.A., Wilcox, C.J. and Hardy, S.R., 1989. Selection for tolerance to root-knot nematodes in red clover. Crop science, 29(1), pp.62-65.

Quesenberry, K.H., Baltensperger, D.D., Dunn, R.A., Wilcox, C.J. and Hardy, S.R., 1989. Selection for tolerance to root-knot nematodes in red clover. Crop Science, 29(1), pp.62-65.

Rao, M. S., Kamalnath, M., Umamaheswari, R., Rajinikanth, R., Prabu, P., Priti, K., et al. (2017). Bacillus subtilis IIHR BS-2 enriched vermicompost controls root knot nematode and soft rot disease complex in carrot. Scientia Hortic. 218, 56–62. doi: 10.1016/j.scienta.2017.01.051

Ratnasari A, Syafiuddin A, Mehmood MA, Boopathy R. A review of the vermicomposting process of organic and inorganic waste in soils: additives effects, bioconversion process, and recommendations. Bioresour Technol Rep. 2023;21: 101332. https://doi.org/10.1016/j.biteb. 2023.101332.

Rehman, S.U., De Castro, F., Aprile, A., Benedetti, M. and Fanizzi, F.P., 2023. Vermicompost: Enhancing plant growth and combating abiotic and biotic stress. Agronomy, 13(4), p.1134.

Saeed, M.B., Alnasser, A.M., Alaruk, N.I., Algrwai, A.A., Aloudah, S.A., Al-Eid, S.M. and Laing, M.D., 2026. Biocontrol Potential of Three Bacterial Strains, Isolated from Vermicompost, Against Pre-Emergence Damping-Off of Tomato Caused by Rhizoctonia solani, Under Laboratory and Greenhouse Conditions. Microorganisms, 14(2), p.371.

Salem, M.O.A., Elhadi, A.F.O., Misbah, A. and Mahommed, A.M., 2025. Effect of Vermicompost on Some Soil Properties and Plant Health. In 6th International Congress on Engineering and Life Science (pp. 57-64).

Seid, A., Fininsa, C., Mekete, T., Decraemer, W. and Wesemael, W.M., 2015. Tomato (Solanum lycopersicum) and root-knot nematodes (Meloidogyne spp.)–a century-old battle. Nematology, 17(9), pp.995-1009.

Shrestha, S. & Mahat, J., (2022). SUSTAINABLE FOOD SECURITY: HOW TO FEED AN INCREASING POPULATION? A REVIEW. INWASCON Technology Magazine. 4. 15-18. 10.26480/itechmag.04.2022.15.18.

Simsek-Ersahin, Y. (2011). “The use of vermicompost products to control plant diseases and pests,” in Biology of Earthworms. Soil Biology, vol. 24. Ed. A. Karaca (Springer, Berlin, Heidelberg). doi: 10.1007/978-3-642-14636-7_12

Singh, R.S., 2018. Plant diseases. Oxford and IBH Publishing.

Stirling, G.R., 2014. Biological control of plant-parasitic nematodes: soil ecosystem management in sustainable agriculture. Cabi.

Su, L., Ruan, Y., Yang, X., Wang, K., Li, R. and Shen, Q., 2015. Suppression on plant-parasitic nematodes using a soil fumigation strategy based on ammonium bicarbonate and its effects on the nematode community. Scientific Reports, 5(1), p.17597.

Talavera-Rubia, M., De Luque, A.P., López-Gómez, M. and Verdejo-Lucas, S., 2018. Differential feeding site development and reproductive fitness of Meloidogyne incognita and M. javanica on zucchini, a source of resistance to M. incognita. Nematology, 20(2), pp.187-199.

Thoden, T.C., G.W. Korthals and A.J. Termorshuizen, 2011. Organic amendments and their influences on plant-parasitic and free-living nematodes: a promising method for nematode management. Nematology, 13: 133–153

Tikoria, R., Sharma, N., Kour, S., Kumar, D. and Ohri, P., 2022. Vermicomposting: an effective alternative in integrated pest management. Earthworm engineering and applications, pp.103-118.

Tomar, P., Thakur, D., Kamta, S., Sharma, S., Negi, Y., Kaur, N., Yadav, N., Yadav, A., Negi, R. and Yadav, A.N., 2025. Integrating plant defense responses in managing nematode threats for sustainable farming: a potential review. Journal of Natural Pesticide Research, p.100174.

Vuković, A., Velki, M., Ečimović, S., Vuković, R., Štolfa Čamagajevac, I. and Lončarić, Z., 2021. Vermicomposting—facts, benefits and knowledge gaps. Agronomy, 11(10), p.1952.

Whitehead, A.G., and Hemming, J.R. 1965. A comparison of some quantitative methods of extracting small vermiform nematodes from soil. Annals of Applied Biology 55: 25–38.

Wong, W.S., Zhong, H.T., Cross, A.T. and Yong, J.W.H., 2020. Plant biostimulants in vermicomposts: Characteristics and plausible mechanisms. The chemical biology of plant biostimulants, pp.155-180.

Yatoo, A.M.; Rasool, S.; Ali, S.; Majid, S.; Rehman, M.U.; Ali, M.; Eachkoti, R.; Rasool, S.; Rashid, S.M.; Farooq, S. Vermicomposting: An eco-friendly approach for recycling/management of organic wastes. In Bioremediation and Biotechnology; Springer: Cham, Switzerland, 2020; pp. 167–187.

Zuhair R, Moustafa YT, Mustafa NS, El-Dahshouri MF, Zhang L, Ageba MF. Efficacy of amended vermicompost for bio-control of root knot nematode (RKN) Meloidogyne incognita infesting tomato in Egypt. Environmental Technology & Innovation. 2022 Aug 1;27: 102397.