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Performance of Green Manures in the Control of *Meloidogyne incognita*

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Abstract

The root-knot nematode *Meloidogyne incognita* is one of the most prevalent species in Brazil, causing significant damage to several crops. This pathogen induces the formation of root galls through hypertrophy and hyperplasia of cells. To mitigate these losses, cultural control with cover crops has shown promising results, since antagonistic species can reduce nematode reproduction while improving soil physical and chemical properties. This study evaluates the efficacy of nine green manure species in controlling the root-knot nematode *Meloidogyne incognita* in a greenhouse experiment. Using a susceptible soybean cultivar as a control, the authors measured nematode final population and reproduction factor (RF). The study found that all tested green manures were resistant (RF < 1), with *Stylosanthes capitata* demonstrating immunity (RF = 0), effectively suppressing nematode reproduction.

Keywords

Root-Knot Nematode, Cultural Control, Cover Plants

1. Introduction

Nematodes are invertebrate, cylindrical, and filamentous organisms that inhabit a wide range of aquatic environments, including marine and freshwater systems, and even the thin water films between soil particles, which are critical for their mobility into the soil [1] [2]. More than 4,100 species of plant-parasitic nematodes have been identified, causing an estimated USD 125 billion in annual agricultural losses [3] [4].

Plant-parasitic nematodes represent a substantial global constraint to crop production, accounting for notable yield reductions and posing increasing biosecurity threats under climate change scenarios [5]-[7]. In Brazil, these pests are among the most significant phytosanitary problems impacting grain systems, with *Meloidogyne*, cyst (*Heterodera*), and lesion (*Pratylenchus*) nematodes particularly affecting crops like soybean [8].

Root-knot nematodes of the genus *Meloidogyne*, commonly referred to simply as root-knot nematodes, are among the most destructive soil-borne pests affecting global agriculture [3] [9]. These organisms are obligate sedentary endoparasites: second-stage juveniles invade plant roots, establishing permanent feeding sites by inducing host cell hypertrophy and hyperplasia, resulting in characteristic galls and disruption of vascular integrity, which subsequently impairs root development [10]. Aboveground symptoms, such as stunted growth, chlorotic or necrotic foliar patches, and general vigor loss, are commonly observed, stemming from impaired nutrient and water translocation [11].

However, such symptoms, stunted growth, chlorosis, wilting, and general vigor reduction, can closely resemble those caused by nutrient deficiencies or water stress, often delaying accurate diagnosis and potentially exacerbating crop losses. Furthermore, root-knot nematodes are typically highly polyphagous, which complicates the selection of effective crop rotation strategies [12].

To mitigate the adverse effects of this nematode, several management strategies are commonly employed, including the use of resistant cultivars, chemical and biological nematicides, and crop rotation. Among these, the most effective strategy is rotation or succession with non-host or antagonistic cover crops, which suppress nematode reproduction and enhance soil quality through green manure incorporation [13] [14].

Due to the escalating damage potential of lesion nematodes and their broad host range, continuous research into green manure–based rotational systems is imperative. Such systems not only contribute to effective nematode suppression but also deliver multiple agronomic benefits to producers, including enhanced soil health and ecosystem stability [15] [16].

The objective of this study was to evaluate the efficacy of green manure crops as antagonists against *M. incognita* under controlled greenhouse conditions.

2. Materials and Methods

2.1. Experimental Site and Conditions

The experiment to evaluate the control of the root-knot nematode *M. incognita* was carried out under controlled greenhouse conditions equipped with an automatic irrigation system. The irrigation was calibrated to operate in 15-minute intervals, applying approximately 7 mm of water per cycle. The greenhouse was located at the Centro Universitário Dinâmica das Cataratas (UDC), in the municipality of Medianeira, western Paraná State, Brazil (25˚17'19" S, 54˚7'39" W, altitude 378 m).

2.2. Inoculum Preparation of *M. incognita*

The inoculum of *M. incognita* was obtained from a commercial tomato cultivation area located at Foz do Iguaçu, Paraná State, Brazil, and subsequently multiplied on soybean plants under greenhouse conditions. Nematode extraction from soybean roots was performed following the methodology described by Hussey & Barker, as adapted by Bonetti & Ferraz. The roots were washed and cut into pieces of approximately 1 cm (**Figure 1(A)**), then blended with water for 30 seconds in the presence of a 0.5% sodium hypochlorite solution (**Figure 1(B)**). The sodium hypochlorite was used to dissolve the egg masses of *M. incognita*, thereby increasing extraction efficiency.

Figure 1. Nematode extraction: root cutting (A); root processing with sodium hypochlorite in a blender (B).

2.3. Inoculum Extraction and Purification

After blending, the suspension was poured onto a 100-mesh sieve placed over a 400-mesh sieve (**Figure 2(A)**). The material retained on the 400-mesh sieve (**Figure 2(B)**) was collected into centrifuge tubes using a wash bottle with water and a funnel (**Figure 2(C)**). The tubes were centrifuged for 5 min at 1750 rpm (rotor radius 15 cm) (**Figure 2(D)**). The resulting supernatant was discarded, and a sucrose solution (45.4%) was added to the tubes, which were centrifuged again for 1 min at 1750 rpm (rotor radius 15 cm). Subsequently, the supernatant was poured over a 500-mesh sieve, washed with water to remove the sucrose, and the retained material was collected into a beaker using a wash bottle, thus obtaining the suspension used for inoculation.

The inoculum suspension was counted using Peters' chamber under an optical microscope. The analysis revealed a concentration of approximately 27,200 *M. incognita* specimens (eggs + second stage juveniles – J2) in 90 mL of suspension.

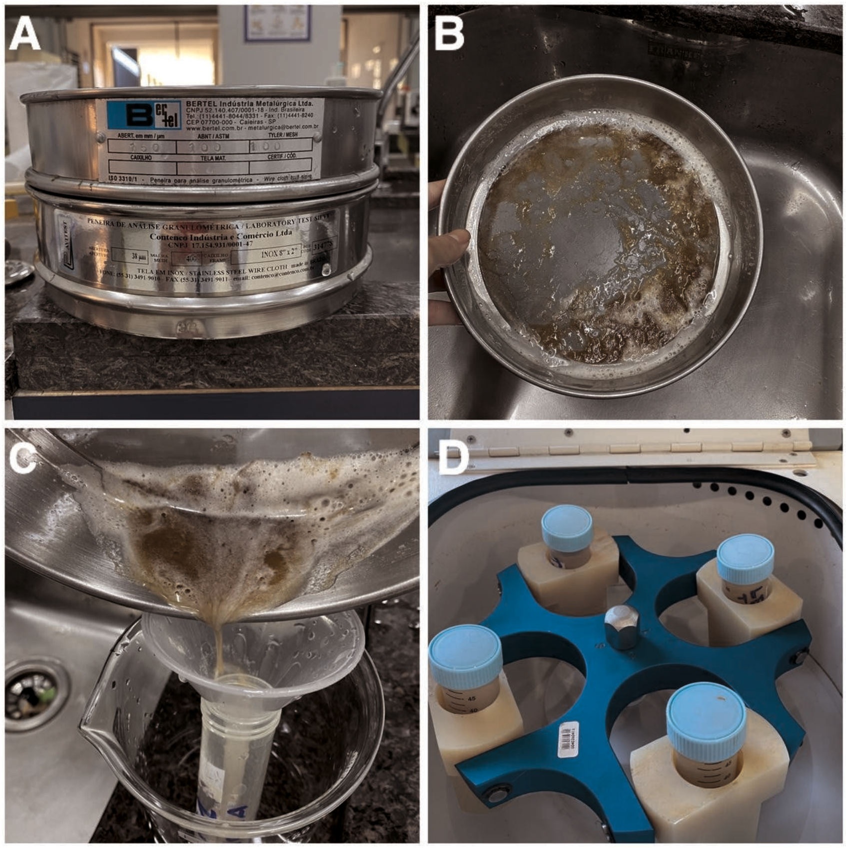

Figure 2. Nematode extraction: 100-mesh sieve placed over a 400-mesh sieve (A); suspension retained on the 400-mesh sieve (B); suspension being transferred into *Falcon* tubes (C); tubes during centrifugation (D).

2.4. Sowing of Green Manure Species and Inoculation

The experiment was conducted under greenhouse conditions, with climatic variables monitored using a thermo-hygrometer. The mean maximum and minimum air temperatures reached 42˚C and 18˚C, respectively, while relative humidity ranged from 67.40% (maximum) to 17.42% (minimum).

The experimental design consisted of a completely randomized design (CRD) with 10 treatments and four replicates per treatment. Treatments comprised different green manure species, as follows: *Medicago sativa* L.; *Crotalaria juncea* L.; *Crotalaria spectabilis* Roth.; *Crotalaria ochroleuca* L.; *Cajanus cajan* L. Millsp.; *Canavalia ensiformis* L. DC.; *Stylosanthes capitata* Vog.; *Lablab purpureus* L. Sweet; *Mucuna pruriens* L. DC. and *Glycine max* L. Merrill (used as a standard susceptible plant to the nematode).

For sowing, plastic pots with a 3.0 dm^3 capacity were used. Pots were filled with a 1:1 mixture of soil and sand. The soil was previously sterilized by autoclaving at 127˚C and 1 atm for 2 hours. The seeding rate per pot was calculated proportionally according to the supplier's recommended field rate ($kg \cdot ha^{-1}$), considering the pot surface area of 0.025447 m^2.

For inoculation, holes of 4 cm depth were made in the soil at 1 cm from the seeding point (**Figure 3(A)**). Using a 1 mL automatic pipette, 2 mL of the nematode suspension were applied to each pot (**Figure 3(B)**), corresponding to an initial inoculum density of 604 *M. incognita* specimens (eggs + J2) per pot.

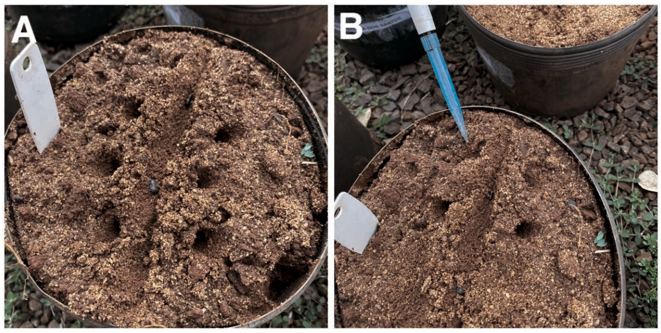

Figure 3. Inoculation of *M. incognita*: holes made near the seed (A); inoculation using a pipette (B).

2.5. Data Collection Statistical Analysis

The evaluation was carried out 70 days after sowing. In the first assessment stage, the shoots were cut at soil level (**Figure 4(A)**). The fresh shoot biomass was recorded, and the material was subsequently dried in a forced-air circulation oven at 65˚C for 72 h (**Figure 4(B)**), to determine the dry shoot biomass of each green manure species. The roots were separated from the soil, washed, and placed on absorbent paper for drying (**Figure 4(C)**). At this stage, root fresh biomass was measured (**Figure 4(D)**).

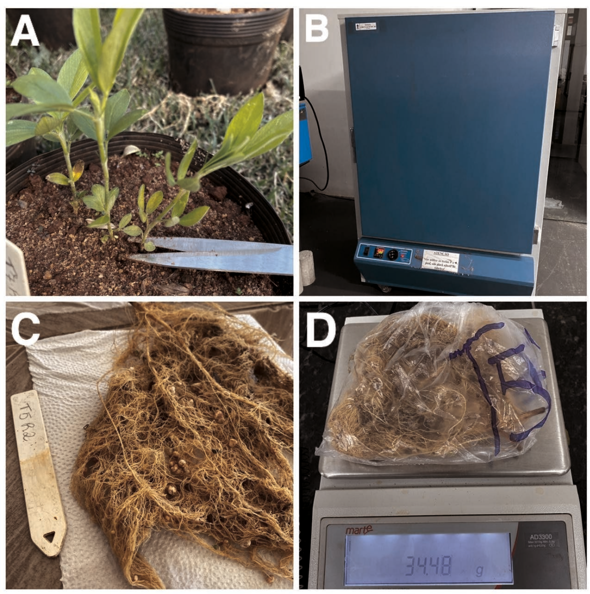

Figure 4. Data collection: shoot cutting (A); forced-air circulation oven (B); root drying (C); fresh root biomass weighing (D).

In a second evaluation stage, the roots were subjected to nematode extraction following the methodology proposed by Hussey & Barker, adapted by Bonetti &

Ferraz, as previously described. The obtained suspension was used to determine the final nematode population in each treatment, using Peters' chamber. In each sample, the number of *M. incognita* specimens was quantified, specifically eggs (Figure 5(A)) and J2 juveniles (Figure 5(B)). The reproduction factor (RF) was calculated by dividing the final population by the initial inoculum.

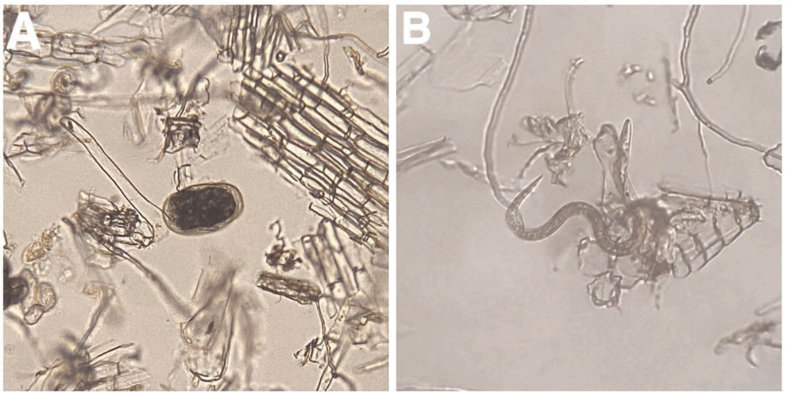

Figure 5. Analysis of *Meloidogyne incognita*: egg (A); second-stage juvenile (J2) (B).

2.6. Statistical Analysis

The variables analyzed were the final population of *M. incognita*, final population per gram of root, nematode reproduction factor, final population per gram of shoot fresh weight, and final population per gram of shoot dry weight.

Data on shoot fresh weight, shoot dry weight, and root fresh weight were not subjected to analysis of variance, since biomass accumulation was not compared among the plants studied, as they belonged to different species. However, these measurements were used to obtain nematological variables, relating nematode populations to plant biomass accumulation.

All data were tested for homogeneity and normal distribution using Cochran's and Shapiro-Wilk's tests, respectively, at a 5% significance level. Variables meeting these assumptions were subjected to analysis of variance (ANOVA), and treatment means were compared using the Scott-Knott test. Both analyses were performed with the SISVAR software [17]. Some data were also analyzed using the nonparametric Kruskal-Wallis test at a 5% significance level. In cases where significant differences were detected, medians were compared using Dunn's test at a 5% probability level.

3. Results and Discussion

The nematological variables, final population of *M. incognita* and reproduction factor (RF), met the assumptions of homogeneity of error variances and normality of experimental error distribution. Only when these assumptions were fulfilled, the statistical models were applied [18]. Therefore, analysis of variance (ANOVA) was performed for these variables, and means were grouped using the Scott–Knott test at the 5% significance level.

In contrast, plant biomass-related variables, such as the final population of *M. incognita* per gram of root fresh weight, per gram of shoot fresh weight, and per gram of shoot dry weight, did not meet the assumptions required for ANOVA. Consequently, the nonparametric Kruskal-Wallis test for completely randomized designs (CRD). When significant differences were detected, multiple comparisons were made using Dunn's test.

3.1. Final Population and Reproduction Factor of *M. incognita*

According to the analysis of variance (**Table 1**), the variables final population and reproduction factor (RF) of *M. incognita* were significant at the 5% probability level, indicating that at least one treatment differed in its reaction to the nematode. The coefficient of variation (CV) was classified as very high for both variables; values exceeding 30% are commonly interpreted as indicative of high variability in agronomic trials. This is expected because RF is a ratio between final and initial populations. Nevertheless, caution is warranted when comparing CVs across distinct crop species or evaluation traits, as dispersion may reflect biological context rather than experimental inconsistency [19].

Table 1. Summary of the analysis of variance for final population and reproduction factor (RF) of *Meloidogyne incognita* in a completely randomized design.

Source variation	df	Mean square	
		Final population	RF
Treatment	9	119.9919,22*	0.319*
Error	39	9.500,00	0.026
Mean		202,50	0.335
CV (%)		48,130	48,130

Note: (*) Significant at 5% probability by the F test.

Each pot received 604 *M. incognita* specimens (eggs + J2). The overall mean final population and RF were 202.50 and 0.335, respectively, about a 66.5% reduction relative to the initial inoculum, indicating a suppressive effect. Such reduction can be modulated by host suitability and microclimatic conditions that influence development rate and generation time, under favorable temperature regimes, *M. incognita* typically completes a cycle within 3 - 8 weeks [20].

According to the Scott-Knott test for both final population and RF (**Table 2**), all green manure species grouped apart from the susceptible control (soybean), with consistently lower values. On average, the RF of green manures was 0.25 versus 1.07 for soybean, representing ~77% lower multiplication.

The control (soybean cv. BRS 284), known to be susceptible to *M. incognita*, showed a final population of 650 individuals and RF = 1.07 (susceptible threshold RF ≥ 1), validating inoculum viability and the adequacy of environmental conditions for pathogen development. Considering the life cycle described above, the

70-day greenhouse assay likely encompassed at least two nematode generations, allowing a robust assessment of host responses [20].

Table 2. Final population of *Meloidogyne incognita* and reproduction factor (RF).

Treatments	Final population	RF
Medicago sativa	125[b]	0.20[b]
Crotalaria juncea	137.5[b]	0.22[b]
Crotalaria spectabilis	112.5[b]	0.18[b]
Crotalaria ochroleuca	237.5[b]	0.39[b]
Cajanus cajan	125[b]	0.20[b]
Canavalia ensiformis	250[b]	0.41[b]
Stylosanthes capitata	0[b]	0[b]
Lablab purpureus	212.5[b]	0.35[b]
Mucuna pruriens	175.0[b]	0.28[b]
Positive control (soybean)	650[a]	1.07[a]

Note: Means followed by the same letter within a column do not differ statistically according to the Scott-Knott test at 5% probability.

All green manure species produced final populations and RF < 1, characterizing resistance, while *Stylosanthes capitata* achieved immunity (RF = 0). Thus, *Medicago sativa*, *Crotalaria juncea*, *C. spectabilis*, *C. ochroleuca*, *Cajanus cajan*, *Canavalia ensiformis*, *Lablab purpureus*, and *Mucuna pruriens* behaved as resistant, whereas *S. capitata* was immune. Although statistically similar to other resistant species, *S. capitata* reached 100% reduction in final population. Recent reviews highlight that legume-derived secondary metabolites (e.g., phenolics, tannins, and triterpenoid saponins) can deter penetration and impair development of root-knot nematodes, supporting the immunity observed for *Stylosanthes* spp. and the strong antagonism of alfalfa (*M. sativa*) [15] [21].

Beyond direct effects, cover crops can also reduce root-knot nematode pressure by shaping soil microbiota and improving soil quality, contributing to suppression at the system level. In our data, the three *Crotalaria* species were resistant (RF < 1), consistent with contemporary evidence that rotation with legumes limits infection and multiplication of *Meloidogyne* spp. [16] [22].

Canavalia ensiformis displayed moderate resistance (RF ≈ 0.41), which contrasts with contexts where it behaves as a good host. However, recent work has documented ovicidal and nematostatic activities of jack-bean seed extracts, especially when formulated with nanoparticles [23].

Cajanus cajan was resistant to M. incognita under our conditions; however, host-nematode compatibility is species-specific. Other pulses (peas, chickpeas, lentils) are susceptible to *M. enterolobii* [24], underscoring the need for regional screening before recommending legumes for rotation where multiple *Meloidogyne* species occur.

Lablab purpureus and *Mucuna pruriens* also presented resistance (RF = 0.35 and 0.28, respectively). Their volatile organic compounds and secondary metabolites are increasingly recognized as nematicidal agents [25].

Finally, discrepancies among studies may stem from genetic and virulence variability in *Meloidogyne* populations, as well as from plant genotype and soil environment [26]. These factors justify localized evaluations and the integration of resistant cover crops with complementary biological or cultural tactics for durable nematode management.

3.2. Final Population Per Gram of Root and Shoot

Based on the experimental results for the variables final nematode population per gram of root (FRM), final population per gram of fresh shoot mass (FSM), and final population per gram of dry shoot mass (DSM), a non-parametric analysis was performed using the Kruskal-Wallis test at 0.05 significance. The results provided evidence that at least one median differed significantly from the others (Table 3).

Table 3. Final nematode population per gram of fresh root mass (MFR), final population per gram of fresh shoot mass (FSM), and final population per gram of dry shoot mass (DSM).

Treatments	Final population/g FRM	Final population/g FSM	Final population/g DSM
Medicago sativa	9.88 [ab]	27.38 [a]	101.9 [a]
Crotalaria juncea	1.95 [ab]	2.26 [ab]	8.97 [ab]
Crotalaria spectabilis	2.22 [ab]	1.90 [ab]	8.67 [ab]
Crotalaria ochroleuca	7.78 [ab]	4.98 [ab]	12.36 [ab]
Cajanus cajan	5.91 [ab]	6.77 [ab]	20.65 [ab]
Canavalia ensiformis	7.90 [ab]	2.78 [ab]	10.42 [ab]
Stylosanthes capitata	0 [b]	0 [b]	0 [b]
Lablab purpureus	6.19 [ab]	7.14 [ab]	23.73 [ab]
Mucuna pruriens	2.31 [ab]	3.66 [ab]	11.48 [ab]
Positive control (soybean)	18.46 [a]	24.68 [a]	91.33 [a]
H	28.17	31.74	30.51

Note: Medians followed by the same letter in the column do not differ statistically from each other according to Dunn's test at the 5% probability level.

Once the Dunn's multiple comparison test at the 5% probability level was performed, it was observed that *S. capitata* reduced the final nematode population per gram of root to zero and differed statistically from the control (soybean), which presented a population of 18.46 specimens of *M. incognita*. However, the other green manures did not differ statistically for the root-based variable.

For the variables final nematode population per gram of fresh shoot mass (FSM) and per gram of dry shoot mass (DSM), the treatments with *M. sativa* and the control (soybean) differed significantly from *S. capitata*, which achieved a 100% reduction in the final nematode population per gram of FSM and DSM. Nevertheless, the remaining treatments did not statistically differ from the other green manure species.

The results obtained for *S. capitata* are consistent with reports showing legume species with strong suppressive effects against root-knot nematodes via production of allelochemicals and phenolic compounds [27]. These studies demonstrate that certain plant extracts can reduce nematode juveniles and inhibit egg hatch, supporting the possibility that *S. capitata* may produce similar bioactive compounds.

In earlier work, plants such as *C. juncea, C. spectabilis, C. ochroleuca, C. cajan* and *C. ensiformis* also demonstrated antagonistic interactions by reducing nematode reproduction. Recent investigations now show that green cover species can suppress nematode penetration or development by modulating soil health and microbiome [28]. These findings help bridge older observations and modern mechanisms of suppression.

Canavalia ensiformis exhibited moderate resistance (RF = 0.41). In recent research, seed extracts from *C. ensiformis* have been shown to exhibit ovicidal effects when combined with nanoparticle formulations, highlighting an advanced method to boost nematicidal efficacy [23].

C. cajan exhibited resistance in this study; yet caution is required because host response can vary depending on cultivar and nematode species. Recent screening studies of pulses such as peas, chickpeas, and lentils have documented high susceptibility to *M. enterolobii*, underlining the need for genotype-specific evaluation before recommending legume species in rotation [24].

L. purpureus and *M. pruriens* also presented resistance (RF = 0.35 and 0.28, respectively). Species such as these are known to emit volatile organic compounds and secondary metabolites that can impair nematode chemotaxis or development. For instance, recent studies consolidate that essential oils and plant volatiles are promising nematicidal agents targeting *Meloidogyne* spp. [29].

Discrepancies among studies may often be traced back to genetic variation among plant genotypes, nematode isolates, and soil environment. Virulence variability in *Meloidogyne* populations across agroecological zones has been documented [26]. Such variability incentivizes localized tests and reinforces combining resistant green manures with other biological or cultural control measures.

Overall, the green manure species evaluated here show significant promise for suppression of *M. incognita*. Further research should explore integrated management, combining resistant legumes, botanical extracts, beneficial microbes, or soil amendments, to enhance nematode control under field conditions.

4. Conclusions

All green manure species tested contributed to the reduction of the final population and reproduction factor (RF) of *M. incognita*. Regarding the parameters of final nematode population per gram of fresh root mass, fresh shoot mass and dry shoot mass, *S. capitata* showed the best results when compared to the nematode concentration per unit of plant biomass produced. This species also presented the most favorable performance for the variable reproduction factor (RF), classified as immune (RF = 0).

M. sativa, *C. juncea*, *C. spectabilis*, *C. ochroleuca*, *C. cajan*, *C. ensiformis*, *L. purpureus*, and *M. pruriens* were classified as resistant, with RF < 1, and can therefore be considered antagonistic plants to root-knot nematodes.

Thus, for management strategies based on crop rotation in areas infested with *M. incognita*, all green manure species evaluated can be recommended. Moreover, they represent a suitable management option for the second crop cycle, since they are winter-season planting species.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Neher, D.A. (2010) Ecology of Plant and Free-Living Nematodes in Natural and Agricultural Soil. *Annual Review of Phytopathology*, **48**, 371-394. https://doi.org/10.1146/annurev-phyto-073009-114439

[2] Treonis, A.M., Marais, E. and Maggs-Kölling, G. (2022) Nematode Communities Indicate Diverse Soil Functioning across a Fog Gradient in the Namib Desert Gravel Plains. *Ecology and Evolution*, **12**, e9013. https://doi.org/10.1002/ece3.9013

[3] Khan, A., Chen, S., Fatima, S., Ahamad, L. and Siddiqui, M.A. (2023) Biotechnological Tools to Elucidate the Mechanism of Plant and Nematode Interactions. *Plants*, **12**, Article 2387. https://doi.org/10.3390/plants12122387

[4] Mesa-Valle, C.M., Garrido-Cardenas, J.A., Cebrian-Carmona, J., Talavera, M. and Manzano-Agugliaro, F. (2020) Global Research on Plant Nematodes. *Agronomy*, **10**, Article 1148. https://doi.org/10.3390/agronomy10081148

[5] Dutta, T.K. and Phani, V. (2023) The Pervasive Impact of Global Climate Change on Plant-Nematode Interaction Continuum. *Frontiers in Plant Science*, **14**, Article ID: 1143889. https://doi.org/10.3389/fpls.2023.1143889

[6] Carvalho, R.P., Guerra, C., Cano-Díaz, C., Mendes, S. and Costa, S.R. (2025) Distribution of Plant-Parasitic Nematode Communities across Land-Use Types in the North of Portugal. *Applied Soil Ecology*, **206**, Article 105852. https://doi.org/10.1016/j.apsoil.2024.105852

[7] Kantor, C., Eisenback, J.D. and Kantor, M. (2024) Biosecurity Risks to Human Food Supply Associated with Plant-Parasitic Nematodes. *Frontiers in Plant Science*, **15**, Article ID: 1404335. https://doi.org/10.3389/fpls.2024.1404335

[8] de Souza, V.H.M., Philadelphi, S.M., Galbieri, R., Sonawala, U. and Eves-van den Akker, S. (2024) An Emergent Plant-Parasitic Nematode in Brazil: *Aphelenchoides besseyi*. Current Status and Research Perspectives. *Plant Pathology*, **73**, 478-491. https://doi.org/10.1111/ppa.13829

[9] Rusinque, L., Camacho, M.J., Serra, C., Nóbrega, F. and Inácio, M.L. (2023) Root-knot Nematode Assessment: Species Identification, Distribution, and New Host Records in Portugal. *Frontiers in Plant Science*, **14**, Article ID: 1230968. https://doi.org/10.3389/fpls.2023.1230968

[10] Bui, H.X. and Desaeger, J.A. (2022) Plant-Parasitic Nematodes Associated with Asian Vegetables in Florida.

[11] Tapia-Vázquez, I., Montoya-Martínez, A.C., De los Santos-Villalobos, S., Ek-Ramos, M.J., Montesinos-Matías, R. and Martínez-Anaya, C. (2022) Root-Knot Nematodes (Meloidogyne Spp.) a Threat to Agriculture in Mexico: Biology, Current Control Strategies, and Perspectives. *World Journal of Microbiology and Biotechnology*, **38**, Article No. 26. https://doi.org/10.1007/s11274-021-03211-2

[12] Pun, T.B., Thapa Magar, R., Koech, R., Owen, K.J. and Adorada, D.L. (2024) Emerging Trends and Technologies Used for the Identification, Detection, and Characterisation of Plant-Parasitic Nematode Infestation in Crops. *Plants*, **13**, Article 3041. https://doi.org/10.3390/plants13213041

[13] Gill, H.K., Grabau, Z.J. and McSorley, R. (2023) Cover Crops for Managing Root-Knot Nematodes.

[14] Fullana, A.M., Expósito, A., Escudero, N., Cunquero, M., Loza-Alvarez, P., Giné, A., *et al.* (2023) Crop Rotation with *Meloidogyne*-Resistant Germplasm Is Useful to Manage and Revert the (a)virulent Populations of *Mi1.2* Gene and Reduce Yield Losses. *Frontiers in Plant Science*, **14**, Article ID: 1133095. https://doi.org/10.3389/fpls.2023.1133095

[15] Yadav, H., Roberts, P.A. and Lopez-Arredondo, D. (2025) Combating Root-Knot Nematodes (Meloidogyne Spp.): From Molecular Mechanisms to Resistant Crops. *Plants*, **14**, Article 1321. https://doi.org/10.3390/plants14091321

[16] Zhang, H., Guo, D., Lei, Y., Lozano-Torres, J.L., Deng, Y., Xu, J., *et al.* (2025) Cover Crop Rotation Suppresses Root-knot Nematode Infection by Shaping Soil Microbiota. *New Phytologist*, **245**, 363-377. https://doi.org/10.1111/nph.20220

[17] Ferreira, D.F. (2014) Sisvar: A Guide for Its Bootstrap Procedures in Multiple Comparisons. *Ciência e Agrotecnologia*, **38**, 109-112. https://doi.org/10.1590/s1413-70542014000200001

[18] Sousa, N. (2017) Planeamento experimental usando ANOVA de 1 e 2 fatores com R: uma breve abordagem prática. http://acervodigital.unesp.br/handle/10400.2/6389

[19] Tokatlidis, I.S., Vrochidis, I., Sistanis, I., Pankou, C.I., Sinapidou, E., Papathanasiou, F., *et al.* (2023) Testing the Validity of CV for Single-Plant Yield in the Absence of Competition as a Homeostasis Index. *Agronomy*, **13**, Article 176. https://doi.org/10.3390/agronomy13010176

[20] Truong, N.M., Chen, Y., Mejias, J., Soulé, S., Mulet, K., Jaouannet, M., *et al.* (2021) The *Meloidogyne incognita* Nuclear Effector Mieff1 Interacts with Arabidopsis Cytosolic Glyceraldehyde-3-Phosphate Dehydrogenases to Promote Parasitism. *Frontiers in Plant Science*, **12**, Article ID: 641480. https://doi.org/10.3389/fpls.2021.641480

[21] Meel, S. and Saharan, B.S. (2025) Microbial Warfare against Nematodes: A Review of Nematicidal Compounds for Horticulture, Environment, and Biotechnology. *The*

Microbe, **9**, Article 100557. https://doi.org/10.1016/j.microb.2025.100557

[22] Garba, I.I., Stirling, G.R., Stirling, A.M. and Williams, A. (2024) Cover Crop Functional Types Alter Soil Nematode Community Composition and Structure in Dryland Crop-Fallow Rotations. *Applied Soil Ecology*, **194**, Article 105196. https://doi.org/10.1016/j.apsoil.2023.105196

[23] Ceballos-Ceballos, A.G., Ochoa-Fuentes, Y.M., Cerna-Chávez, E. and Cano-García, A. (2025) Ovicidal Effect of Canavalia Ensiformis Seed Extract with Sio2 Nanoparticles on *Meloidogyne incognita*. *Revista Mexicana de Fitopatología*, *Mexican Journal of Phytopathology*, **43**. https://doi.org/10.18781/r.mex.fit.2404-5

[24] Pinto, T.J.B., Cunha, D.F., Silva, G.O., Pinheiro, J.B., Correia, V.R., Ragassi, C.F., *et al.* (2024) Reaction of Brazilian Genotypes of Pulses (Pea, Chickpea and Lentil) to the Root-Knot Nematode Meloidogyne Enterolobii. *Nematology*, **26**, 299-307. https://doi.org/10.1163/15685411-bja10309

[25] Ferreira, R., Maleita, C., Fonseca, L., Esteves, I., Sousa-Ferreira, I., Cabrera, R., *et al.* (2025) Chemical Screening and Nematicidal Activity of Essential Oils from Macaronesian and Mediterranean Plants for Controlling Plant-Parasitic Nematodes. *Plants*, **14**, Article 337. https://doi.org/10.3390/plants14030337

[26] Mondal, S., Purohit, A., Hazra, A., Das, S., Chakrabarti, M., Khan, M.R., *et al.* (2024) Intraspecific Variability of Rice Root Knot Nematodes across Diverse Agroecosystems for Sustainable Management. *Scientific Reports*, **14**, Article No. 30032. https://doi.org/10.1038/s41598-024-73980-x

[27] Díaz-González, S., Andrés, M.F., González-Sanz, C., Sacristán, S. and González-Coloma, A. (2025) Nematicidal and Antifeedant Activity of Ethyl Acetate Extracts from Culture Filtrates of Arabidopsis Thaliana Fungal Endophytes. *Scientific Reports*, **15**, Article No. 11332. https://doi.org/10.1038/s41598-025-94939-6

[28] Yumi Futigami, C., Calandrelli, A. and Dias-Arieira, C.R. (2023) Application of Herbicides in Green Cover Crops to Reduce Meloidogyne Javanica Inoculum in Soybean Plants. *Agronomía Colombiana*, **41**, e109740. https://doi.org/10.15446/agron.colomb.v41n3.109740

[29] Abd-Elgawad, M. (2025) Integrated Nematode Management Strategies: Optimization of Combined Nematicidal and Multi-Functional Inputs. *Plants*, **14**, Article 1004. https://doi.org/10.3390/plants14071004