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New *Trichoderma* Morphotypes for Southeastern Mexico: *In vitro* Effectiveness and Control of *Meloidogyne incognita* in Tomato

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Abstract

Meloidogyne incognita is a sedentary endoparasitic nematode that parasitizes and causes damage to tropical vegetables, such as tomato (*Solanum lycopersicum* L.); synthetic chemical nematicides are used for its management. The objective of this study was to determine the effectiveness of *Trichoderma* morphotypes in controlling second-stage juveniles (J2s) *in vitro*, reducing *M. incognita* reproduction, and decreasing disease severity in creole tomato. Two experiments were conducted: 1) *In vitro*, culture medium filtrates from 10 *Trichoderma* morphotypes were evaluated against J2s, and mortality was assessed at 24 and 48 h; and 2) The *in vitro* active strains were evaluated against *M. incognita* in *S. lycopersicum;* each morphotype was considered a treatment, and a nematicide and a control were included in a completely randomized experimental design. After 35 days, the galling index (GI), the number of females (NF), and the number of eggs (NE) per gram of root, as well as agronomic variables, were evaluated. *In vitro*, the CAM43, CAM44, CAM49, and CAM50 morphotypes caused 100% mortality of J2s within 48 h of evaluation. The GI was reduced by 22.35% upon inoculation with the CAM43 morphotype. *Trichoderma* morphotypes reduced the NF by 57%, while CAM43 and CAM44 reduced the NE by 48.59%, showing superior control compared to the nematicide. Plants with the greatest height (60.93 cm) and dry leaf biomass (2.27) were obtained with CAM50, while the highest root dry weight was achieved with CAM43, with increases of up to 70.52% relative to the control. This study demonstrates that *Trichoderma* morphotypes from southeastern Mexico have the potential to control *M. incognita* in tomato.

Keywords: nematode, root-knot, *Solanum lycopersicum*, antagonist

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Nuevos morfotipos de *Trichoderma* para el sureste de México: Efectividad *in vitro* y control de *Meloidogyne incognita* en jitomate

Resumen

Meloidogyne incognita es un nematodo endoparásito sedentario que parasita e induce daños en hortalizas tropicales como el jitomate (*Solanum lycopersicum L.*); para su manejo se emplean nematicidas químicos sintéticos. El objetivo del estudio fue conocer la efectividad de morfotipos de *Trichoderma* en el control de juveniles de segundo estadio (J2) *in vitro*, y en la reducción de la reproducción de *M. incognita* y la severidad de la enfermedad en jitomate criollo. Se establecieron dos experimentos: 1) *In vitro,* se evaluaron filtrados del medio de cultivo de 10 morfotipos de *Trichoderma* contra J2, estimando la mortalidad a las 24 y 48 h. 2) Los morfotipos activos *in vitro* se evaluaron contra *M. incognita* en *S. lycopersicum*, cada cepa se consideró un tratamiento, se tuvo un nematicida y un control, dispuestos en un diseño experimental completamente al azar. Transcurridos 35 días se estimó el índice de agallamiento (IA), el número de hembras (NHE) y huevos (NHU) por gramo de raíz y las variables agronómicas. *In vitro*, los morfotipos CAM43, CAM44, CAM49 y CAM50 causaron 100 % de mortalidad de los J2 a las 48 h de evaluación. El IA se redujo 22,35 % con la inoculación del morfotipo CAM43. Los morfotipos de *Trichoderma* redujeron en 57 % el NHE; CAM43 y CAM44 redujeron el NHU en 48,59 % y presentaron efecto de control superior al nematicida. Las plantas con mayor altura (60,93 cm) y biomasa seca foliar (2,27 g) se obtuvieron con CAM50, y el mayor peso seco de raíz con CAM43, con incrementos de hasta 70,52 % respecto al control. Este estudio demuestra que los morfotipos de *Trichoderma* del sureste de México tienen el potencial de controlar *M. incognita* en tomate.

Palabras clave: nematodo, agallador, *Solanum lycopersicum*, antagonista

Novas morfotipos de *Trichoderma* do sudeste do México: Efetividade *in vitro* e controle de *Meloidogyne incognita* em tomate

Resumo

Meloidogyne incognita é um nematóide endoparasita sedentário que parasita e causa danos em hortaliças tropicais, como o tomate (*Solanum lycopersicum* L.); para seu manejo, são utilizados nematicidas químicos sintéticos. O objetivo do estudo foi avaliar a eficácia de morfotipos de *Trichoderma* no controle de juvenis do segundo estágio (J2) *in vitro*, na redução da reprodução de *M. incognita* e na gravidade da doença no tomate crioulo. Foram realizados dois experimentos: 1) *In vitro,* avaliaram-se filtrados do meio de cultura de 10 morfotipos de *Trichoderma* contra J2, estimando-se a mortalidade às 24 e 48 h. 2) Os morfotipos ativos *in vitro* foram avaliados contra *M. incognita* em *S. lycopersicum*; cada morfotipo foi considerada um tratamento, com um nematicida e um controle, dispostos em um delineamento experimental completamente aleatório. Após 35 dias, estimou-se o índice de galhamento (IA), o número de fêmeas (NHE) e de ovos (NHU) por grama de raiz e variáveis agronômicas. *In vitro*, os morfotipos CAM43, CAM44, CAM49 e CAM50 causaram 100% de mortalidade dos J2 às 48 horas de avaliação. O índice IA reduziu-se em 22,35% com a inoculação do morfotipo CAM43. Os morfotipos de *Trichoderma* reduziram em 57% o NHE; CAM43 e CAM44 reduziram o NHU em 48,59% e apresentaram efeito de controle superior ao nematicida. A maior altura das plantas (60,93 cm) e a maior biomassa foliar seca (2,27 g) foram observadas com a CAM50, enquanto o maior peso seco da raiz foi registrado com a CAM43, com aumentos de até 70,52% em relação ao controle. Este estudo demonstra que as morfotipos de *Trichoderma* do sudeste do México têm o potencial de controlar *M. incognita* no tomate.

Palavras-chave: nematoide, galhador, *Solanum lycopersicum*, antagonista

1. Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most important vegetables grown in Mexico, due to its economic value and the high demand it presents both nationally and internationally (Ortiz-Salazar et al., 2025). In the southeast of the country, it is used in the preparation of traditional dishes and grown under open-field and protected production systems (Leana-Acevedo et al., 2022; Orona Castillo et al., 2022). During 2024, a total of

2,154.84 ha were allocated for cultivation, with a production volume of 97,137.49 t and a yield of 137.45 t ha^{-1} (Servicio de Información Agroalimentaria y Pesquera, 2025).

However, production is affected by diseases caused by soilborne phytopathogens, such as root-knot nematodes of the genus *Meloidogyne*, which are among the main pathogens that induce disease and cause economic losses in agricultural crops worldwide (Matas-Baca et al., 2023; Poveda et al., 2020). Among these, *Meloidogyne incognita* is a highly virulent species that parasitizes tropical horticultural species (Jaiswal et al., 2025) and forms galls in the hosts' roots, hindering the absorption of water and nutrients, causing poor growth, wilting, and yield reductions (Ake-Kuyoc et al., 2025; Jaiswal et al., 2025). As a result, the sustainability of agricultural systems in tropical and subtropical regions is compromised, as environmental conditions favor its proliferation (Contreras-Soto et al., 2025; González-León et al., 2022).

The control of *M. incognita* has traditionally relied on the intensive use of chemical nematicides; however, their constant application has caused environmental problems, such as soil and groundwater contamination, affecting human health and biodiversity (Matas-Baca et al., 2023; Zheng et al., 2024). This situation has driven the search for sustainable and safe alternatives, with biological control emerging as a key tool for the integrated management of pests and diseases in today's agriculture (Cortez-Lázaro et al., 2025; Poveda et al., 2020). In this regard, fungi of the genus *Trichoderma* are considered potential agents for biological control, due to their diverse and complex mechanisms of action against phytopathogens (Yao et al., 2023). These mechanisms include the production of lytic enzymes such as chitinases and glucanases, that degrade the cell wall of nematode eggs and juveniles; the induction of systemic resistance in host plants, enhancing their tolerance to attack by *M. incognita*; direct mycoparasitism, and the release of volatile nematicide compounds (Herrera-Parra et al., 2023; Jaiswal et al., 2025; Zheng et al., 2024), which may explain the biological efficacy of *Trichoderma*. In addition to antagonizing the pathogen, it promotes plant growth and health, improving efficiency in nutrient uptake (Bhandari et al., 2021; Cortez-Lázaro et al., 2025).

Recent studies have demonstrated the positive effect of *Trichoderma* strains in the control of *M. incognita* (Yao et al., 2023; Zheng et al., 2024), highlighting its potential as a sustainable tool for nematode control and its contribution to resilient and environmentally friendly agricultural practices. This study aims to assess the effectiveness of *Trichoderma* strains in the control of second-stage juveniles (J2s) of *M. incognita* and in the reduction of nematode reproduction and disease severity in tomato (*S. lycopersicum* L.).

2. Materials and Methods

2.1 Origin of Native *Trichoderma* Morphotypes

Native *Trichoderma* morphotypes were isolated by washing soil particles (Bills et al., 2004) from the rhizosphere of established tomato crops, in Holpechén, Campeche (19° 24' 39.5" N and 89° 24' 06.4" W). Preliminary morphological identification was based on the strain colony color in Potato-Dextrose-Agar (PDA), conidia shape, and types of phialides (Kubicek & Harman, 1998; Samuels et al., 2022).

2.1.1 Preparation of Fungal Filtrates

From each *Trichoderma* morphotype grown in PDA culture medium, four 5-mm-diameter mycelium discs were taken with a punch, deposited in 500 mL flasks containing 200 mL of dextrose potato broth culture medium, and incubated for 15 days at 26 ± 2 °C. At the end of this period, the supernatant was removed, centrifuged twice for 15 minutes at 3000 rpm and filtered through a 0.45 µm Millipore filter. Finally, the fungal filtrates were collected in 50 mL Falcon tubes and kept refrigerated at 4 °C (Ake-Kuyoc et al., 2025).

2.1.2 In Vitro *Evaluation of Fungal Filtrates against* M. incognita *J2s*

Culture plates were used for the establishment of the bioassay; 2 mL of filtrate from each *Trichoderma* morphotype was added to each well, immediately followed by the addition of 10 *M. incognita* J2s, captured using a nematode picker under a stereomicroscope (Leica Zoom 2000). The J2s larvae were obtained from egg masses, which were extracted from galls present on tomato plant roots, and were incubated for 48 hours at 28 °C until the larvae hatched. The bioassay consisted of 10 treatments corresponding to the filtrate of each *Trichoderma* morphotype tested (CAM42, CAM43, CAM44, CAM45, CAM46, CAM47, CAM48, CAM49, CAM50, and CAM51). In addition, three treatments were included: the chemically synthesized nematicide Oxamyl (Vidate® 1 mL L^{-1} water), the liquid culture medium used for *Trichoderma* growth, and sterile distilled water (control). Each treatment had three replicates, and each replicate contained 10 J2s, distributed in a completely randomized experimental design.

The effectiveness of the filtrates was evaluated based on *M. incognita* J2s after 24 and 48 h of exposure. To confirm the immobilization of the J2s, the cephalic region of the nematode was stimulated with a brush; if it did not show any movement, it was considered unfeasible. The mortality percentage was estimated and transformed using the arcsine function. Subsequently, an analysis of variance and mean comparison were performed using the Scott & Knott method ($P \leq 0.05$), with the InfoStat statistical package.

2.2 Bioassay of *M. incognita* Control in Tomato

2.2.1 Preparation of Spore Dilution

From the *in vitro* bioassays, the most effective strains were selected for greenhouse evaluation in native tomato plants (*S. lycopersicum*) inoculated with the nematode. *Trichoderma* morphotypes were cultured in PDA medium and after 10 days at 25 °C. Conidia were harvested by flooding the plates with sterile water and scraping the colony surface. The resulting suspension was filtered through sterile gauze to remove mycelial fragments, obtaining a concentrated stock suspension. From this stock, a final suspension was prepared by making a 1:1000 (v/v) dilution in sterile distilled water to achieve a final concentration of 1×10^3 conidia/mL. The adjusted concentration was collected in 50 mL Falcon tubes and kept refrigerated at 4 °C.

2.2.2 Seedling Production and Inoculation

Tomato seeds were disinfected with 2% sodium hypochlorite and rinsed with sterile distilled water. Subsequently, sowing was carried out in polystyrene trays of 200 cavities with Cosmopeat® substrate. Each seed was inoculated with 1 mL of *Trichoderma* conidial suspension of 1×10^3 mL^1. Trays were then covered with black plastic and kept in the dark until the seeds germinated. Additionally, three *Trichoderma* inoculations were carried out at 5, 10, and 15 days after germination. The seedlings were kept in greenhouse conditions at 28 ± 2 °C, with a relative humidity of 64% and a light intensity of 400 lux, and were irrigated at field capacity. After 22 days, the seedlings had reached an adequate size for transplantation.

2.2.3 Experimental Setup

The crop was established in greenhouse conditions. Before establishment, the soil was sterilized by steam dragging at 90 °C. Plastic pots with a capacity of 2 kg were filled with the sterile soil. In each pot, a hole of 3 cm in diameter and 5 cm deep was made, and a tomato seedling was deposited and inoculated directly around the root with 1 mL of water containing 1000 eggs and 300 J2s of *M. incognita*. Six treatments were established: each of the *Trichoderma* morphotypes (CAM43, CAM44, CAM49, and CAM50), a treatment with chemically synthesized nematicide (Oxamyl, 1 mL L^{-1} water), and a control treatment with nematodes (without *Trichoderma*). Each treatment consisted of 15 plants, representing both replicates and experimental units, distributed in a completely randomized design.

After 35 days of inoculation with *M. incognita*, variables associated with crop growth were estimated: plant height (cm), stem diameter (mm), root length (cm), root volume (cm^3), dry leaf biomass, and dry root biomass (g). Likewise, variables associated with disease severity and nematode reproduction were estimated: the gall index was evaluated according to the severity scale proposed by Taylor and Sasser (1978), the number of eggs per gram of macerated root, and the number of females per gram of dyed root (Ake-Kuyoc et al., 2025).

Data expressed as percentages were transformed by the arcsine function to comply with the assumptions of normality. Subsequently, analyses of variance were performed, and mean comparisons were conducted using the Scott & Knott method ($P \leq 0.05$) with the InfoStat statistical package.

3. Results

3.1 Effect of Fungal Filtrates against J2s of *M. incognita*

The filtrates of the *Trichoderma* morphotypes showed variable responses in the mortality of *M. incognita* J2s. After 24 h of evaluation, 40% of the filtrates showed a significant effect ($P < 0.0001$). The filtrates from the CAM44 strain caused 100% nematode mortality, equivalent to the chemical nematicide (Oxamyl). Likewise, filtrates from the CAM43, CAM49, and CAM50 strains caused mortality from 70% to 83.44%. The lowest nematode mortality rates (3.33% to 41.21%) were recorded for filtrates of strains CAM45, CAM46, and CAM48. In contrast, filtrates of morphotypes CAM42, CAM47, and CAM51 did not cause mortality, similar to the control treatment and the treatment with culture medium only, where all J2s remained viable (Table 1). After 48 h of evaluation, the filtrates of the morphotypes CAM43, CAM44, CAM49, and CAM50 showed a significant effect and were statistically equivalent ($P < 0.0001$) to the nematicide that recorded 100% mortality of the J2s. Filtrates from morphotypes CAM42, CAM45, CAM46, and CAM48 caused mortality from 8.56% to 60.55%, while the filtrates of the morphotypes CAM47 and CAM51 caused no nematode death, comparable to the control and culture medium treatments (Table 1).

Table 1. *In vitro* effect of filtrates of *Trichoderma* morphotypes on second stage juveniles (J2s) of *M. incognita*, isolated from the rhizosphere of tomato (*S. lycopersicum*)

Treatments	J2s Mortality (%)	
	24 h	48 h
CAM42	0.00 ± 0.00 d	39.22 ± 2.96 b
CAM43	83.44 ± 1.75 b	100.00 ± 0.00 a
CAM44	100.00 ± 0.00 a	100.00 ± 0.00 a
CAM45	3.33 ± 3.33 d	60.55 ± 11.07 b
CAM46	5.23 ± 2.71 d	8.56 ± 1.02 c
CAM47	0.00 ± 0.00 d	0.00 ± 0.00 d
CAM48	41.21 ± 12.61 c	41.21 ± 12.61 b
CAM49	75.35 ± 4.07 b	100.00 ± 0.00 a
CAM50	70.00 ± 5.77 b	96.67 ± 3.33 a
CAM51	0.00 ± 0.00 d	0.00 ± 0.00 d
Nematicide (Oxamil)	100.00 ± 0.00 a	100.00 ± 0.00 a
Control (water)	0.00 ± 0.00 d	0.00 ± 0.00 d
Culture medium	0.00 ± 0.00 d	0.00 ± 0.00 d
P-value	0.0001	0.0001

The table shows means ± Standard Error; different letters in the same column indicate statistically significant differences (Scott & Knott, $P \leq 0.05$). n=30.

3.2 Effect of *Trichoderma* on the Control of *M. incognita* in Tomato

Tomato plants were susceptible to the nematode, developing root galls. The analysis of variance showed significant differences between treatments (P < 0.0016). Inoculation with morphotype CAM43 reduced root damage by 22.35% and 18% compared to the control and the nematicide treatment, respectively. The reduction of females per gram of root was significant (P < 0.0001). In the nematicide treatment, 44.40 females were estimated on average, while *Trichoderma* morphotypes caused a significant reduction of females of up to 57% compared to the control, which presented the highest number of females (120.6 per gram of root). Egg production was significantly affected (P < 0.0020) by the inoculation of morphotypes CAM43 and CAM44, and the number of eggs was reduced by up to 48.59% compared to the nematicide, the control, and the rest of the morphotypes that presented statistical equality (Table 2).

Table 2. Antagonistic effect of native *Trichoderma* morphotypes on the severity of root damage and reproduction of *M. incognita* estimated 35 days after inoculation in tomato plants (*S. lycopersicum*) under protected conditions

Treatments	Galling index (%)	Number of females per g of root	Number of eggs per g of root
CAM43	68.33 ± 5.86 b	60.20 ± 8.31 b	317.60 ± 40.41 b
CAM44	78.00 ± 3.27 a	67.40 ± 10.53 b	412.60 ± 45.58 b
CAM49	83.00 ± 2.67 a	52.20 ± 11.09 b	522.80 ± 37.37 a
CAM50	79.67 ± 3.15 a	51.80 ± 1.93 b	569.40 ± 79.96 a
Nematicide (Oxamil)	83.00 ± 2.67 a	44.40 ± 1.78 b	617.80 ± 11.28 a
Control (water)	88.00 ± 0.00 a	120.60 ± 14.12 a	528.40 ± 37.48 a
P-value	0.0016	0.0001	0.0020

The table shows means ± Standard Error; different letters in the same column indicate statistically significant differences (Scott & Knott, P ≤ 0.05). n = 15.

In plant height, significant statistical differences (P < 0.0001) were recorded for plants inoculated with morphotype CAM50 and the nematicide treatment, reaching 60.93 and 62.47 cm, respectively, resulting in greater dry leaf biomass with increases of 123.42% and 104.50%, respectively, compared to the control. Plants treated with the nematicide obtained longer roots (20.04 cm), while those inoculated with *Trichoderma* morphotypes and the control presented shorter roots (9.67 to 14.57 cm). The greatest dry root weight was obtained with the CAM43 treatment, with an increase of up to 77.89% compared to the roots of the plants inoculated with CAM49, CAM50, and the control, and up to 34.73% compared to CAM44 and the nematicide. No significant differences were found among treatments for stem diameter (P < 0.0631) or root volume (P < 0.0947) (Table 3).

Table 3. Effect of inoculation of native *Trichoderma* morphotypes on the growth and development of tomato plants (*S. lycopersicum*) inoculated with *M. incognita* under protected conditions

Treatments	Plant height (cm)	Stem diameter (mm)	Dry leaf biomass (g)	Root length (cm)	Root volume (cm^3)	Dry root biomass (g)
CAM43	49.00 ± 1.49 b	4.89 ± 0.14 a	1.48 ± 0.15 b	13.73 ± 1.49 b	4.00 ± 0.31 a	0.95 ± 0.23 a
CAM44	50.67 ± 3.91 b	4.52 ± 0.36 a	1.83 ± 0.31 b	13.67 ± 1.63 b	3.29 ± 0.61 a	0.62 ± 0.07 b
CAM49	50.87 ± 2.57 b	4.59 ± 0.18 a	1.50 ± 0.24 b	9.67 ± 0.88 c	2.14 ± 0.34 a	0.28 ± 0.7c
CAM50	60.93 ± 1.21 a	4.99 ± 0.20 a	2.27 ± 0.17 a	11.53 ± 1.46 c	3.71 ± 0.57 a	0.34 ± 0.07 c
Nematicide (Oxamil)	62.47 ± 1.54 a	5.38 ± 0.13 a	2.48 ± 0.13 a	20.04 ± 1.07 a	3.86 ± 0.51 a	0.55 ± 0.07 b
Control	46.93 ± 2.81 b	4.90 ± 0.18 a	1.11 ± 0.12 b	14.57 ± 1.31 b	3.14 ± 0.34 a	0.21 ± 0.02 c
P-value	0.001	0.0631	0.0001	0.0001	0.0947	0.0002

The table shows means ± Standard Error; different letters in the same column indicate statistically significant differences (Scott & Knott, P ≤ 0.05). n=15.

4. Discussion

Sedentary endoparasitic nematodes, such as *M. incognita*, reproduce in a wide range of hosts and adapt to extreme climatic variations, which allows their establishment in various tomato-producing regions in Mexico (Guzmán-Plazola et al., 2008; Martínez Gallardo et al., 2019), where synthetic chemical nematicides are commonly applied (Tapia-Vázquez et al., 2022) in the absence of products formulated with regional microorganisms capable of ensuring effective pathogen control. In this regard, the *in vitro* results of this study demonstrated the existence of *Trichoderma* morphotypes (CAM43, CAM44, CAM49, CAM50) from the southeastern region of the country, capable of causing *M. incognita* J2s mortality within 24 h of exposure, with a consistent control effect at 48 h equivalent to that of the nematicide treatment (Table 1). This effectiveness was associated with the production of secondary metabolites produced in the culture medium. Although these active secondary metabolites were not identified in this study, previous reports have described compounds such as koninginins, steroids, anthraquinones, lactones, trichothecenes, obtained from *T. pseudo-harzianum* (T113, T136), *T. asperelloides*, *T. viride*, *T. hamatum*, associated with morphological changes, rupture, cell wall disintegration in *Ralstonia solanacearum*, *Xanthomonas campestris*, and *M. incognita* J2s. Other reported compounds include iludine, naematoline, 4ß scirpenol, 3,7,8,15-scirpenetetrol, from isolates of *T. harzianum*, *T. koningiopsis*, *T. ghanense*, associated with the inhibition of protein synthesis, egg hatching, and *M. javanica* J2s mortality (Moo-Koh et al., 2022; Olivas-Tarango, et al., 2024). Additionally, huperzine A and acetic acid, produced by *Paecilomyces tenuis,* exhibit antifeeding activity and inhibit egg hatching (Kassam et al., 2023). This demonstrates the potential of *Trichoderma* secondary metabolites for the control of root-knot nematodes.

In the experiment with tomato plants, the effectiveness of *Trichoderma* morphotypes as biological control agents against *M. incognita* varied according to fungal morphotype and competitive capacity. In particular, morphotypes CAM44 and CAM43 stood out for their effectiveness in reducing egg production and gall index, with better results than nematicide treatment and control treatments. Likewise, the *Trichoderma* morphotypes and nematicide treatment had the same potential to prevent the formation of females, with greater effects than the control. These reductions of nematode reproduction and gall formation in tomato plants were associated with the mechanisms *Trichoderma* has developed against root phytopathogens (Kassam et al., 2023). These microbial inoculants compete with the nematode's infective phases for resources such as root colonization and nutrients, such as nitrogen, iron, and carbon, derived from the host plant (Galli et al., 2024). They parasitize nematode eggs, juveniles, and adults, and produce secondary metabolites that affect their viability, and enzymes such as proteases, chitinases, β-1,3-glucanases, which hydrolyze chitin, polysaccharides, and other constituent compounds of the nematode cuticle (Alizadeh et al., 2024; Fan et al., 2020). Moreover, *Trichoderma* can induce systemic resistance by activating plant defense molecules through ethylene, salicylic acid, or jasmonic acid signaling pathways, which trigger defense signaling to produce secondary metabolites such as flavonoids and the activation of physiological mechanisms that enhance plant protection against these phytopathogens (Alizadeh et al., 2024; Zheng et al., 2024).

It is important to note that only the CAM50 morphotype promoted plant growth despite nematode infestation, as reflected in greater plant height and dry leaf biomass; this was followed by the CAM43 and CAM44 morphotypes, which produced the highest dry root biomass. This differential response is associated with *Trichoderma* ability to synthesize phytohormones such as cytokinins and auxins, specifically indole-3-acetic acid (IAA), which stimulate cell division and elongation in the root system, thereby increasing its volume and dry biomass (Cortéz-Hernandez et al., 2023; Fan et al., 2020). Furthermore, this fungus contributes to plant nutrition by solubilizing essential soil nutrients such as phosphorus, iron, manganese, and magnesium (González-León et al., 2022). In contrast, the remaining morphotypes did not exhibit any promoting activity in terms of stem diameter, root length, or root volume. This variability demonstrates that the ability of each *Trichoderma* morphotype to act as a biostimulant or nematode biocontrol agent depends on its ecological history and previous interactions with other soil

microorganisms. Such evolutionary and environmental events regulate the expression of gene clusters involved in the biosynthesis of defensive secondary metabolites and the secretion of lytic enzymes that are key to successful endophytic establishment in the host root.

5. Conclusions

Forty percent of the isolated morphotypes (specifically CAM43, CAM44, CAM49, and CAM50) caused 100% mortality of *Meloidogyne incognita* J2s after 48 h *in vitro*. Furthermore, all *Trichoderma* morphotypes reduced female nematode production by 57%. Notably, morphotypes CAM43 and CAM44 decreased egg production by 48.59%, demonstrating a biocontrol efficacy superior to that of the chemical nematicide. Tomato disease severity was also reduced by 22.35% under CAM43 inoculation. Regarding plant growth promotion, plants inoculated with CAM50 exhibited significantly greater height and dry leaf biomass, whereas CAM43 increased dry root weight by up to 70.52% compared to the non-inoculated control.

This study contributes significantly to the exploration of native microorganisms from southeastern Mexico with high potential for the biological control of *M. incognita* in tomato crops. However, given the morphological plasticity of this genus, accurate molecular identification of these active *Trichoderma* morphotypes is an essential next step. Resolving their taxonomic identity at the species level will ensure biosafety, facilitate strain registration, and establish a solid baseline for reproducible future research evaluating these antagonists within conventional and large-scale cropping systems.

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Transparency of Data

The entire data set that supports the results of this study was published in the article itself.

Author Contribution Statement

	DJ Matu-Yam	CI Basto-Pool	E Herrera-Parra
Conceptualization			■
Data curation	■	■	■
Formal analysis	■	■	■
Funding acquisition			■
Investigation	■	■	■
Methodology	■	■	■
Project administration			■
Resources			■
Software		■	■
Supervision		■	■
Validation		■	
Visualization		■	■
Writing – original draft	■	■	■
Writing – review and editing		■	■

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