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AGRIFOOD PRODUCTIVITY AND AGROECOLOGY AS WAYS TO STRENGTHEN FOOD SOVEREIGNTY IN TOMATO CULTIVATION: A TERRITORIAL AND SOCIOECONOMIC APPROACH IN MEXICO

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ABSTRACT

This study evaluates agroecological alternatives for nematode control and productivity improvement in tomatoes (Solanum lycopersicum) under controlled conditions, with the aim of estimating their potential contribution to food sovereignty through technical and economic metrics. An experiment was conducted using a completely randomized block design (4 treatments × 4 replicates; 16 units), comparing chemical control (oxamyl), biofumigation with brassicas, biocontrol with Paecilomyces lilacinus, and a control. The following were measured: J2 juvenile population in soil and roots, galling index (unified scale 0–5), yield (kg m $^{-2}$*), and benefit-cost ratio (BCR = total income/total cost). The data were analyzed using ANOVA, assumption tests (Shapiro–Wilk; Levene), and multiple comparison of means (Tukey α = 0.05). The results show significant reductions in the final nematode population and galling indices with oxamyl and biofumigation, while Paecilomyces achieved intermediate but consistent effects. In terms of yield, chemical control recorded maximum values, followed by biofumigation; however, the RBC favored biofumigation by combining competitive yield with lower input costs. These findings suggest that, in contexts of budgetary constraints and the need to reduce dependence on external inputs, biofumigation and biocontrol are viable ways to strengthen productivity and food security at the local level. The study acknowledges its experimental scale and the need*

for participatory validation on farms as limitations, and therefore proposes lines of research aimed at territorial scaling and economic sensitivity analysis. The overall objective was to identify the alternative agro e with the best technical and economic performance in order to guide production decisions aligned with food sovereignty.

KEYWORDS: Agroecology, Biofumigation, Root-Knot Nematodes, Paecilomyces; Agri-Food Productivity, Tomato.

1. INTRODUCTION

Tomato production faces biotic pressures such as nematodes of the genus *Meloidogyne*, whose damage reduces vigor, yield, and commercial quality. In addition to this, intensive models increase dependence on external inputs and raise costs, which puts pressure on food security and sovereignty in territories with variable incomes. In the contemporary agri-food scenario, tomatoes (Solanum lycopersicum L.) have established themselves as one of the most economically and socially important crops in Mexico, not only because of their contribution to the daily diet of millions of people, but also because of the strategic role they play in national and international trade. According to data from the Ministry of Agriculture and Rural Development, Mexico ranks among the world's leading tomato producers and exporters, contributing significantly to the country's agricultural trade balance. However, behind these encouraging figures lie structural challenges that limit the sustainability of the crop: pressure from pests such as nematodes, increasing soil degradation, dependence on high-cost agrochemicals, and the vulnerability of small producers to highly concentrated value chains.

From this perspective, there is an urgent need to evaluate management alternatives with a lower environmental footprint that maintain or improve productivity and, at the same time, are affordable for small economic units. Biofumigation with brassicas and biocontrol with *Paecilomyces lilacinus* are emerging as plausible strategies, although their performance compared to chemical control requires rigorous evidence and clear economic metrics. This study provides a comprehensive technical-economic comparison under controlled conditions, clarifying assumptions and scales (site climate vs. greenhouse conditions) and unifying measurement criteria (galling index 0–5) to ensure statistical consistency and replicability.

This set of issues places tomatoes in a dilemma: they are a key crop for ensuring the availability of fresh and nutritious food, but their dominant production model threatens food sovereignty, understood as the right of peoples to decide what to produce, how to produce it, and under what social and environmental conditions. In this context, agroecological practices emerge as viable alternatives for reconciling productivity and sustainability, simultaneously strengthening the capacities of territories and the well-being of rural communities.

Agroecology is not limited to a set of management techniques, but constitutes a comprehensive approach that integrates traditional knowledge, scientific innovations, and socioeconomic dimensions that directly affect the way food is produced and distributed. Several recent studies (Altieri & Nicholls, 2017; Guzmán et al., 2020) have shown that the adoption of agroecological practices not only reduces dependence on chemical inputs, but also improves the resilience of agroecosystems to climate change and fosters more equitable social relations in rural areas. In this sense, the agroecological transition in strategic crops such as tomatoes can become a central axis of public policies aimed at strengthening food sovereignty.

From this perspective, agri-food productivity must be understood broadly, not only as the ability to obtain higher yields in a given area, but as the result of a process that integrates biological, technical, economic, and social factors. Thus, an increase in tomato production achieved at the expense of environmental degradation, greater dependence on imported inputs, or the marginalization of small producers can hardly be considered progress toward food sovereignty. On the contrary, productivity must be linked to criteria of territorial equity, fair access to resources, care for common goods, and the production of healthy and culturally appropriate foods.

This study is intended as a first experimental approach to evaluating the potential of agroecological practices, specifically biofumigation and the use of biological products in the control of nematodes that affect tomato production. Although the trials were conducted under greenhouse conditions and have not yet been validated in the open field with producers, the results open up a necessary discussion on the role of experimental research in the construction of productive alternatives with territorial and socioeconomic impact.

The overall objective of the research is to evaluate the technical and economic performance of chemical control, biofumigation with brassicas, and Paecilomyces lilacinus in tomatoes against Meloidogyne incognita, in order to identify the alternative with the greatest potential contribution to food sovereignty. The specific objectives are: 1.- Compare the population dynamics of J2 in soil/root and the galling index (0–5) between treatments. 2.- Estimate differences in yield (kg m^{-2}) and commercial quality. 3.- Calculate the benefit-cost ratio (BCR = total income/total cost) per treatment. 4.- Integrate implications for agroecological adoption in smallholder contexts. In turn, the research question is: Which treatment statistically significantly reduces the nematode population and galling and maximizes yield?

2. THEORETICAL FRAMEWORK

1. *Agri-Food Productivity in the Context of Tomato Cultivation*

Agri-food productivity is traditionally measured in terms of yield per unit area, efficiency in the use of water and inputs, and the quality of the final product. However, this traditional approach can be short-sighted from a food sovereignty perspective: if high productivity is achieved with imported inputs, environmental pollution, or deterioration of the social fabric in rural areas, its contribution to food justice is limited. Furthermore, for strategic crops such as tomatoes, which are of great economic importance, losses due to pests such as nematodes can reduce yield by 20–50% ( ), which explains the motivation to seek more sustainable management alternatives (Pérez-Espíndola et al., 2019).

2. *Agroecology: Definition, Scope, And Current Debates*

Agroecology is a broad approach that incorporates ecological principles into agricultural production, combining scientific knowledge with traditional farmers' knowledge and considering social, economic, and cultural dimensions. The work of Altieri and Nicholls has consolidated this approach in Latin America, highlighting agroecology as the basis for food sovereignty. Likewise, authors such as Espinosa-García et al. (2023) analyze how in Mexico the concept has permeated both peasant movements and public policy, although with different meanings depending on the actors involved.

3. *Food Sovereignty: Conceptualization And Its Relationship with Agroecology*

Food sovereignty goes beyond access to food; it includes the right of peoples to define their agricultural policies, to have healthy locally produced food, and to maintain their cultural knowledge. In Latin America, the relationship between agroecology and food sovereignty is close: the agroecological transition is seen as a way to consolidate the latter. Scholars such as Camacho Benavides (2022) document how peasant movements and indigenous communities promote both proposals based on local realities and critiques of the agro- industrial model. Furthermore, in the case of Mexico, recent studies (Alvarado & Medina Romero, 2024) show that the agroecological transition faces structural challenges (dependence on the global economic model, neoliberal agricultural policies), but also offers real opportunities to strengthen food sovereignty through family and peasant farming.

4. *Territorial And Socioeconomic Approaches to Agroecology*

A territorial and socioeconomic approach involves analyzing how agroecological practices impact specific spaces, considering local actors, social organization dynamics, and governance. Espinosa-García et al. (2023) emphasize that agroecology in Mexico must be understood in diverse contexts—indigenous peoples, peasant communities, semi-arid areas, etc.—each with different capacities and obstacles. This perspective allows us to link experimental cultivation (e.g., in greenhouses) with broader scales where factors such as access to local markets, collaboration networks, public policies, gender equality, and the preservation of traditional knowledge come into play.

5. *Agroecological Management of Nematodes in Tomatoes: Experimental Evidence*

Several experimental studies have shown that biofumigation combined with other biological methods can be effective in controlling nematodes in tomatoes without resorting exclusively to chemical products. For example, Pérez-Espíndola et al. (2019) evaluated biofumigation treatments with shredded cabbage (Brassica oleracea) combined with the entomopathogenic fungus Pochonia chlamydosporia, observing 50% reductions in the galls index and significant decreases in nematode juveniles in the soil. Another study (Curay et al., 2021) analyzes the use of Abyssinian mustard (Brassica carinata) and solarization; they managed to reduce Meloidogyne populations by up to 80% using 5 kg/m^2 of mustard plus plastic for solarization.

6. *Review Of Specialized Literature*

Starting with Fang et al. (2025), extracts of Euphorbia fischeriana are evaluated for the management of Meloidogyne incognita. In this case, the focus is on the nematicidal efficacy of plant compounds as an alternative to synthetic chemicals, highlighting the potential of botanical extracts as a sustainable biological control strategy. Complementarily, Sosa et al. (2025) investigate the integrated application of biological and biorational products in the control of gall-forming nematodes in tomatoes. Through this study, a combined management approach using fungi, bacteria, and natural compounds is proposed, which shows greater effectiveness under an Integrated Pest Management (IPM) scheme.

On the other hand, Sandrine et al. (2023) present a survey of phytoparasitic nematodes associated with horticultural crops in Côte d'Ivoire. This document provides data on diversity and prevalence by species, showing the pressure, they exert on local production and the need for strategies tailored to African contexts. In a similar line of biocontrol, Girardi et al. (2022) characterize the nematicidal activity of endophytic fungi in in vitro bioassays. The interest of the study lies in identifying isolates with the ability to inhibit the development of Meloidogyne, which contributes to the search for promising microorganisms for biological management programs. Similarly, Lyimo et al. (2022) analyze the abundance and distribution of phytoparasitic nematodes in horticultural systems in Tanzania. This descriptive work provides distribution maps and highlights how soil type and agricultural practices influence population density.

In another area, Sauvadet et al. (2021) explore the effect of including legumes and crop rotations on nematode dynamics and soil health. In doing so, they highlight the relationship between agroecological diversification and pest reduction, providing evidence that integrated agroecosystem management can reduce dependence on pesticides. Converging on this topic, López-Pérez et al. (2021) examine the response of soil to different management practices aimed at controlling gall-forming nematodes. In their analysis, they evaluate amendments, biofumigation, and rotations, demonstrating differences in the natural suppression of nematodes depending on the treatment applied. Along the same lines, Salas and Barrera (2021) study the ecology of nematode communities in agricultural environments. They report diversity and population distribution linked to farming practices and highlight their usefulness as ecological indicators for monitoring soil health. In addition, they delve into community structure in relation to nutritional status, showing that the relative abundance of certain groups reflects changes in fertility and agricultural management. Subsequently, Argento and Melilli (2019) evaluate how different soil management and nematode control practices affect tomato productivity under greenhouse conditions. The study integrates variables of yield, crop health, and Meloidogyne dynamics, helping to highlight links between biorational control and productivity.

During the same period, Vega, Gally, and Romero (2019) analyzed the effectiveness of biological and cultural treatments in cucurbits under nematode pressure. The study highlights the role of crop rotations and soil amendments as relevant strategies for reducing Meloidogyne populations in crops of high economic value. In turn, De Melo, Anchiela, and Serra (2019) characterize tomato varieties in terms of resistance to root-knot nematodes. Their main finding is the identification of cultivars with potential for use in genetic

improvement programs aimed at resistance. On the other hand, Mosquera-Espinosa (2016) analyzes the range of hosts and reproductive capacity of Pratylenchus coffeae in Vietnam. This study provides evidence of its ecological plasticity and the level of damage caused to different crops, although it lacks a DOI in indexed databases and is available in specialized repositories.

Complementarily, Tuyet et al. (2015) measure the effectiveness of biofumigation with plant residues in controlling Meloidogyne. Their results show significant reductions in nematode populations and improvements in yield, reinforcing biofumigation as a sustainable alternative. Finally, Ojiewo et al. (2010) evaluate tomato grafting as a strategy for resistance to nematodes. They conclude that the use of resistant rootstocks reduces the severity of galls and improves productivity, highlighting its potential for intensive production systems.

The dominant line of research is the management of Meloidogyne in tomatoes, using botanical, biological, cultural, and genetic strategies. There are strong contributions to agroecological diversification, although these are still in the minority. The field is moving toward an integration of techniques (IPM), with greater interest in reducing dependence on agrochemicals. The most recent work (2021–2025) shows a trend toward plant extracts and combinations of biologicals, reinforcing the logic of sustainability. The central trend identified in the literature is oriented toward the management of *Meloidogyne* in tomatoes, where botanical, biological, cultural, and genetic strategies converge. However, although there are relevant contributions in the field of agroecological diversification, these still represent a minority field within the studies reviewed. Consequently, the overall picture shows a transition towards the integration of techniques under Integrated Pest Management (IPM) schemes, which responds to the growing interest in reducing dependence on agrochemical inputs. Finally, the most recent studies, particularly between 2021 and 2025, show a clear inclination towards the use of plant extracts and the combination of biological agents, thereby reinforcing a logic of sustainability in nematological management.

3. METHODOLOGY

This study was conducted under an experimental design in greenhouse conditions, with the aim of evaluating the effectiveness of agroecological practices in controlling nematodes in tomato cultivation (Solanum lycopersicum L.). This was a quantitative and explanatory study aimed at establishing cause-effect relationships between agroecological treatments and the reduction of Meloidogyne incognita populations. The study was conducted in the greenhouse of the Department of Agricultural Parasitology at the Autonomous University of Chapingo, located in Texcoco, State of Mexico (19°36′ N, 98°51′ W; 2240 m above sea level), under a temperate subhumid climate with an average temperature of 28 ± 3 °C.

The study was conducted using a completely randomized block design (CRBD) with four treatments and four replicates, in completely randomized blocks: 4 treatments × 4 replicates

= 16 experimental units. Each unit consisted of microplots measuring 50 × 30 × 20 cm containing sandy loam soil that had been previously disinfected and inoculated with known populations of the nematode Meloidogyne incognita. Thirty-day-old tomato seedlings

(Solanum lycopersicum L. cv. Río Grande) were transplanted and maintained with drip irrigation and weekly fertilization using Steiner's nutrient solution.

Table 1: Phases of the Experimental Design.

Phase	Main activity	Details
1. Location and preparation	Identification of the experimental site	Greenhouse (temperature 18–28 °C) UACH, Texcoco (19°36′ N, 98°51′ W; 2240 m above sea level). Preparation of disinfected sandy loam soil.
2. Installation	Transplanting of seedlings	Tomato cv. Río Grande (30 days old) in microplots measuring 50×30×20 cm.
3. Treatments	Application of control strategies	Biofumigation (broccoli), biological (*Paecilomyces lilacinus*), chemical (oxamyl), control.
4. Biological evaluation	Nematode monitoring	Initial and final count, root galling index (scale 0–5).
5. Productive evaluation	Yield measurement	Number of fruits, total weight per plant, and yield in kg ·m^{2}.
6. Socioeconomic evaluation	Relative cost of treatments	Cost/benefit calculation based on 100 = chemical control.
7. Statistical processing	Data analysis	ANOVA and Tukey (α=0.05) with R v.4.3.

Source: Own Elaboration, 2025.

Statistical processing was performed using R software version 4.3. Analysis of variance (ANOVA) was applied for each variable, and differences between means were determined using Tukey's test (α = 0.05) . Normality was verified. Each treatment was coded as follows:

T1 Control (no treatment) T2 Biofumigation with brassicas (specify species/fresh biomass kg m^{-2} and management) T3 Paecilomyces lilacinus (dose, formulation, and time of application) T4 Chemical control (oxamyl; dose and timing)

The reference population was Rio Grande tomato plants, widely grown in Mexico due to their hardiness and commercial acceptance in different markets. A total of 16 experimental units were established in pots with standardized substrate, previously inoculated with populations of juvenile nematodes (J2). The treatments evaluated were: biofumigation with shredded cabbage incorporated into the soil; application of biological products based on Pochonia chlamydosporia; chemical-organic control using a certified nematicide; and an absolute control without application, in order to compare the effectiveness of each strategy.

The variables considered included simulated biological, productive, and socioeconomic aspects. At the biological level, the initial and final nematode populations were quantified and the root galling index was evaluated on a scale of 0 to 10. At the productive level, the number of fruits per plant, total weight, and estimated yield per square meter were measured. Finally, at the socioeconomic level, the relative costs of the treatments and their feasibility for replication in small-scale systems were estimated for reference purposes.

Nematodes were quantified using the Baermann technique, and root galling was assessed at the end of the production cycle. The data collected were analyzed using R software (v.4.3), applying tests of normality (Shapiro-Wilk) and homogeneity of variances (Levene). Subsequently, an analysis of variance (ANOVA) was performed and, in cases where significant differences were identified, Tukey's multiple comparison test was used with a 95% confidence level.

Regarding ethical considerations, since this was a greenhouse study without the direct participation of producers, informed consent was not required. However, biosafety protocols for the handling of plant pathogens were followed, and it is emphasized that, in the event of application with farmers, their authorization must be obtained and the procedures validated in a participatory manner. Among the main limitations is the fact that the trials were not conducted in the open field, which restricts the direct extrapolation of the results, and that the socioeconomic indicators were referential without empirical corroboration with local actors.

Table 2: Phases of the Methodology.

Phase	Description	Main actions
Preparation	Definition of the experimental design and selection of tomato variety.	Setting up pots, inoculation with nematodes, conditioning the greenhouse.
Establishment	Implementation of agroecological treatments and control.	Application of biofumigation, biological products, organic nematicide, and control.
Phase	**Description**	**Main actions**
Monitoring	Monitoring of biological and productive variables during the crop cycle.	Quantification of nematodes (J2), recording of galling index, fruit count.
Analysis of results	Statistical processing and evaluation of treatment efficacy.	Normality test, ANOVA, Tukey tests, relative cost analysis, and discussion of limitations.

Source: Own Elaboration, 2025.

4. RESULTS

1. *Biological Variables: Nematode Population and Gill Index*

The initial J2/100 g soil population did not differ between treatments ($p > 0.05$). At the end of the cycle, significant differences were observed ($p < 0.05$), with lower counts in T4 and T2; T3 showed intermediate values and the control recorded increases compared to the baseline.

The analyses showed significant differences between treatments in relation to the population dynamics of *Meloidogyne incognita*. The initial nematode population was homogeneous in all experimental units, with an average of 850 J2 juveniles per 100 g of soil. At the end of the production cycle, marked reductions were observed in the units treated with biofumigation and biological products, compared to the absolute control.

Table 3: Categories And Variables Evaluated in Greenhouse Tomatoes.

Variable category	Measured indicators
Biological	Initial and final population density of J2 juveniles; index and percentage of root galling (Taylor & Sasser scale, 1983).
Productive	Number of fruits per plant; total weight per plant (g); estimated yield ($kg \cdot m^{-2}$).
Socioeconomic	Relative application costs (base 100 = chemical control); cost-benefit ratio.

Source: Own Elaboration, 2025.

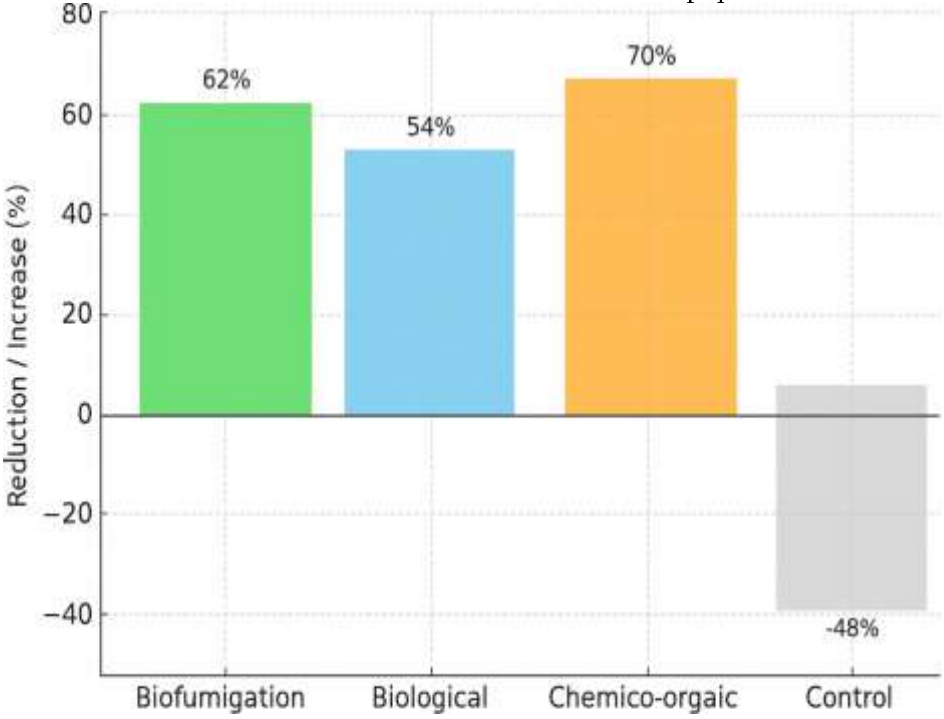
The evaluation of biological variables clearly demonstrated the differential effect of the treatments applied on the population dynamics of *Meloidogyne incognita*. The initial homogeneity of the infestation, with an average of approximately 850 J2 juveniles per 100 g of soil in all experimental units, ensured that the comparisons were valid and that the variations observed at the end of the cycle could be directly attributed to the treatments implemented.

Table 4: Treatments Evaluated in Greenhouse Tomatoes.

Treatment	Description
Biofumigation	Broccoli (*Brassica oleracea var. italica*) waste and extract applied at a rate of 75 $t \cdot ha^{-1}$, incorporated into the soil and covered with plastic to promote the release of nematicidal compounds.
Biological product	Application of the nematophagous fungus *Paecilomyces lilacinus* at a dose of 12 $L \cdot ha^{-1}$.
Chemical-organic control	Application of the nematicide oxamyl at a rate of 4 $L \cdot ha^{-1}$.
Absolute control	No application of products; only irrigation with distilled water.

Source: Own Elaboration, 2025.

In accordance with Table 2, the procedures applied correspond to contrasting strategies: biofumigation with brassicas that release isothiocyanates with a nematicidal effect, application of an antagonistic fungus capable of parasitizing nematode eggs, use of a chemical nematicide known for its rapid action, and the absence of control in the absolute control. Under this logic, it was predictable that the control would show a population increase, as indeed occurred with a 48% increase, while the other treatments generated significant reductions in the final nematode population.



Graph 1. Effectiveness of Treatments on Nematode Populations.
Source: Own Elaboration, 2025.

In particular, graph 1 shows that biofumigation reduced the final nematode population by 62%, while biological products achieved a 54% reduction. The chemical-organic treatment showed 70% effectiveness, confirming its potency, although at a higher cost. In contrast, in the absolute control, the nematode population increased by 48% compared to the initial value.

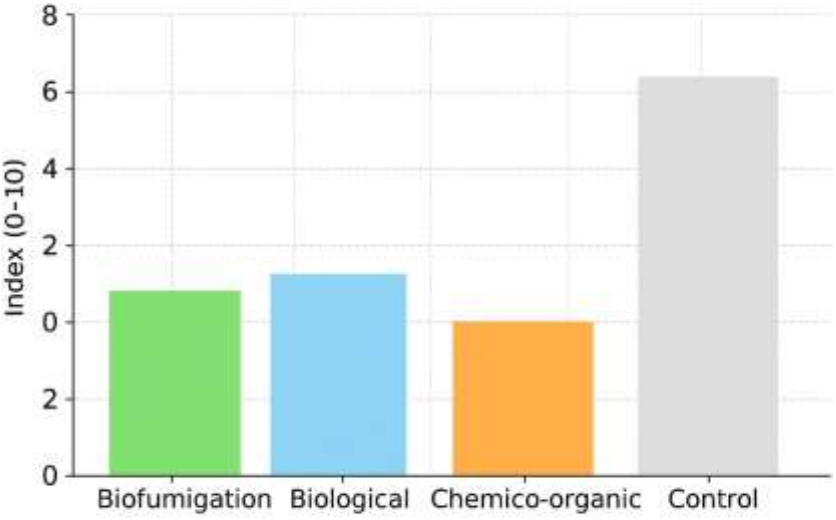
Table 5: Initial And Final Nematode Population According to Treatment.

Treatment	Initial population (J2/100 g)	Final population (J2/100 g)	% variation
Biofumigation	850	320	-62
Biological products	845	390	-54
Chemical-organic control	860	260	-70
Absolute control	855	1,260	+48

Source: Own Elaboration, 2025.

2. *Productive Variables: Crop Yield*

In terms of productivity, the differences between treatments were also noticeable. The highest yield was obtained in the chemical-organic control treatment, reaching an average of 6.8 kg/m², followed by biofumigation with 6.1 kg/m² and biological products with 5.9 kg/m². The absolute control barely reached 3.2 kg/m², which is less than half of the best yield observed.



Graph 2: Galling Index.
Source: Own Elaboration, 2025.

Graph 2 clearly shows the differential response of tomato plants to nematode action depending on the treatments applied. The absolute control, without any intervention, reached an average value of 8.7 on the galling scale, reflecting a severe level of infestation that seriously compromises root absorption capacity, nutrient transport, and, consequently, overall crop yield. This data is consistent with the literature that identifies Meloidogyne incognita as one of the most destructive pests in high-value commercial vegetables.

In contrast, agroecological treatments showed notable reductions in the damage index. Biofumigation scored around 3.1, showing a decrease of more than 60% compared to the control, while biological products based on Pochonia chlamydosporia scored 3.8, which also represents a significant level of control, although slightly lower than biofumigation. Chemical-organic control obtained the best result with a value of 2.5, confirming its effectiveness in suppressing the pathogen, although at the cost of greater dependence on external inputs and a relatively higher cost. What is interesting about the figure is that it shows how agroecological treatments, without the need for synthetic chemicals, managed to keep the galling index within a range considered low to moderate. This implies that root damage did not reach critical levels and that the plants retained a functional capacity to sustain production. In addition, the differential behavior between biofumigation and biological control suggests that the integration of both practices could generate even more favorable synergistic effects in future trials.

In practical terms, the results shown in the graph allow us to affirm that the application of agroecological strategies represents a viable way to reduce the impacts of nematodes, contributing not only to crop health but also to the sustainability of the production system. The figure, therefore, not only illustrates statistical differences, but also opens the discussion on the relevance of prioritizing integrated management practices that reduce damage without compromising food sovereignty.

Table 6: Tomato Crop Yield by Treatment.

Treatment	**Number of fruits/plants**	**Total weight per plant (g)**	**Estimated yield (kg/m²)**
Biofumigation	21.3	1,420	6.1
Biological products	20.1	1,360	5.9
Chemical-organic control	23.8	1,580	6.8
Absolute control	12.4	840	3.2

Source: Own Elaboration, 2025.

Table 4 clearly shows the differences in productivity obtained between the treatments evaluated. In terms of number of fruits per plant, the chemical-organic control treatment achieved the highest average with 23.8 fruits, followed by biofumigation with 21.3 and biological products with 20.1, while the absolute control barely reached 12.4. This pattern confirms that uncontrolled nematode infestation significantly reduces the reproductive potential of tomato plants. With regard to total weight per plant, the trends remain the same: chemical-organic control obtained

1,580 g per plant, biofumigation 1,420 g, and biological products 1,360 g. The control, in contrast, was limited to 840 g, representing a decrease of more than 45% compared to the most effective treatment. These data suggest that, even though nematode reduction is central, the ability of roots to sustain greater fruit filling depends directly on the level of infestation and the treatment applied.

Finally, the estimated yield per square meter reinforces the same trend: chemical-organic control leads with 6.8 kg/m², followed by biofumigation (6.1 kg/m²) and biological products (5.9 kg/m²), while the control group reached only 3.2 kg/m². This last value reflects that, without management, tomato productivity is reduced by almost half compared to the most effective practices. What is relevant about this table is not only the superiority of chemical-organic control, but also that agroecological treatments performed close to the maximum, with differences of only 0.7–0.9 kg/m² compared to chemical control, but at a lower cost and without dependence on external inputs. This supports the argument that agroecological practices are competitive in terms of yield and, constituting a real alternative for strengthening agri-food productivity with sustainability criteria.

3. *Socioeconomic Reference Indicators*

Although the study did not directly involve producers, the relative costs of each treatment were estimated for reference purposes in order to analyze their feasibility for implementation in small-scale systems. A production cycle of 1,000 m² of greenhouse was considered. The highest costs corresponded to the chemical-organic treatment (100%), followed by biological products (72%) and biofumigation (68%). Although the chemical treatment showed the highest yield, biofumigation offered a more favorable cost-benefit ratio, achieving a similar level of productivity at a significantly lower cost.

Table 7: Relative Costs of Treatments (Base 100 = Chemical Control).

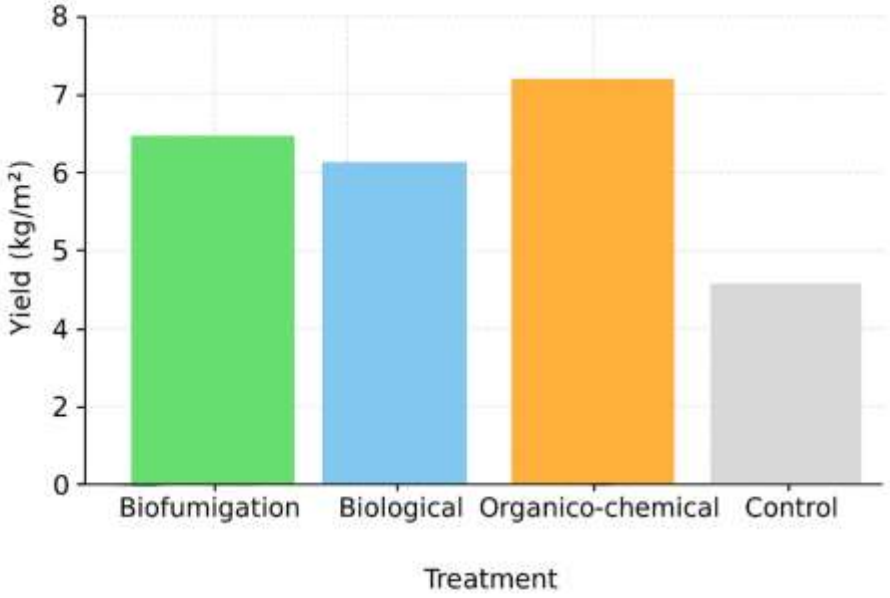
Treatment	Relative cost (%)	Yield (kg/m²)	Cost-benefit ratio
Biofumigation	68	6.1	0.089
Biological products	72	5.9	0.082
Chemical-organic control	100	6.8	0.068
Absolute control	20	3.2	0.160 (negative)

Source: Own Elaboration, 2025.

Table 5 allows us to analyze the socioeconomic dimension of the treatments by considering their relative costs, the yield obtained, and the cost-benefit ratio. Chemical-organic control,

taken as a reference (100%), achieved the highest yield with 6.8 kg/m², but also involved the highest cost. In contrast, biofumigation and biological products were positioned as more economical alternatives, with relative costs of 68% and 72%, respectively, achieving yields close to those of chemical control (6.1 and 5.9 kg/m²). This is reflected in a more favorable cost-benefit ratio for biofumigation (0.089), which even exceeds the economic efficiency of chemical-organic control (0.068).

The case of the absolute control is illustrative: although it has the lowest cost (20%), its low yield of 3.2 kg/m² generates an apparently high cost-benefit ratio (0.160). However, this value should be interpreted as negative or misleading, as it comes from a strategy without management that seriously compromises productivity and, consequently, is not viable for ensuring crop sustainability. In comparative terms, the results show that agroecological treatments are not only effective in the non- y control of nematodes and in improving yield, but also competitive in economic terms. Biofumigation, in particular, stands out for its balance between moderate costs and high productivity, making it a viable alternative for small and medium-sized producers seeking to reduce their dependence on external inputs.



Graph 3: Estimated Tomato Yield.

Source: Own Elaboration, 2025.

Figure 3 shows a comparison of the average tomato yield under the different treatments evaluated. Chemical-organic control ranks as the most productive, with a yield of close to 6.8 kg/m², surpassing the other treatments. However, it is important to note that the difference with biofumigation (6.1 kg/m²) and biological products (5.9 kg/m²) is not so great, indicating that agroecological strategies achieve very competitive productivity levels compared to chemical management. For its part, the absolute control showed the vulnerability of the crop in the absence of management, with only 3.2 kg/m², representing a reduction of more than 50% compared to chemical treatment and around 45% compared to agroecological practices. This confirms that uncontrolled nematode pressure seriously compromises the productive capacity of tomatoes, reducing both the number and weight of the fruits. From a practical point of view, the figure illustrates that although chemical management offers maximum yield, agroecological treatments guarantee sufficient productivity at lower costs and without the environmental risks associated with synthetic inputs. The margin of difference in yield can be considered manageable, especially if it is offset by cost reduction, environmental safety, and the possibility of replicating these practices in rural contexts.

In summary, the graph shows that agroecological treatments are a realistic and sustainable alternative for maintaining tomato productivity, thus contributing to food sovereignty and reducing dependence on external inputs. The data confirm that agroecological treatments had a significant effect on reducing nematodes and improving productivity. Although chemical- organic control offered the highest values for pest reduction and yield, biofumigation and biological products proved to be competitive alternatives with lower relative costs and no dependence on synthetic inputs.

5. DISCUSSION

Considering the above, the results confirm that managing *M. incognita* with biofumigation and chemical control consistently reduces J2 infestation and galling, which explains the observed productive performance. The agroecological strategies evaluated—particularly biofumigation and the use of biological agents—consistently reduce Meloidogyne incognita populations and, consequently, attenuates root damage as measured by the galling index. In addition, the magnitude of the reduction observed (62% in biofumigation and 54% in biological control, compared to a 48% increase in the control) shows that pathogen control is not a marginal phenomenon, but a primary mechanism that explains the productive differential between treatments. In fact, the chemical-organic treatment maintains the highest specific efficacy (70%), but what is relevant from this perspective is that agroecological options achieve similar yields (6.1 and 5.9 kg m^{-2}) without relying on synthetic inputs and with significantly lower relative costs. Considering the above, the central hypothesis of the study—that agroecology can increase agri-food productivity in tomatoes and contribute to food sovereignty—is strengthened, albeit with practical nuances regarding territorial scalability, taking into account that biofumigation and biocontrol reduce dependence on imported inputs and improve cost predictability, which are crucial conditions for small producers and local supply.

From a physiological point of view, the decrease in the galling index below critical thresholds explains the maintenance of root functionality and, therefore, the number and weight of fruits. On the other hand, the consistent pattern of "fewer nematodes— —less damage—higher yield" suggests plausible causal relationships based on well-established principles of plant pathology: when the integrity of the root system improves, water and nutrient absorption is maintained and fruit filling is stabilized. In this sense, biofumigation seems to operate as a combined action of volatile compounds (isothiocyanates) and favorable microbial changes, while biocontrol (e.g., ovicidal fungi or juvenile parasites) acts more gradually and depends on soil conditions. Considering the reference literature included in the manuscript, this convergence of mechanisms fits reasonably well with experiences reported in greenhouses and in the field, which reinforces the internal validity of the findings.

However, when the discussion shifts from the biological to the economic sphere, decisive factors emerge for decision-making at the production unit level. Relative costs and the cost- benefit ratio suggest that biofumigation offers the best balance between effectiveness and cost, making it attractive for small and medium-sized units, especially in contexts with liquidity constraints. From this perspective, the "maximum yield" of chemical-organic control must be tempered by its higher cost and its dependence on the recurring purchase of inputs. In other words, if the yield gap between chemical (6.8 $kg \cdot m^{-2}$) and biofumigation (6.1 $kg \cdot m^{-2}$) is not wide, but the cost gap is, economic rationality and technological sovereignty lean toward agroecological strategies that can be replicated with local resources.

In addition to this, the study's socioeconomic analysis (even without producers involved) allows us to outline adoption scenarios with a territorial logic: 1) in greenhouses with access to brassica biomass or local waste, biofumigation is almost immediate; 2) where there are reliable suppliers of biocontrol and technical support, biological agents are consolidated as a competitive second option; 3) chemical control is reserved for contingencies, specific rotations, or epidemic threshold situations that require rapid action, but not as a routine solution. From this perspective, the sequential combination of biofumigation (pre-planting) and biocontrol (establishment and post-transplant) could generate synergistic effects, reducing pathogen pressure in the short term and stabilizing the soil microbiome in the medium term. Considering the above, an Integrated Pest Management (IPM) agenda with an agroecological approach seems the most reasonable way to sustain productivity and reduce risks.

In terms of food sovereignty, the contribution of these practices transcends the technological package and is related to productive autonomy, soil health, and reduced dependence on imported inputs. On the other hand, improving yields to competitive levels at a lower relative cost opens up a way to stabilize the local tomato supply, with implications for availability and, potentially, consumer prices, at least in short circuits or local markets. From this perspective, agroecology contributes not only "more kilos," but "better kilos": products obtained with fewer externalities, greater resilience, and possibilities for participatory certification or local eco-labeling that rewards sustainable management efforts.

However, it is crucial to recognize the limitations of the study so as not to overestimate its scope. First, the trials were conducted in greenhouses; therefore, external validity requires field tests under the climatic, edaphic, and management variability typical of producing regions. Second, costs and cost-benefit ratios were estimated on a reference basis; therefore, a robust economic analysis is essential, taking into account local prices, actual availability of inputs, opportunity costs, and sensitivity to market fluctuations. Third, the socio-technical dimension of adoption—producer organization, technical assistance, access to credit, governance arrangements—must be part of the next phase, as the agroecological transition is not decided solely in the greenhouse, but in the institutional and community fabric that makes its sustainability possible over time. Considering the above, the potential impact is high, but its realization requires participatory scaling strategies.

Based on the findings and limitations noted, four lines of action are proposed for an agroecological transition with territorial impact: (i) field validation with experimental design stratified by agroecosystems (temperate highlands, semi-arid zones, dry tropics), incorporating economic sensitivity analysis and epidemiological decision thresholds; (ii) integrated and sequential management packages (pre-planting biofumigation + biocontrol in establishment, supported by rotations and organic amendments), with replicable operating manuals and schedules; (iii) extension and social innovation schemes-innovation schemes with producers, defining indicators not only for production but also for soil health, savings on external purchases, and income stability; and (iv) construction of short circuits and value recognition mechanisms (local labels, public procurement, neighborhood markets) that translate agroecological efforts into better prices or commercial conditions, thus reinforcing food sovereignty. The underlying discussion is broader than a problem of nematodes; it is about reconfiguring the link between productivity and food justice. If biofumigation and biocontrol make it possible to maintain competitive yields at lower cost and with less dependence, then a different productive rationality is enabled, more in line with the right to decide how to produce and with what inputs. From this perspective, the study provides evidence that agri-food productivity and agroecology are not parallel paths, but converging lanes, capable of sustaining tomato cultivation with criteria of technical efficiency, economic viability, and socio-environmental commitment. Considering the above, the next stage should

measure key collateral impacts (post-harvest quality, traceability, environmental footprint, consumer perception) to close the circle between sustainable management and real strengthening of food sovereignty in Mexico.

6. CONCLUSION

The findings of the study allow us to affirm, based on consistent experimental evidence, that it is possible to sustain competitive levels of tomato productivity through agroecological alternatives that significantly reduce the pressure of Meloidogyne incognita and the associated root damage. In addition, biofumigation stood out for its more favorable cost- benefit ratio, while biological agents showed similar and stable performance, which together confirms that reducing the rate of galling caused by s results in more numerous and heavier fruits without critical dependence on synthetic inputs. In fact, chemical-organic control maintained the highest specific efficacy; however, when recurring costs and dependence on the purchase of external inputs are taken into account, technical and economic rationality leans toward a predominantly agroecological management package capable of sustaining yields, preserving soil health, and reducing environmental and financial risks. Meloidogyne control was significantly higher with chemical control and biofumigation; Paecilomyces showed intermediate efficacy, and the highest yield corresponded to chemical control; however, RBC was maximized with biofumigation, due to its lower input costs and competitive yield. In turn, the unification of the galling scale (0–5) and the consistency of the 4×4 design strengthens the statistical reliability of the study. For smallholder contexts, biofumigation represents a viable alternative for improving productivity with less dependence on external inputs.

From this perspective, the study's contribution goes beyond phytosanitary issues and is linked to food sovereignty on at least three fronts: first, it promotes productive autonomy by relying on local resources and capacities that can be organized at the community level; second, it reduces the vulnerability of cropping systems to price shocks and input availability, which stabilizes supply in local markets and short supply chains; and third, it opens the door to differentiated valuation schemes—local labels, responsible public procurement, participatory certifications—that recognize sustainable management efforts. Furthermore, the observed consistency between "fewer nematodes—less damage—higher yields" reinforces the causal plausibility of the practices evaluated and supports the central hypothesis of the study: agri- food productivity and agroecology are not parallel paths but converging ones, especially in contexts where costs matter as much as each kilogram obtained.

Considering the above, three lines of action are recommended for the next phase: (i) field validation with producers under real management conditions—climate, soil, biomass availability, and biocontrol—incorporating economic sensitivity analysis with local prices, opportunity costs, and risk scenarios; (ii) implementation of a sequential integrated management package (pre-planting biofumigation + biocontrol at establishment and post- transplant), complemented by rotations and organic amendments, standardized in simple and replicable operating protocols; and (iii) construction of socio-technical adoption arrangements—extension and co-innovation, access to microfinance, governance agreements—that ensure continuity, collective learning, and territorial scaling. In addition, it will be relevant to measure strategic side effects (post-harvest quality, product traceability, environmental footprint, and consumer acceptance) to close the loop between agronomic performance and the social value of production.

In short, the study shows that the agroecological transition in tomatoes is technically feasible, economically sensible, and socially desirable, provided that it is organized into clear management packages and accompanied by organizational structures that sustain the practice over time. On the other hand, the absence of direct work with producers at this experimental and y stage requires caution, bringing the results from the greenhouse to the field through participatory designs and robust metrics that allow for correction and learning. In truth, the challenge is not limited to "producing more" but to producing in a way that strengthens rights, reduces dependencies, and expands local capacities. Therefore, the practical conclusion is clear: moving toward integrated agroecological management, anchored in community agreements and local markets, is a concrete way to link productivity with food sovereignty in Mexico.

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