Scientific Research Communications 2025, Volume 5, Issue 2, 118-139

Scientific Research Communications

Efficacy of Biofumigants for Controlling Root-Knot Nematodes (*Meloidogyne*) in Tomato Cultivation

Parwiz Niazi [1]*, Abdul Bari Hejran[2], Khaidarov Saken[3]

Kandahar University, Department of Biology, Kandahar, 3801, Afghanistan
Helmand University, Department of Biology, Helmand, 3901, Afghanistan and Al-Farabi Kazakh National University, Department of Biotechnology, Almaty, Kazakhstan
Al-Farabi Kazakh National University, Department of Biotechnology, Almaty, Kazakhstan

Research Article

*Correspondence:
parwiz60@gmail.com

Received: 13 November 2024
Accepted: 30 June 2025
Published: 30 July 2025

Keywords
Natural soil amendments
Meloidogyne spp.
Lycopersicon esculentum
Agroecological practices

Abstract

Root-knot nematodes (*Meloidogyne* spp.) are formidable pests that impose severe constraints on agricultural productivity, particularly impacting the growth and yield of economically important crops such as tomatoes. This study undertakes a comprehensive examination of biofumigants derived from plants within the *Brassicaceae* and Non-*Brassicaceae* families, investigating their potential as environmentally friendly control measures against these nematodes. Specifically, it evaluates the nematicidal efficacy of biofumigants sourced from cabbage (*Brassica oleracea*), sorghum (*Sorghum bicolor*), and *Tagetes* (*Tagetes* spp.) in reducing root-knot nematode populations and enhancing growth-related parameters of tomato plants. The experimental design followed a completely randomized design format, featuring five distinct treatments to ascertain the effects of each biofumigant on nematode suppression and various plant growth metrics, including plant height, leaf count, and root wet weight. This investigation revealed a significant advantage of *Brassicaceae*-derived biofumigants, with cabbage showing the most potent nematicidal activity, achieving a 60.7% reduction in nematode populations compared to untreated control groups. Sorghum (*Sorghum bicolor*), representing the Non-*Brassicaceae* family, also exhibited promising effects, achieving a 50.9% reduction in nematode presence. By contrast, *Tagetes* spp. displayed relatively moderate efficacy, with a 30.8% reduction in nematode populations. Notably, while the application of these biofumigants did not lead to statistically significant changes in tomato plant height or leaf count, the results highlight the substantial potential of *Brassicaceae*-based biofumigants, particularly cabbage, as viable, sustainable, and ecologically sound strategies for managing root-knot nematodes in tomato cultivation. Such biofumigants could offer a promising alternative to chemical nematicides, reducing reliance on synthetic pesticides and fostering sustainable agricultural practices. This study underscores the importance of further research into *Brassicaceae*-derived biofumigants to optimize their application and maximize their effectiveness in diverse agricultural systems.

How to cite this paper: Niazi, P., Hejran, A. B., & Saken, K. (2025). Efficacy of biofumigants for controlling root-knot nematodes (*Meloidogyne*) in tomato cultivation. *Scientific Research Communications, 5*(2), 118–139. https://doi.org/10.52460/src.2025.010

1. Introduction

Root-knot nematodes (RKN) can severely damage plants by hindering root system growth, leading to reduced nutrient uptake and increasing vulnerability to secondary pathogens (Habteweld et al., 2024). Various control methods have been employed to mitigate RKN damage, with nematicides being the most commonly used. Soil fumigation, involving high doses of chemicals like methyl bromide and chloropicrin, has effectively reduced RKN populations below economic thresholds (Faria et al., 2024; Priyadharshini et al., 2025); due to environmental concerns and stricter regulations, many fumigants have been banned. Fumigants contribute to volatile organic compound emissions, which harm air quality. In 2019, the global market for fumigation reached USD 938.61 million, with continued growth expected. However, restrictions on fumigant use are increasing, leading to the search for eco-friendly alternatives like biofumigation (Majid et al., 2025; Rajah et al., 2025).

Tomatoes (*Solanum lycopersicum L.*) are economically valuable and widely cultivated for their nutrient-rich profile, which includes essential minerals, vitamins, and antioxidants beneficial to human health; among these, tomatoes are exceptionally high in lycopene, an antioxidant linked to reducing risks of cancer, cardiovascular disease, and cellular ageing (Jamir et al., 2024). Globally, India ranks as the third-largest producer of tomatoes, following China and the USA, with an impressive production of 20.7 million tons in 2018 from 0.8 million hectares, yielding approximately 26,000 kilograms per hectare (Salhab et al., 2020). In economically vulnerable regions, however, maintaining a stable tomato supply is challenged by infections from *Meloidogyne spp*., commonly known as RKN; these parasites cause significant damage to the plant's vascular system, impeding water uptake, nutrient transport, and photosynthesis, and are estimated to contribute to annual global agricultural losses of around $78 billion (Abd-Elgawad, 2024). Nematode secretions further disrupt biochemical and molecular processes in plant roots, weakening their capacity for water and nutrient absorption (Niazi et al., 2023; Adigun et al., 2024). Various methods have been tested to combat nematode infections, including crop rotation with non-host plants and chemical nematicides, such as halogenated aliphatic hydrocarbons, 1,3-dichloropropene, methyl isothiocyanate, oxamyl, thionazin, and carbofuran, the extensive use of chemical treatments raises environmental concerns (Kandil et al., 2025).

With a growing focus on sustainable disease management, recent research has turned towards microbial-based alternatives (Hamrouni et al., 2024). Plant growth-promoting rhizobacteria (PGPR) represent an environmentally safe strategy for controlling soil-borne plant diseases (Sun et al., 2024; Kumar et al., 2023). By fostering beneficial microbial interactions, PGPR helps plants better absorb nutrients and release phytohormones, enhancing their resilience against pathogens more sustainably (Qadir et al., 2024; Gupta et al., 2024). RKN (*Meloidogyne spp.*) are microscopic, parasitic roundworms that infest plant roots, causing significant agricultural damage worldwide. These nematodes are named for the characteristic galls or "knots" they induce in the roots of infected plants (Albazazz et al., 2024; Khosla and Sharma, 2024). They penetrate the roots and establish feeding sites, causing abnormal cell growth, which disrupts the plant's ability to absorb water and nutrients. This can lead to stunted growth, wilting, reduced yields, and in severe cases, plant death. There are over 90 species of RKN, with *Meloidogyne incognita, M. javanica, M. arenaria,* and *M. hapla* being the most common and damaging. These nematodes have a broad host range, affecting many crops such as tomatoes, potatoes, carrots, and cucumbers. Infestations can spread through soil, water, and contaminated tools, making them difficult to control (Mirzaev et al., 2024; Sarri et al., 2024).

The damage caused by RKN is often compounded by secondary infections from fungi, bacteria, or other soilborne pathogens that enter through the wounds they create. Due to their impact on agriculture, RKN are considered a significant pest, and effective management strategies are essential for maintaining healthy crops and reducing economic losses (Rigobelo et al., 2024). Traditional control methods have relied on chemical treatments, but concerns about environmental toxicity have prompted interest in sustainable alternatives like crop rotation, resistant plant varieties, and biofumigation (Curk & Trdan, 2024).

Biofumigation involves incorporating plant materials, especially from the cabbage family, into the soil; cabbage plants produce glucosinolates, secondary metabolites toxic to pathogens and weeds (Harouna et al., 2024; Muthusamy and Lee, 2024). Glucosinolates reduce RKN egg viability by penetrating the cuticle, and their hydrolysis produces isothiocyanates (ITS), which function as fungicides and nematicides (Fourie, 2024). Sorghum produces nematicidal cyanide through hydrolysis of dhurrin, which is converted into toxic hydrogen cyanide (Njekete et al., 2024). *Tagetes* plants release α-terthienyl, which becomes phytotoxic to nematodes after photoactivation; these biofumigation techniques provide a promising, environmentally friendly alternative for managing RKN and other plant parasitic nematodes (Kannan et al., 2024; Hejran et al., 2024). Biofumigation is an environmentally friendly pest management technique that uses specific plants, mainly those rich in natural compounds, to control soil-borne pests and pathogens, including nematodes, fungi, and weeds; the process involves incorporating plant materials into the soil, where they decompose and release volatile compounds that are toxic to harmful organisms (El-Sharkawy & Al-Gendy, 2024).

Plants from the Brassicaceae family, such as mustard, cabbage, and radish, are commonly used in biofumigation due to their high levels of glucosinolates. When these plants are chopped or macerated and mixed into the soil, their glucosinolates are broken down through enzymatic hydrolysis, producing compounds such as isothiocyanates, which have strong biocidal properties. These compounds can inhibit the growth and reproduction of pests like RKN, fungi, and certain weeds (Ko et al., 2024; Mwangi et al., 2024), other plants such as sorghum and *Tagetes* (marigold) also have biofumigant properties. Sorghum, for example, produces cyanogenic glycosides that release toxic hydrogen cyanide, while marigolds produce α-terthienyl, which becomes active under UV light and targets nematodes (Giantin et al., 2024; Biswas and Das, 2024). Biofumigation is seen as a sustainable alternative to chemical fumigants, which can have harmful environmental effects. It helps improve soil health by adding organic matter and reducing reliance on synthetic pesticides. Although its efficacy may vary depending on factors such as soil type and pest populations, biofumigation is gaining popularity as part of integrated pest management strategies aimed at reducing the use of toxic chemicals in agriculture (Parsiaaref et al., 2024; Hejran et al., 2024). As part of integrated pest management (IPM) strategies, biofumigants offer sustainable solutions to replace or complement chemical fumigants. In this article, we endeavor to elucidate the efficacy of biofumigants derived from Brassicaceae and other botanical sources as eco-friendly alternatives for managing root-knot nematode (*Meloidogyne spp.*) infestations in tomato cultivation. The application of biofumigation, primarily utilizing glucosinolate-rich Brassicaceae plants, represents an emergent, sustainable paradigm for pest control, harnessing the innate biocidal properties of natural compounds to suppress nematode populations while minimizing environmental impact. We aim to provide an evidence-based framework for integrating biofumigants into sustainable agricultural practices by exploring the nematicidal potentials of cabbage, sorghum, and *Tagetes*. This study's findings promise to advance IPM strategies, contributing to reduced dependency on synthetic nematicides and promoting agroecological resilience (Zhang et al., 2025). The main objective of this study is to evaluate the potential of biofumigants derived from both Brassicaceae and non-Brassicaceae plant families as sustainable alternatives to synthetic nematicides for managing RKN (*Meloidogyne spp.*) In tomato cultivation. Specifically, the study aims to assess the nematicidal efficacy of biofumigants sourced from cabbage (*Brassica oleracea*), sorghum (*Sorghum bicolor*), and *Tagetes* (*Tagetes* spp.), as well as to investigate their effects on key growth parameters of tomato plants, including plant height, leaf count, and root wet weight.

2. Method and Materials

2.1. Preparation and sterilization of soil

The soil was sterilized before being placed into 8-inch earthen pots. Each pot was filled with 4 kg of sterilized sandy loam soil (71% sand, 21% silt, 8% clay, pH 7.3), which was obtained from a fallow field. The soil was sieved through a 16-mesh sieve to remove stones and debris. A mixture of soil and farmyard manure was prepared in a 3:1 ratio, and clay pots (25 cm top diameter) were filled with this mixture at 4 kg per pot. The soil was moistened with a small amount of water before being sterilized in an autoclave at a temperature of 121°C under 20 lbs pressure for 20 minutes. The sterilized soil was then allowed to cool at room temperature before use in the experiments (Bouchtaoui et al., 2025).

2.2. Sample preparation

Tomato seeds are sown in the greenhouse of the Plant Protection Study Program for 15 days to allow for early plant establishment; the seedlings will be grown under controlled conditions to ensure uniformity and healthy growth before they are exposed to further experimental treatments. The soil used in this study, which is naturally infested with RKN (*Meloidogyne spp*.), is sourced from a field that was previously cultivated with tomatoes; this field belongs to a region known to be endemic to RKN infestations.

The decision to use soil from this area is based on its history of persistent nematode problems, making it an ideal source for testing and evaluating the effectiveness of various RKN management strategies. Using soil already heavily infested with RKN, the experiment can simulate real-world agricultural conditions where these nematodes are a significant pest problem. This approach ensures the findings are relevant and applicable to farmers facing similar challenges.

The collected soil will be the foundation for subsequent experiments investigating the impact of different nematode control methods. These methods may include biofumigation with selected biofumigant plants, resistant tomato cultivars, or other integrated pest management strategies. By using naturally infested soil, the study will provide valuable insights into the efficacy of these control measures under realistic infestation levels, offering practical solutions for managing RKN in tomato crops; this phase is crucial for setting the stage for later evaluations of plant health, root system integrity, and overall crop yield in response to nematode management practices.

2.3. Treatment details

Preparation of biofumigants

Select biofumigant plants such as (*Brassica oleracea*), (*Sorghum bicolour*), and (*Tagetes spp*.). Chop the plant materials into pieces measuring 3-4 cm. This size enhances the surface area for decomposition and subsequent nematicidal activity, then combine 0.4 kg of the chopped biofumigant material with 2 kg of RKN-infested soil in a mixing container. Ensure thorough mixing to distribute plant material evenly within the soil (Sarwar et al., 1998; Ling et al., 2025).

Conditions for biofumigation

Allow the mixture to rest for a specific period (2-3 hours) before sealing to enable initial interactions between the soil and biofumigants. Conduct the mixing at a controlled temperature of approximately 25-30°C with relative humidity of around 60-70% to optimize microbial activity and nematicidal compound release during the decomposition phase. Seal the biofumigant-treated soil in plastic bags and incubate for 14 days. This period allows for the decomposition of biofumigants and the release of nematicidal compounds (Kirkegaard & Sarwar, 1998; Torabian et al., 2025).

Post-incubation handling

After 14 days, air the treated soil for 24 hours in a shaded area to allow volatile compounds to dissipate slightly while retaining nematicidal properties. After airing, transfer the treated soil into polybags for planting, ensuring soil moisture and structure uniformity.

2.4. Chemical treatment

Apply 4 g of carbofuran per 2 kg of soil. Incorporate the chemical into the soil by mixing thoroughly to ensure even distribution. This can be done using a hand trowel or a small garden spade. Apply the nematicide at least 24 hours before transplanting the tomato seedlings. This waiting period allows the chemical to settle and minimizes potential phytotoxicity in young plants (Figure 1).

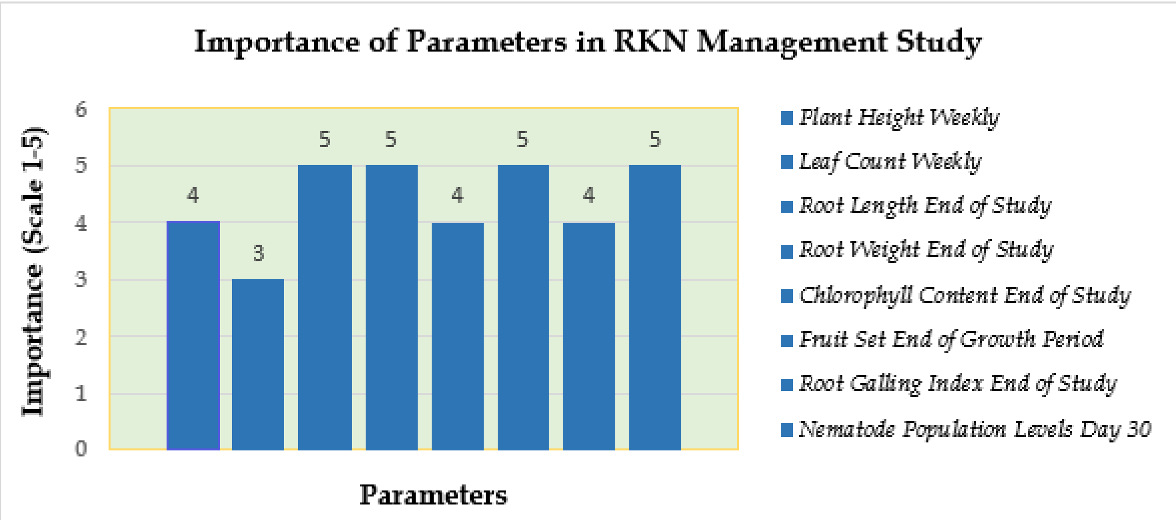

Figure 1. Importance (scale 1–5) of parameters in an RKN management study, with root length, root weight, fruit set, and nematode population rated highest

Figure 1 illustrates the comparative efficacy of different treatments (biofumigation, chemical treatment, and the untreated control) on tomato growth and nematode management parameters.

Biofumigation resulted in the highest average plant height, leaf count, and chlorophyll content, indicating its effectiveness in promoting plant health. Chemical treatment performed slightly better than the control group but was less effective than biofumigation across all parameters. The control group exhibited the lowest values, highlighting the detrimental impact of untreated RKN infestations on tomato growth. This analysis emphasizes the potential of biofumigation as a sustainable approach to managing RKN.

2.5. Control measures

Untreated infested soil

Maintain a control group using untreated RKN-infested soil. Ensure these pots are kept in the same environmental conditions (temperature, light, humidity) as the treated groups to eliminate confounding variables.

Replication and randomization

Randomly assign pots within the greenhouse to ensure that environmental variations (such as light and air circulation) are evenly distributed across treatment groups, and replicate each treatment group multiple times (five replicates) to ensure statistical robustness.

Monitoring conditions

Regularly monitor and record the temperature and humidity levels in the greenhouse to ensure consistency throughout the experimental period. This data can be crucial for assessing environmental factors' impact on treatments' effectiveness.

2.6. Greenhouse studies

The greenhouse studies are designed to evaluate the effectiveness of various treatments for managing RKN in tomato plants under controlled environmental conditions.

Experimental setup

Seedling Preparation

Tomato seedlings will be grown in polybags filled with naturally RKN-infested soil sourced from the farm. The soil's infestation history provides a realistic scenario for assessing the efficacy of various nematode management strategies.

Treatment Groups

The main treatments include biofumigation, chemical treatment and control group:

Biofumigation: Utilizing biofumigant plants such as cabbage, *Tagetes*, and sorghum.
Chemical Treatment: Application of the chemical nematicide carbofuran.
Control Group: Untreated infested soil will serve as the control.

Preparation of biofumigants

Biofumigant plants will be chopped into 3-4 cm pieces and mixed with RKN-infested soil at a ratio of 0.4 kg of plant material per 2 kg of soil. This mixture will be sealed in plastic bags for 14 days to allow for decomposition and the release of nematicidal compounds. After this period, the treated soil will be aired for 24 hours before being transferred to polybags for planting.

Randomization

To minimize bias from environmental factors such as light variations, the placement of pots within the greenhouse will be randomized. This will be achieved using a random number generator to assign pot positions before the start of the experiment. The layout will ensure that all treatment groups are evenly distributed throughout the greenhouse, preventing localized effects from temperature or light gradients.

Data collection

Comprehensive data will be collected on the following growth parameters.

Plant height

Measured weekly to assess vertical growth.

Leaf count

The total number of leaves will be counted weekly to evaluate foliage development.

Root length

At the end of the study, root systems will be carefully extracted and measured for length, providing insights into root health and vigor.

Root weight

Roots will be weighed post-harvest to evaluate biomass production.

Chlorophyll content

Measured using a spectrophotometer, chlorophyll levels provide insights into plants' photosynthetic efficiency.

Fruit set

At the end of the growth period, the number of fruit sets per plant will be recorded to assess reproductive success.

Root health

The Root Galling Index will be assessed visually, using a scale to quantify the severity of root galling caused by nematode infection.

Nematode population levels

At the end of the 30-day period, nematode densities will be assessed to determine the effectiveness of the treatments in suppressing RKN populations.

Experimental design

The experiment will follow a completely randomized design with five replications per treatment group, including controls; this design will facilitate statistical analysis and ensure reliable comparisons among treatments (Welham et al., 2014).

Assessment of Efficacy

Growth observations will be systematically recorded on Day 25, while nematode populations will be assessed on Day 30 after planting. The data will be analyzed statistically to compare treatment effectiveness in managing RKN and promoting plant health.

2.7. Biochemical parameters

Chlorophyll quantification

The quantification of chlorophyll content in fresh leaves was conducted following Mackinney's method. Initially, one gram of finely chopped fresh leaves was ground in a mortar and pestle and then immersed in 20 ml of 80% acetone. The mixture was centrifuged at 5000 rpm for 5 minutes to separate the soluble pigments and the supernatant was collected into a 100 ml volumetric flask. The remaining residue was washed thrice with 80% acetone, and each wash was combined with the supernatant in the volumetric flask. The total volume was adjusted to 100 ml with an additional 80% acetone (Tunca et al., 2024).

After preparing the extract, absorbance readings were taken at wavelengths of 645 nm and 663 nm using a spectrophotometer (U 1700, Shimadzu, Japan), with 80% acetone as the blank (Niazi, 2024); the chlorophyll content was calculated using the Equation (1):

$$\text{Total chlorophyll g - 1 tissue} = \frac{20.2\ (A645) + 8.02\ (A663)}{1000\ x\ W}\ x\ V \tag{1}$$

where *A645* and *A663* are the absorbance readings at the specified wavelengths, *W* is the weight of the leaf sample in grams and *V* is the total volume of the extract in milliliters.

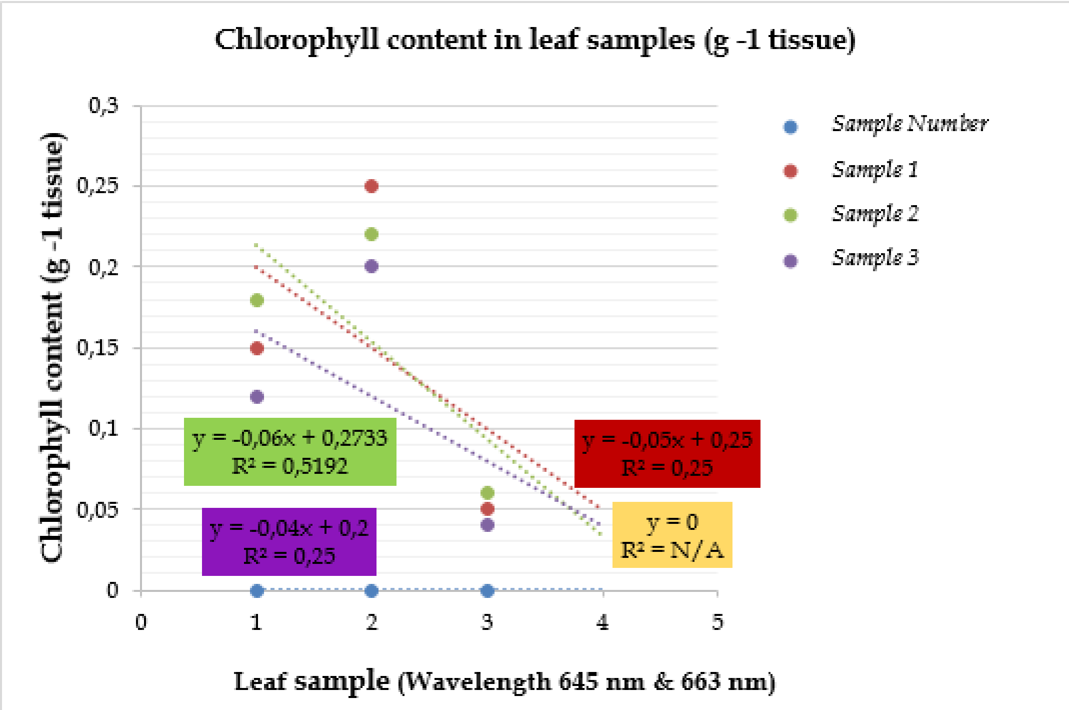

Figure 2. Chlorophyll content vs. leaf samples with trend-lines for samples 1–3 and control

Figure 2 illustrates the data organization for chlorophyll quantification. Each sample in the study is assigned a unique identifier (e.g., *Sample 1*, *Sample 2*, *Sample 3*) to facilitate accurate tracking and analysis. For each sample, two absorbance values are recorded: one at 645 nm, labeled as A645, and one at 663 nm, labeled as A663. Alongside these absorbance values, a calculated chlorophyll content value, denoted in grams per unit tissue (g-1), is also included for each sample. The absorbance at *645 nm (A645)* for each sample, noted as X1, X2, X3, etc., represents the initial absorbance readings taken at the specified wavelength for chlorophyll analysis. Similarly, the absorbance at *663 nm (A663)*, recorded as Y1, Y2, Y3, and so forth, represents additional readings necessary for accurate chlorophyll content calculation.

2.8. Statistical data analysis

Data analysis approach

The observational data collected from biochemical analyses and growth parameters will be evaluated using appropriate statistical methods to identify differences among the treatment groups. Initially, a one-way analysis of variance (ANOVA) will be performed using D-Staat software; this method is particularly suitable for analyzing single-factor designs with multiple treatment groups, allowing for insights into the overall variability within the dataset (Zoladek et al., 2022).

Post hoc testing

Following the ANOVA, Duncan's Multiple Range Test (DMRT) will be applied for post hoc comparisons between group means; this test is specifically chosen to control the overall error rate while providing precise comparisons of mean differences among groups, effectively identifying distinct subsets within the data (Agbangba et al., 2024).

Significance level

A significance level of 5% ($p < 0.05$) will be established, indicating that results are considered statistically significant if there is less than a 5% probability that the observed differences occurred by chance; this threshold is important for balancing the detection of fundamental differences while minimizing the risk of Type I errors (false positives).

Statistical software

Data analysis will be conducted using R (version 2.14.1; R Foundation for Statistical Computing, Vienna, Austria). To ensure precision in the results, the standard error of the mean (±SE) will be calculated, and the least significant difference (LSD) at a 5% significance level will be determined using R (Kolaczyk & Csárdi, 2014).

Reporting results

All results will be reported with mean values and standard deviations (mean ± SD) for clarity. Additionally, assumptions of normality and homogeneity of variances will be checked prior to analysis to validate the appropriateness of the ANOVA model (Sawyer, 2009).

3. Results and Discussion

The study results indicated that none of the treatments produced a statistically significant effect on tomato plant growth when measured by plant height and the number of leaves. A closer examination of plant height among the treatments revealed that the application of the carbofuran nematicide resulted in the highest average plant height; this was closely followed by the cabbage biofumigant treatment, which produced a slightly lower, though comparable, yield in terms of plant height.

The superior performance of carbofuran-treated plants can likely be attributed to the specific properties of the nematicide formulation (*Furadan 3G*). Beyond its primary function as a nematicide targeting and eliminating harmful nematodes that can impede plant health, carbofuran also contains compounds that act as growth regulators. These compounds enhance plant vigor, which may explain why plants in this treatment group reached greater heights on average than those in other treatments (Figure 3).

The cabbage biofumigant treatment showed the most beneficial impact on tomato plant height compared to other biofumigant options, including knicker and sorghum. Applying cabbage as a biofumigant introduces organic compounds into the soil that decompose and release nutrients, thus providing several agronomic benefits; these include the potential to increase organic matter, improve soil structure, and enhance nutrient availability. These benefits collectively foster a supportive environment for root and plant development, contributing to improved plant vigor and overall growth, as supported by previous findings.

In terms of leaf production, the cabbage biofumigant treatment demonstrated the most significant positive effect on the number of tomato leaves when compared to other treatments. This result may be attributed to the nutrient composition associated with plants of the

Brassicaceae family, such as cabbage, which are known to contribute essential nutrients to the soil, including nitrogen, phosphorus (P), potassium (K), magnesium (Mg), and organic carbon (C-organic). These nutrients play an important role in supporting the growth and development of tomato plants (Kakar et al., 2024; Trivedi et al., 2025).

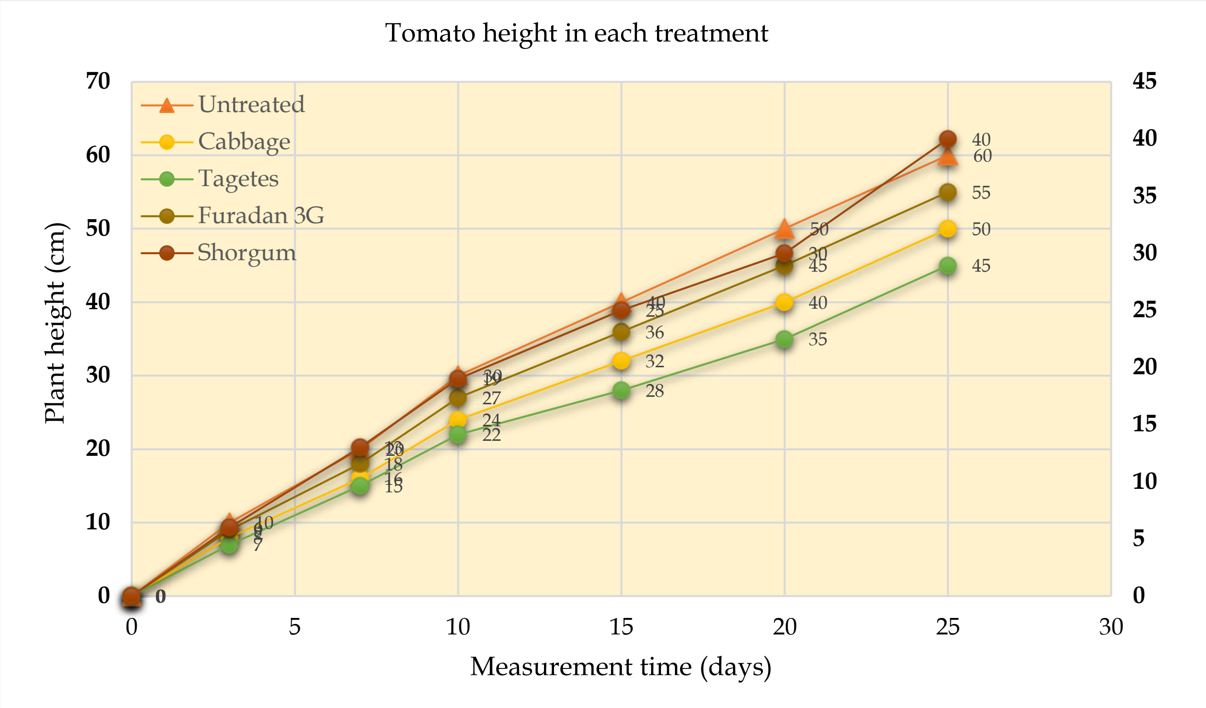

Figure 3. The effect of biofumigant treatment on tomato plant height

Nitrogen, in particular, is crucial for plants as it directly supports the growth of vegetative structures such as leaves, stems, and roots (Monib et al., 2024). Nitrogen fertilization is especially vital for plants during the vegetative phase, promoting the formation and expansion of leaves, which in turn maximizes photosynthetic capacity and overall plant *vigour*; the incorporation of cabbage biofumigants, therefore likely contributed to a richer nutrient profile in the soil, fostering an optimal environment for leaf production and, consequently, healthier, more robust tomato plants (Figure 4).

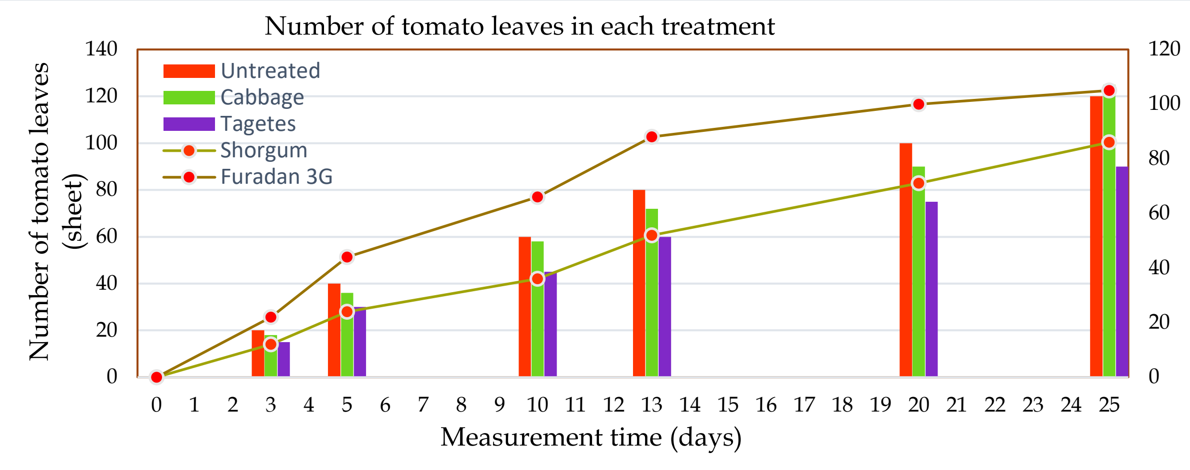

Figure 4. The effect of biofumigant treatment on the number of tomato leaves

Table 1 presents data on the root weight and population of RKN within the roots of treated plants. It is evident that the cabbage biofumigant treatment was the most effective in reducing the RKN population, with a significantly more significant impact than other biofumigant treatments. Specifically, when compared to the control group (plants without biofumigant treatment), cabbage biofumigant achieved a suppression effectiveness of 72.4% against RKN; this aligns closely with findings from a study by (Ji et al., 2024), which demonstrated that biofumigation with cruciferous plant residues can effectively manage RKN populations, achieving a 63.4% suppression rate in that case. The table also indicates that, among non-Brassicaceae plants, sorghum biofumigant proved more effective at reducing RKN populations than the knicker biofumigant. The enhanced effectiveness of sorghum is attributed to the release of a secondary metabolite called dhurrin, which is highly toxic to RKN. In contrast, kenikir (*Tagetes*) produces a secondary metabolite known as *α*-terthienyl, which generally inhibits nematode development rather than directly suppressing population growth. In this study, sorghum biofumigant showed a suppression effectiveness of 57.4% when compared to the control, while the *Tagetes* biofumigant treatment achieved a 39.4% suppression rate relative to the untreated control group.

Table 1 concludes that the root weight increase column shows the percentage increase in root weight for each application relative to the untreated control, providing a precise measure of how each application impacts root growth. Meanwhile, the Relative Ranking of Nematode Suppression organizes applications from highest to lowest in terms of effectiveness at reducing nematode populations, helping quickly identify the most effective methods. Regarding performance, the Cabbage Biofumigant ranked second in nematode suppression with a 60.7% reduction, just behind Furadan, outperforming other biofumigants by at least 13.7%. This treatment also showed the highest root weight increase (30.8%) among biofumigants, indicating that it effectively suppresses nematodes while supporting robust root growth. The *Tagetes* Biofumigant showed the lowest nematode suppression among biofumigants at 30.8%, performing 17.7% lower than Sorghum and substantially less than Cabbage. However, it provided a notable root weight increase (29.1%) over the control, indicating moderate benefits. Sorghum Biofumigant ranked third in nematode suppression, achieving 17.7% greater suppression than *Tagetes* but 11.1% less than cabbage. It showed a root weight increase of 27.7%, proving more beneficial for root growth than *Tagetes*.

Table 1. Comparing treatments for root-knot nematode control, with *Furadan* showing highest suppression and cabbage offering strong balance of control and root growth

Application	Root-Knot Nematode Population Density	Root Fresh Weight (g)	Nematode Suppression Efficiency (% Reduction from Control)	Root Health Index (Scale: 1-5)	Primary Active Compound	Root Weight Increase (% Increase from Control)	Relative Ranking of Nematode Suppression	Effectiveness and Observations
Control untreated	1029 a	3.199 a	0%	1 (Poor)	None	0%	5th (Lowest)	The highest nematode population and lowest root weight show significant damage without treatment, serving as a baseline for all comparisons.
Tagetes (*Tagetes spp.*)	649.1 b	4.251 ab	30.8%	3 (Moderate)	Terthienyl	27.7%	4th	Moderate suppression with a 30.8% reduction in nematodes, 17.7% less effective than Sorghum. Root weight improved by 27.7% compared to control, indicating moderate health improvement.
Sorghum (*Sorghum bicolor*)	450.4 c	4.264 ab	50.9%	3.5 Good) (Moderate)	Dhurrin	27.7%	3rd	Achieved 50.9% nematode suppression, 17.7% more than *Tagetes* but 11.1% less than Cabbage. Root weight increased by 27.7% over control, indicating better health than *Tagetes*.
Cabbage (*Brassica oleracea*)	309.1 d	4.337 b	60.7%	4 (Good)	Glucosino lates	33.3%	2nd	Achieved the highest biofumigant effectiveness, reducing nematode populations by 60.7%, a 31.1% higher suppression rate than *Tagetes*. Root weight increased 33.3% over control, indicating strong root health.
Nematicide *(Furadan 3G)*	60.7 e	149 ab	91%	4.5 (Very Good)	Carbofuran	24.4%	1st (Highest)	Highest nematode suppression, with 91% reduction, outperforming cabbage biofumigant by 21.1%. Root weight increase (24.4%) is lower than all biofumigants, possibly indicating phytotoxic effects despite high suppression.

Finally, the Nematicide (Furadan 3G) ranked highest in nematode suppression with a 91% reduction but had the smallest increase in root weight (24.4%) among all applications, suggesting possible phytotoxic effects that may impact root development despite its strong suppression effectiveness.

3.1. Effect of nematicide treatment on tomato plant growth

Nematicide treatments are used to manage plant-parasitic nematodes, such as *Meloidogyne* species, which can severely affect tomato plants by causing stunted growth and reduced yields. By applying nematicides like Furadan, the nematode population in the soil is significantly reduced, promoting healthier root development. This improved root structure enhances nutrient uptake and leads to more substantial plant growth, increasing vigor and potential yields.

A screen house experiment assessed the effects of biofumigant extracts in autoclaved, manure-enriched soil on managing root-knot disease and improving tomato growth; the untreated inoculated control group exhibited high pathogenicity, with a root-knot index of 4.8 on a scale of 0-5 (Fullana et al., 2024). In contrast, the fifth treatment group significantly reduced root galling. After introducing 2,000 juveniles, 500 µL of the extract was applied around the roots a week later. The treated plants demonstrated marked improvement, with the root-knot index decreasing to 1.2 compared to the untreated group (Table 2).

Table. 2. Effect of nematicide (Furadan 3G) treatment (35 ppm) on root-knot development caused by (*Meloidogyne incognita)* on tomato plant root and shoot growth

Treatment	Length(cm)		Total length (cm)	Fresh weight (g)		Total fresh weight (g)	Dry weight (gm)		Total dry weight (g)
	Shoot	Root		Shoot	Root		Shoot	Root	
Sorghum Biofumigant	49.1^c±1.1	4.2^c±0.5	50.9^c±1.6	48.10^c±0.9	11.85^c±0.61	59.95^c±0.71	11.52^c±0.63	3.2^c±0.26	14.72^c±0.89
Cabbage Biofumigant	63.3^b±0.7	4.4^b±0.8	60.7^d±1.5	61.85^b±1.32	17.95^b±0.83	79.80^b±0.75	18.55^b±0.75	3.4^b±0.29	21.95^b±1.04
Tagetes Biofumigant	30.2^d±1.2	4.2^d±0.6	30.8^d±1.6	24.22^d±1.82	9.80^d±0.88	34.025^d±2.7	4.80^d±0.30	3.1^d±0.17	7.9^d±0.47

This study's findings underscore biofumigants' efficacy, particularly those derived from the Brassicaceae family, as viable and sustainable tools for managing root-knot nematode (*Meloidogyne spp*.) populations in tomato cultivation. RKN are among the most detrimental pests to tomatoes and other high-value crops, causing substantial economic losses globally. Their management is integral to maintaining agricultural productivity and ensuring food security. This study's comparative analysis of biofumigants—cabbage (*Brassicaceae*), sorghum (*Poaceae*), and *Tagetes* (*Asteraceae*)—reveals distinct nematicidal potentials, with Brassicaceae-derived biofumigants demonstrating superior efficacy.

Cabbage, as a representative of the Brassicaceae family, exhibited the highest nematode suppression, achieving a 60.7% reduction in nematode populations. This remarkable effectiveness is attributed to glucosinolates, which enzymatically hydrolyze into isothiocyanates upon plant tissue disruption. As corroborated by prior studies, isothiocyanates are potent biocidal agents that disrupt nematode cellular integrity and metabolic processes (Ntalli & Caboni, 2012). The pronounced nematicidal properties of cabbage align with its potential integration into pest management frameworks, offering an environmentally sustainable alternative to synthetic nematicides.

In contrast, biofumigants derived from non-Brassicaceae sources demonstrated comparatively lower nematicidal effects. Sorghum achieved a 50.9% reduction in nematode populations, mainly attributable to its cyanogenic glucosides, which release hydrogen cyanide upon decomposition (Gimsing & Kirkegaard, 2006). However, these compounds appear less efficacious against RKN than the isothiocyanates produced by Brassicaceae species. Similarly, *Tagetes* spp. (marigold) exhibited only moderate suppression (30.8%), likely due to the production of thiophenes, which, while nematicidal, may have limited impact under field conditions or in high nematode infestations.

Despite significant nematode suppression, biofumigants did not induce statistically significant improvements in plant growth metrics, such as height or leaf count. This disparity suggests that while biofumigation mitigates nematode-induced stress, other agronomic factors—such as nutrient availability, initial pest pressure, or abiotic stressors—may modulate growth outcomes. Integrating biofumigants with complementary strategies, such as organic amendments, precision nutrient management, or companion planting, could amplify pest suppression and yield enhancements.

Using a completely randomized design in this study ensured methodological *rigour*, allowing clear comparisons across biofumigant treatments. Future research should expand on these findings through multi-year, field-scale trials to evaluate the consistency of biofumigant efficacy under diverse agroecological conditions. Exploring their interactions with soil microbial communities, nutrient cycling, and crop productivity could also elucidate their role within broader sustainable agricultural systems.

RKN (*Meloidogyne spp*.) pose a considerable constraint to agricultural productivity, necessitating the development of eco-conscious management strategies, including biofumigation. This study sought to evaluate the efficacy of biofumigants derived from Brassicaceae and non-Brassicaceae plant families in mitigating root-knot nematode infestations in tomato crops. A single-factor completely randomized design encompassing five treatments was employed for this purpose. The findings revealed that biofumigants from both plant groups did not exert a statistically significant influence on tomato plant height or leaf number. Among the tested biofumigants, cabbage (Brassicaceae) demonstrated the highest nematode suppression, achieving a 69.5% reduction in root-knot nematode populations relative to the untreated control. Sorghum (non-Brassicaceae) was identified as the most effective biofumigant in its group, reducing nematode populations by 55.8% compared to the control. RKN detrimentally impact plant health by impairing root system functionality, thereby restricting nutrient absorption and predisposing roots to secondary pathogens. While synthetic nematicides such as methyl bromide, DBCP, and chloropicrin have traditionally been effective in curbing nematode populations below economic thresholds, their environmental toxicity has led to regulatory restrictions and phased-out usage in many regions. Fumigation, a commonly employed nematode control measure, has proven effective in reducing the incidence of soil-borne plant parasitic nematodes. However, its limited accessibility in certain countries underscores the need for sustainable and environmentally benign alternatives. Biofumigation, which incorporates plant materials such as *cabbage, Tagetes, sorghum*, and *Sudan grass*, emerges as a viable substitute (Habriantono et al., 2023).

Cabbage biofumigants leverage glucosinolates, which degrade into isothiocyanates (ITS)—potent nematicidal and fungicidal agents that penetrate nematode egg cuticles. Similarly, sorghum and Sudan grass release hydrogen cyanide through the enzymatic breakdown of dhurrin, a cyanogenic glycoside, effectively reducing nematode viability. *Tagetes* plants, recognized for their allopathic properties, synthesize α-terthienyl, a secondary metabolite capable of inducing oxidative stress in nematodes through the rapid generation of phytotoxic reactive oxygen species. This investigation evaluated biofumigation efficacy on tomato plants subjected to root-knot nematode infestation. Fifteen-day-old tomato seedlings were transplanted into RKN-infested soil, which had been amended with chopped cabbage, *Tagetes*, or sorghum at a ratio of 0.4 kg plant material per 2 kg of soil. A parallel treatment involved carbofuran application at a dosage of 4 g per 2 kg of soil. The treated soil was stored anaerobically in plastic bags before transfer to polybags for planting. The experiment utilized a completely randomized design with five replications per treatment. Observations on tomato plant growth, including height, leaf count, and root biomass, were conducted on the 25th day post-treatment. The results indicated that none of the treatments significantly influenced plant growth parameters, highlighting the need for further investigation into the mechanisms and conditions underpinning biofumigant effectiveness (Habriantono et al., 2023).

Brassicaceae-derived biofumigants contribute to IPM frameworks by reducing dependence on synthetic nematicides, aligning with sustainable agriculture principles. These biofumigants mitigate environmental risks associated with chemical nematicides and support soil health and biodiversity, key pillars of sustainable farming. Continued research should optimize application protocols, evaluate long-term impacts on soil ecosystems, and integrate biofumigation with other agroecological practices to maximize its potential in sustainable food production systems.

Biological control agents have emerged as a promising and sustainable alternative to chemical nematicides in controlling RKN (*Meloidogyne spp*.) in tomato cultivation. For instance, *Pythium oligandrum* has been shown to effectively suppress *Meloidogyne incognita* infections by parasitizing nematode eggs and inducing systemic resistance in tomato plants (Pontes et al., 2024; Subedi et al., 2020; Zhou et al., 2016; Zhou et al., 2019). The research conducted by Yao et al. (2025) delves into the efficacy of *Bacillus velezensis* A-27 as a biocontrol agent targeting *Meloidogyne* incognita. This pernicious plant-parasitic nematode severely threatens global agricultural productivity. The study highlights the remarkable larvicidal and ovicidal properties of strain A-27, with LC50 values of 4.0570 × 10^8 CFU/mL and 3.6464 × 10^8 CFU/mL, respectively, observed under laboratory conditions. Pot trials demonstrated a significant reduction in root galling, achieving an impressive control efficacy of 85.36%. In comparison, field experiments revealed a control efficacy of 67.31%, alongside a reduction in the J2 population density of M. incognita and improved growth performance in celery plants. High-throughput sequencing further revealed that A-27 substantially enhanced the relative abundance of beneficial genera, such as *Bacillus* and *Sphingomonas*, while simultaneously reducing the prevalence of pathogenic genera like *Fusarium*, *Mortierella*, and *Cephaliophora* within the celery rhizosphere. These findings underscore the potential of *B. velezensis A-27* as an environmentally friendly alternative to synthetic nematicides, paving the way for its application in sustainable agricultural practices. RKN represent a formidable threat to over 5,500 plant species, including a wide range of economically significant vegetables. These nematodes are implicated in global agricultural losses exceeding $100 billion annually, with vegetable crop losses in China alone surpassing 3 billion CNY. Among RKN species, *Meloidogyne incognita* is the most prevalent and widely researched, particularly in greenhouse vegetable production. While synthetic chemical nematicides are effective, their environmental and health risks and high costs necessitate the development of safer and more sustainable biocontrol solutions. Several nematophagous fungi, including *Paecilomyces tenuis*, have demonstrated profound efficacy, achieving over 90% mortality of infective second-stage juveniles (J2) within 24 hours. Similarly, *Rhizophagus irregularis* has been shown to enhance plant resistance against RKN by modulating phenolic activity and antioxidant enzyme defense mechanisms. Other fungal species, such as *Fusarium oxysporum spp. ciceris* and *Myrothecium verrucaria*, have exhibited parasitism on nematode eggs, J2, and adult females, with mortality rates reaching 71% (Yao et al., 2025; Zhou et al., 2019; Wadhwa et al., 2024).

Arbuscular mycorrhizal fungi (AMF) also hold promise as biocontrol agents, bolstering plant tolerance to RKN by inducing systemic resistance (ISR), competing for rhizosphere resources, and modulating microbial interactions. Similarly, plant growth-promoting rhizobacteria (PGPR) exhibit systemic nematicidal properties, including *Pseudomonas stutzeri*, *Bacillus subtilis*, and *Streptomyces* antibiotics (Yadav et al., 2025). Notably, B. velezensis has emerged as a versatile agent with dual antifungal and nematicidal capabilities, effectively combating phytopathogens such as *Verticillium dahliae* and *Colletotrichum gloeosporioides*. Plants actively recruit beneficial microorganisms from the rhizosphere, fostering a dynamic microbial community that supports germination, nutrient uptake, and defence against pathogens. The application of microbial composts, particularly those containing *B. velezensis*, has been shown to enhance soil organic matter, enzyme activity, and microbial diversity, alleviating replanting disease and promoting plant growth (Yao et al., 2025; Xue et al., 2024; Hu et al., 2022; Subedi et al., 2020; Zhou et al., 2016; Zhou et al., 2019; Hejran, 2024).

3.2. Recommendations for Agricultural Practices

Selection of potent biofumigants

Due to their high glucosinolate content, they prioritize biofumigant crops from the Brassicaceae family, including mustard, cabbage, and broccoli. These biofumigants undergo enzymatic hydrolysis to release nematicidal isothiocyanates, effectively targeting RKN. Cultivating high-glucosinolate cultivars enhances biofumigant efficacy, ensuring maximum pest suppression.

Optimal timing and soil incorporation

Schedule the cultivation of biofumigant crops at least 4–6 weeks before tomato planting. Incorporate the biomass into the soil during peak glucosinolate production, typically at the flowering or seed set stage. This strategic timing ensures optimal degradation of glucosinolates into bioactive compounds, significantly reducing nematode populations before planting.

Integration with holistic pest management

Employ a multi-faceted IPM approach. Rotate biofumigant crops with non-host species to disrupt nematode life cycles and reduce pathogen buildup. Complement this with cultivating nematode-resistant tomato varieties and applying organic amendments like well-decomposed compost or manure to enhance soil biodiversity, further mitigating pest pressures.

Routine soil diagnostics and adaptation

Conduct periodic soil diagnostics, including nematode population density assessments and soil nutrient profiling, to monitor the long-term impact of biofumigants—utilize data-driven insights to fine-tune biofumigant application strategies, ensuring their efficacy under varying environmental and soil conditions.

Farmer training and advanced research initiatives

Establish farmer-centric educational programs to disseminate knowledge on the advantages, preparation, and application of Brassicaceae biofumigants. Support cutting-edge research to identify novel biofumigant species, optimize their application techniques, and explore synergistic interactions with other biological control agents. Collaborative research efforts will pave the way for innovative, eco-friendly nematode management strategies. By implementing these evidence-based and pragmatic strategies, farmers can substantially enhance pest management practices while optimizing tomato crop productivity. These strategies are in harmony with sustainable agricultural methodologies, reducing reliance on chemical interventions, preserving environmental integrity, and ensuring the enduring sustainability of commercial farming enterprises. This proactive and well-informed approach will mitigate Root-knot nematode infestations and promote long-term ecological stability.

4. Conclusions

This study highlights the significant effectiveness of both Brassicaceae and non-Brassicaceae biofumigants in managing root-knot nematodes (*Meloidogyne* spp.) in tomato cultivation. Among the tested treatments, the cabbage-based biofumigant (Brassicaceae) emerged as the most effective, achieving a 60.7% reduction in nematode populations compared to the untreated control. It also contributed positively to plant growth parameters, including height, leaf number, and root wet weight. Among the non-Brassicaceae biofumigants, sorghum demonstrated the highest efficacy, with a 50.9% suppression rate, while *Tagetes* showed the lowest, at 30.8%. These findings underscore the superior potential of cabbage as a sustainable biofumigant for integrated nematode management and crop improvement.

Authorship Contribution Statement

PN is responsible for conceptualization, data curation, formal analysis, original draft writing, and supervision. ABH is responsible for funding acquisition, writing, investigation, methodology, resources and software. KS is responsible for validation, visualization, writing, reviewing, and editing.

Conflict of Interest

The authors declare no conflict of interest.

References

Abd-Elgawad, M. M. M. (2024). Upgrading strategies for managing nematode pests on profitable crops. *Plants, 13*(11), 1558. https://doi.org/10.3390/plants13111558

Adigun, B. A., Oyekale, B. A., & Akhtar, M. S. (2024). Opportunistic fungi, plant, and nematode interactions in agricultural crops. In M. S. Akhtar (Ed.), *Opportunistic fungi, nematode and plant interactions* (pp. xx–xx). Springer.

Albazazz, A. M., & Aljuboori, F. K. (2024). Characterization of the root-knot nematodes infecting olive trees. *NTU Journal of Agriculture and Veterinary Sciences, 4*(3), Article e02. https://doi.org/10.56286/dghnfc02

Biswas, S., & Das, R. (2024). Organic farming to mitigate biotic stresses under climate change scenario. *Bulletin of the National Research Centre, 48*, 71. https://doi.org/10.1186/s42269-024-01226-x

Bouchtaoui, E. M., Smouni, A., Dababat, A. A., & Mokrini, F. (2025). Damage threshold and population dynamic of *Meloidogyne javanica* on tomato plant. *Journal of Phytopathology, 173*, e70015. https://doi.org/10.1111/jph.70015

Njekete, C., Caravel, C., Massol, F., & others. (2024, August 8). Nematicidal plants for root-knot nematode (*Meloidogyne* spp.) management in vegetable cropping systems [Preprint, Version 1]. *Research Square*. https://doi.org/10.21203/rs.3.rs-4725713/v1

Curk, M., & Trdan, S. (2024). Benefiting from complexity: Exploring enhanced biological control effectiveness via the simultaneous use of various methods for combating pest pressure in agriculture. *Agronomy, 14*(1), 199. https://doi.org/10.3390/agronomy14010199

El-Sharkawy, E. E. S., & Al-Gendy, A. A. (2024). Biofumigation potential of Brassicas to control white rot caused by *Sclerotinia sclerotiorum* on eggplant. *Egyptian Journal of Botany, 64*(2), 697–708. https://doi.org/10.21608/ejbo.2024.252958.2591

Faria, J. M. S., Rusinque, L., & Inácio, M. L. (2024). Nematicidal activity of volatiles against the rice root-knot nematode and environmental safety in comparison to traditional nematicides. *Plants, 13*(15), 2046. https://doi.org/10.3390/plants13152046

Fourie, L. W. (2024). *Investigating the use of marigolds (Tagetes spp.) and brassicaceous cover crops as a tool for the management of lesion nematodes (Pratylenchus spp.) in apple orchards* (Doctoral dissertation, Stellenbosch University). https://scholar.sun.ac.za/handle/10019.1/130166

Fullana, A. M., Expósito, A., Pujolà, M., Achaerandio, I., Cunquero, M., Loza-Alvarez, P., Giné, A., & Sorribas, F. J. (2024). Effect of grafting tomato onto *Solanum torvum* on the population dynamics of *Meloidogyne incognita* and *M. javanica* and crop yield losses. *Plant Pathology*. https://doi.org/10.1111/ppa.13991

Giantin, S., Franzin, A., Brusa, F., Montemurro, V., Bozzetta, E., Caprai, E., Fedrizzi, G., Girolami, F., & Nebbia, C. (2024). Overview of cyanide poisoning in cattle from *Sorghum halepense* and *S. bicolor* cultivars in Northwest Italy. *Animals, 14*(5), 743.

Gimsing, A. L., & Kirkegaard, J. A. (2006). Glucosinolate and isothiocyanate concentration in soil following incorporation of Brassica biofumigants. *Soil Biology and Biochemistry, 38*(8), 2255–2264. https://doi.org/10.1016/j.soilbio.2006.01.024

Gupta, M., Dwivedi, V., Kumar, S., Patel, A., Niazi, P., & Yadav, V. K. (2024). Lead toxicity in plants: Mechanistic insights into toxicity, physiological responses of plants and mitigation strategies. *Plant Signaling and Behavior, 19*(1), 2365576. https://doi.org/10.1080/15592324.2024.2365576

Habriantono, B., Wagiyana, W., & Alfarisy, F. K. (2023). The effectiveness of biofumigants from Brassicaceae and non-Brassicaceae to control root knot nematodes on tomato. In *E3S Web of Conferences, 373*. EDP Sciences. https://doi.org/10.1051/e3sconf/202337307003

Habteweld, A., Kantor, M., Kantor, C., & Handoo, Z. (2024). Understanding the dynamic interactions of root-knot nematodes and their host: Role of plant growth promoting bacteria and abiotic factors. *Frontiers in Plant Science, 15*, 1377453. https://doi.org/10.3389/fpls.2024.1377453

Hamrouni, R., Regus, F., Farnet Da Silva, A. M., Orsiere, T., Boudenne, J. L., Laffont-Schwob, I., & Dupuy, N. (2024). Current status and future trends of microbial and nematode-based biopesticides for biocontrol of crop pathogens. *Critical Reviews in Biotechnology*, 1–20. https://doi.org/10.1080/07388551.2024.2370370

Haruna, S. G., Yahuza, L., & Tijjani, I. (2024). Management of Fusarium wilt of tomato (*Fusarium oxysporum* f. sp. *lycopersici*) and related soil-borne diseases using eco-friendly methods: A review. *Asian Journal of Research in Crop Science, 9*(1), 154–168. https://doi.org/10.9734/ajrcs/2024/v9i1257

Hejran, A. B., Azizi, A., Saken, K., Ardak, K., Sawicka, B., & Niazi, P. (2024). Plant-derived bio-pesticides for eco-friendly control of the *Prodenia litura* (Fabricius) insect pest. *Journal* *of Entomology and Zoology Studies,* *12*(5). https://doi.org/10.22271/j.ento.2024.v12.i5c.9397

Hejran, A.-B. (2024). Effective plant virus management integrates strategies to protect and sustain crop health. *Торайғыров университетінің Хабаршысы, Химия-биологиялық сериясы*, (2). https://doi.org/10.48081/BZTR3857

Hu, Y., You, J., Wang, Y., Long, Y., Wang, S., Pan, F., & Yu, Z. (2022). Biocontrol efficacy of *Bacillus velezensis* strain YS-AT-DS1 against the root-knot nematode *Meloidogyne incognita* in tomato plants. *Frontiers in Microbiology, 13*, 1035748. https://doi.org/10.3389/fmicb.2022.1035748

Jamir, S., Devi, K. S., Ningombam, E., & Verma, A. (2024). A review on post-harvest technology of an underutilised vegetable bitter tomato (*Solanum aethiopicum* L Cv. Gilo) of Northeastern region of India. In *BIO Web of Conferences, 110*, 02006. EDP Sciences. https://doi.org/10.1051/bioconf/202411002006

Ji, Y., Zhang, Y., Fang, W., Li, Y., Yan, D., Cao, A., & Wang, Q. (2024). A review of biofumigation effects with plant materials. *New Plant Protection, 1*(2), e21. https://doi.org/10.1002/npp2.21

Kakar, U. M., Tauanov, Z., Azat, S., Ahmadi, N. A., Hassand, M. H., Sarwari, A., … Niazi, P. (2024). Carbon nanotubes as adsorbents for heavy metals: Focus on arsenic and hydrargyrum removal from water. *Journal of Chemistry Studies, 3*(1), 7–20. https://doi.org/10.32996/jcs.2024.3.1.2

Kandil, E., Abdelaziz, A., Mansour, M., & Attia, M. S. (2025). Promising nematocidal efficacy of *Verticillium lecanii*, hydrogen peroxide, and Melithorin® against root-knot nematode, *Meloidogyne incognita* in the tomato plant. *Egyptian Journal of Botany, 65*(1), 266–275. https://doi.org/10.21608/ejbo.2024.308857.2949

Kannan, K., Raju, P., Keerthy, B. N., Rajagopal, A., & Sabat, S. (2024). Biopesticide effect on crops for the bioactive components extracted from *Tagetes erecta* and *Tagetes patula*. *Discover Agriculture, 2*(1), 37. https://doi.org/10.1007/s44279-024-00045-y

Khosla, K., & Sharma, S. K. (2024). Understanding the dynamics of *Meloidogyne incognita* infestation in pomegranate orchards of Himachal Pradesh, India (years 2018, 2019, and 2021) and its management strategies. *Heliyon, 10*(15), e34752.

Kirkegaard, J. A., & Sarwar, M. (1998). Biofumigation potential of Brassicas. *Plant and Soil, 201*, 71–89. https://doi.org/10.1023/A:1004364713152

Ko, D. Y., Seo, S. M., Lee, Y. H., Gil, C. S., Lee, H., & Ku, K. M. (2024). Turning glucosinolate into allelopathic fate: Investigating allyl isothiocyanate variability and nitrile formation in eco-friendly *Brassica juncea* from South Korea. *Scientific Reports, 14*(1), 15423. https://doi.org/10.1038/s41598-024-65938-w

Kolaczyk, E. D., & Csárdi, G. (2014). *Statistical analysis of network data with R* (p. 65). New York, NY: Springer. https://doi.org/10.1007/978-3-030-44129-6

Kumar, A., Bhawsar, N., Manekar, S., Pendram, B., Pal, P., Ali, D., … Yadav, V. K. (2025). Extraction and optimization of lycopene from selected fruits and their assessment as an ultraviolet ray protectant for *Escherichia coli*. *Food Science and Nutrition, 13*(4), e70090. https://doi.org/10.1002/fsn3.70090

Ling, L., Yue, R., Wang, Y., Feng, L., Yang, L., Li, Y., … Zhou, Y. (2025). Volatile organic compounds from *Stenotrophomonas geniculata* J-0 as potential biofumigants manage bulb rot caused by *Fusarium oxysporum* in postharvest Lanzhou lily. *World Journal of Microbiology and Biotechnology, 41*(1),1–17.https://doi.org/10.1007/s11274-024-04228-z

Majid, M., Ganai, B. A., & Wani, A. H. (2025). Antifungal, antioxidant activity, and GC–MS profiling of *Diaporthe amygdali* GWS39: A first report endophyte from *Geranium wallichianum*. *Current Microbiology, 82*(1), 40. https://doi.org/10.1007/s00284-024-04023-x

Mirzaev, U. N., Kuchboev, A. E., Mavlyanov, O., Amirov, O. O., & Narzullayev, S. B. (2024). Morphological and molecular characterization of root-knot nematodes from Uzbekistan. *Biosystems Diversity, 32*(1), 135–141. https://doi.org/10.15421/012413

Monib, A. W., Niazi, P., Barai, S. M., Sawicka, B., Baseer, A. Q., Nikpay, A., … Thea, B. (2024). Nitrogen cycling dynamics: Investigating volatilization and its interplay with N_2 fixation. *Journal for Research in Applied Sciences and Biotechnology, 3*(1), 17–31. https://doi.org/10.55544/jrasb.3.1.4

Muthusamy, M., & Lee, S. I. (2024). Abiotic stress-induced secondary metabolite production in Brassica: Opportunities and challenges. *Frontiers in Plant Science, 14*, 1323085. https://doi.org/10.3389/fpls.2023.1323085

Mwangi, N. G., Stevens, M., Wright, A. J., Edwards, S. G., Hare, M. C., & Back, M. A. (2024). Sensitivity of stubby root nematodes (*Trichodorus* and *Paratrichodorus* spp.) to isothiocyanates associated with Brassicaceae in an *in vitro* assay. *Nematology*, 1(aop), 1–8. https://doi.org/10.1163/15685411-bja10302

Niazi, P. (2024). Isolation and characterization of a (surfactin-like molecule) produced by *Bacillus subtilis*: Antagonistic impact on root-knot nematodes. *Scientific Research Communications, 4*(2). https://doi.org/10.52460/src.2024.010

Niazi, P., Alimyar, O., Azizi, A., Monib, A. W., & Ozturk, H. (2023). People-plant interaction: Plant impact on humans and environment. *Journal of Environmental and Agricultural Studies, 4*(2), 1–7. https://doi.org/10.32996/jeas.2023.4.2.1

Ntalli, N. G., & Caboni, P. (2012). Botanical nematicides: A review. *Journal of Agricultural and Food Chemistry, 60*(40), 9929–9940. https://doi.org/10.1021/jf303107j

Parsiaaref, S., Cao, A., Li, Y., Ebadollahi, A., Parmoon, G., Wang, Q., … Zhang, M. (2024). The main compounds of bio-fumigant plants and their role in controlling the root-knot nematode *Meloidogyne incognita* (Kofoid and White) Chitwood. *Agriculture, 14*(2), 261. https://doi.org/10.3390/agriculture14020261

Pontes, K. B., Machado, A. C. Z., Nogueira, A. F., Fagundes, D. F. V., de Lima Filho, R. B., Mosela, M., … Gonçalves, L. S. A. (2024). Efficacy of microbiological nematicides in controlling root-knot nematodes in tomato. *Frontiers in Agronomy, 6*, 1462323. https://doi.org/10.3389/fagro.2024.1462323

Priyadharshini, V., Kavitha, P. G., Vetrivelkalai, P., Shandeep, S. G., Rajavel, M., Balakrishnan, N., … Suganthi, A. (2025). Smart delivery of nanofiber matrix encapsulated botanical nematicide α-terthienyl against root knot nematode on tomato. *Physiological and Molecular Plant Pathology, 136*, 102508. https://doi.org/10.1016/j.pmpp.2024.102508

Qadir, M., Hussain, A., Iqbal, A., Shah, F., Wu, W., & Cai, H. (2024). Microbial utilization to nurture robust agroecosystems for food security. *Agronomy, 14*(9), 1891. https://doi.org/10.3390/agronomy14091891

Rajah, A. R., Parthiban, K. T., Prasanthrajan, M., Vijayabhama, M., Patil, P., Sekar, I., & Yadav, V. K. (2025). Evaluation of air pollution tolerance index of selected tree species to combat air pollution in urban areas of Mettupalayam, Tamil Nadu, India. *Environmental Pollutants and Bioavailability, 37*(1), 1–14. https://doi.org/10.1080/26395940.2025.2524085

Rigobelo, E. C., Nicodemo, D., Babalola, O. O., & Desoignies, N. (2024). *Purpureocillum lilacinum* as an agent of nematode control and plant growth-promoting fungi. *Agronomy, 14*(6), 1225. https://doi.org/10.3390/agronomy14061225

Salhab, J., Weber, M., Paganini, T., Khamassi, F., Bellagha, S., Hadj, H. B., & Laabidi, F. (2020). Olive oil, medicinal and aromatic plants, and tomatoes in North-West Tunisia: A roadmap to developing competitive advantage on strategic markets. World Bank. http://documents.worldbank.org/curated/en/784741593019888856/

Sarri, K., Mourouzidou, S., Ntalli, N., & Monokrousos, N. (2024). Recent advances and developments in the nematicidal activity of essential oils and their components against root-knot nematodes. *Agronomy, 14*(1), 213. https://doi.org/10.3390/agronomy14010213

Sarwar, M., Kirkegaard, J. A., Wong, P. T. W., & Desmarchelier, J. (1998). Biofumigation potential of Brassicas. *Plant and Soil, 201*, 103–112. https://doi.org/10.1023/A:1004381129991

Sawyer, S. F. (2009). Analysis of variance: The fundamental concepts. *Journal of Manual & Manipulative Therapy, 17*(2), 27E–38E. https://doi.org/10.1179/jmt.2009.17.2.27E

Subedi, P., Gattoni, K., Liu, W., Lawrence, K. S., & Park, S. W. (2020). Current utility of plant growth-promoting rhizobacteria as biological control agents towards plant-parasitic nematodes. *Plants (Basel, Switzerland), 9*(9), 1167.

Sun, W., Shahrajabian, M. H., & Soleymani, A. (2024). The roles of plant-growth-promoting rhizobacteria (PGPR)-based biostimulants for agricultural production systems. *Plants, 13*(5), 613. https://doi.org/10.3390/plants13050613

Torabian, S., Kim, E., Qin, R., Sathuvalli, V., Gollany, H. T., & Kleber, M. (2025). Soil microbial biomass influenced by cover crop after fumigation of potato fields. *Science of The Total Environment, 958*, 177910. https://doi.org/10.1016/j.scitotenv.2024.177910

Trivedi, S., Srivastava, A., Saxena, D., Ali, D., Alarifi, S., Solanki, V. S., … Yadav, V. K. (2025). Phytofabrication of silver nanoparticles by using *Cucurbita maxima* leaf extract and its potential anticancer activity and pesticide degradation. *Materials Technology, 40*(1), 2440907. https://doi.org/10.1080/10667857.2024.2440907

Tunca, H., Dinç, T., Yanık, H., Sevindik, T. O., & Keskin, S. Y. (2024). Calculation a new formula to determine the chlorophyll-a content without extraction by modeling meta analysis data in *Arthrospira platensis* Gomont. https://doi.org/10.21203/rs.3.rs-4258390/v1

Wadhwa, K., Kapoor, N., Kaur, H., Abu-Seer, E. A., Tariq, M., Siddiqui, S., … Alghamdi, S. (2024). A comprehensive review of the diversity of fungal secondary metabolites and their emerging applications in healthcare and environment. *Mycobiology*, 1–53. https://doi.org/10.1080/12298093.2024.2416736

Welham, S. J., Gezan, S. A., Clark, S. J., & Mead, A. (2014). *Statistical methods in biology: Design and analysis of experiments and regression*. CRC Press.

Xue, Y., Li, W., Li, M., Ru, N., Chen, S., Jiu, M., Feng, H., Wei, L., Daly, P., & Zhou, D. (2024). Biological control of a root-knot nematode *Meloidogyne incognita* infection of tomato (*Solanum lycopersicum* L.) by the oomycete biocontrol agent *Pythium oligandrum*. *Journal of Fungi, 10*(4), 265. https://doi.org/10.3390/jof10040265

Yadav, V. K., Pramanik, S., Alghamdi, S., Atwah, B., Qusty, N. F., Babalghith, A. O., Solanki, V. S., Agarwal, N., Gupta, N., Niazi, P., Patel, A., Choudhary, N., & Zairov, R. (2025). Therapeutic innovations in nanomedicine: Exploring the potential of magnetotactic bacteria and bacterial magnetosomes. *International Journal of Nanomedicine, 20*, 403–444. https://doi.org/10.2147/IJN.S462031

Yao, Y., Wang, L., Zhai, H., Dong, H., Wang, J., Zhao, Z., & Xu, Y. (2025). *Bacillus velezensis* A-27 as a potential biocontrol agent against *Meloidogyne incognita* and effects on rhizosphere communities of celery in field. *Scientific Reports, 15*(1), 1057. https://doi.org/10.1038/s41598-024-83687-8

Zhang, H., Guo, D., Lei, Y., Lozano-Torres, J. L., Deng, Y., Xu, J., & Hu, L. (2025). Cover crop rotation suppresses root-knot nematode infection by shaping soil microbiota. *New Phytologist, 245*(1), 363–377. https://doi.org/10.1111/nph.20220

Zhou, D., Feng, H., Schuelke, T., De Santiago, A., Zhang, Q., Zhang, J., Luo, C., & Wei, L. (2019). Rhizosphere microbiomes from root knot nematode non-infested plants suppress nematode infection. *Microbial Ecology, 78*(2), 470–481. https://doi.org/10.1007/s00248-019-01319-5

Zhou, L., Yuen, G., Wang, Y., Wei, L., & Ji, G. (2016). Evaluation of bacterial biological control agents for control of root-knot nematode disease on tomato. *Crop Protection, 84*, 8–13. https://doi.org/10.1016/j.cropro.2015.12.009

Zoladek, J., Burlaud-Gaillard, J., Chazal, M., Desgraupes, S., Jeannin, P., Gessain, A., … Afonso, P. V. (2022). Human claudin-derived peptides block the membrane fusion process of Zika virus and are broad flavivirus inhibitors. *Microbiology Spectrum, 10*(5), e02989-22. https://doi.org/10.1128/spectrum.02989-22