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Nematicidal Potential of some Essential Oils Applied as soil Drench or Foliar Spray against Root-Knot Nematode, *Meloidogyne incognita* Infecting Eggplant under Greenhouse Conditions.

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ABSTRACT

Root knot nematode, *Meloidogyne incognita* is the most serious threat affecting eggplant, *Solanum melongena* L. This study aimed to evaluate the efficiency of essential oils of four plant species (as soil drench/or foliar spray) individually or in integration with oxamyl against *M. incognita* infecting eggplant under greenhouse conditions. Soil drench application of essential oils in eggplant revealed species-specific efficacy and physiological impacts. Peppermint oil emerged as the premier treatment, reducing J2s densities by 85.29% (347 vs. 2358.25 J2s/250ml soil in control) and egg masses by 86.37% - narrowing the gap with oxamyl (96.14% J2s reduction) to just 9.77 percentage points. Garlic oil showed moderate efficacy (53.59% J2s reduction, 78.97% egg mass suppression). In infected plants, dill oil executed extraordinary photosynthetic rescue, elevating chlorophyll by 206.25% while preserving flavonoids (-15.07%). Foliar spray of essential oils on eggplant under identical conditions yielded distinct efficacy against *M. incognita*. Chili pepper oil dominated other treatments, reducing J2s by 80.66% (456.2 J2s/pot) and egg masses by 90.45% (22.25 vs. 233.0). Dill oil enabled systemic resilience in infected plants, recovering 68.8% of loss (49.38cm length) and increasing leaf counts by 82.35%. Biochemically, chili oil boosted chlorophyll by 145.83% in infected plants but incurred significant polyphenol depletion (-34.82%). Oxamyl treatment surpassed all tested applications in suppressing nematode population, number of galls and egg masses. A synergistic interaction was recovered with the integration of peppermint + Oxamyl (94.4% J2 reduction) followed by garlic + Oxamyl (89.1% J2 reduction) compared to essential oils single application.

Keywords: *Meloidogyne incognita*, Essential oils, Eggplant, Bioagents.



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INTRODUCTION

Eggplant represents a nutritionally significant crop, providing dietary fiber (2.5 g/100g), proteins (1.0 g/100g), and essential minerals (potassium: 230 mg/100g; calcium: 9 mg/100g). It is particularly notable for its high polyphenol content (1,423 mg GAE/100g DW), including chlorogenic acid—one of nature's most potent antioxidants (75% of total phenolics)—alongside caffeic and p-coumaric acids (Chumyarn *et al.*, 2013; Uscanga-Sosa *et al.*, 2020). Purple varieties contain substantial anthocyanins (e.g., nasunin at 750 mg/100g) and flavonoids that demonstrate radical-scavenging capacities exceeding many common vegetables (Koley *et al.*, 2019), though provitamin A carotenoid levels (10 µg RAE/100g) remain lower than in tomatoes or peppers (Gürbüz *et al.*, 2018). Egypt's warm climatic conditions (average 22-31°C) facilitate year-round proliferation of phytopathogens. Among constraints limiting vegetable productivity, plant-parasitic nematodes—particularly root-knot nematodes (*Meloidogyne* spp.)—have emerged as pathogens causing >30% yield losses in Solanaceous crops throughout the Nile Delta region (Eddaoudi *et al.*, 1997; Verdejo-Lucas *et al.*, 2002).

Growing recognition of chemical nematicides' environmental and health hazards—including groundwater contamination (fosthiazate DT₅₀ = 20-100 days), non-target toxicity (oxamyl EPA Category I), and resistance development—has intensified demand for sustainable alternatives. Root-knot nematodes, *Meloidogyne* pp.,

comprising >120 species with *M. incognita* (accounting for 65% of infestations), *M. javanica*, *M. arenaria*, and *M. hapla* being most prevalent (Karssen, 2000; Hunt *et al.*, 2005), employ sophisticated parasitic mechanisms: Second-stage juveniles (J₂s) penetrate root tips using a protrusible stylet, injecting effector proteins that reprogram vascular cells into metabolically hyperactive "giant cells." These permanent feeding sites disrupt water/nutrient transport, manifesting as root galls, stunting (height reduction >40%), wilting, and secondary pathogen susceptibility (Abad *et al.*, 2003; Williamson & Hussey, 1996). Integrated management strategies incorporating botanical pesticides offer promising solutions aligned with global sustainability initiatives. Plant-derived compounds—including phenolics (e.g., rosmarinic acid in mint), terpenoids (e.g., menthol), and organosulfur metabolites (e.g., allicin in garlic)—exhibit rapid biodegradation (DT₅₀ < 72 hr) and multi-target modes of action against nematodes: disrupting chemoreception, inhibiting acetylcholinesterase, impairing mitochondrial function, and suppressing egg hatching (>90% inhibition) (Jardim *et al.*, 2020; Desaegeer *et al.*, 2020). Garlic (*Allium sativum*), mint (*Mentha* spp.), dill (*Anethum graveolens*), and chili pepper (*Capsicum* spp.) demonstrate efficacy, with garlic organosulfur compounds achieving juvenile mortality at LC₅₀=36.2µg/mL (Jardim *et al.*, 2020) and chili capsaicinoids reducing gall formation by >50% (Akhtar *et al.*, 2019; Osman *et al.*, 2025).

This research investigates the nematicidal potential of essential oils from these botanicals against *M. incognita* in

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eggplant systems. Through controlled greenhouse experiments we evaluate: Nematicidal activity of essential oils of four plant species as soil drench or as foliar spray individually or in integration with oxamyl against *M. incognita* infecting eggplant.

MATERIALS AND METHODS

Nematode Stock Culture and Inoculum Preparation

Root-knot nematode (*M. incognita*) eggs were cultured on *Coleus blumei* plants grown in 25-cm diameter plastic pots containing sterile sandy loam soil. Nematode females were taxonomically identified according to Taylor and Sasser (1978) at the Nematode Research Unit (NERU), Faculty of Agriculture, Mansoura University, Egypt. After three months of cultivation, plant roots were thoroughly rinsed with distilled water and subsequently immersed for 60 seconds in a 1.0% sodium hypochlorite (NaOCl) solution within a plastic container. The roots were vigorously agitated manually, and the resulting suspension was sequentially filtered through 325-mesh and 500-mesh sieves. Collected eggs underwent extensive washing with tap water to eliminate residual bleach, following the protocol of Hussey and Barker (1973). The egg concentration per unit volume was quantified using a Hawksley counting slide under a dissecting microscope. Prepared inoculum was used to infect plants according to the experimental design in the NERU greenhouse.

Plant Oils

Essential oils of garlic (*Allium sativum* L.), mint (*Mentha piperita* L.), dill (*Anethum graveolens* L.), and chili pepper (*Capsicum frutescens* L.) were procured commercially from certified suppliers in Damietta local market. Oils were stored in dark glass bottles at 4°C to prevent oxidation and degradation of active compounds.

Chemical Nematicide

The carbamate nematicide oxamyl (Vydate® 24% L, Corteva Agriscience; chemical name: Methyl-N,N-dimethyl-N-(methylcarbamoyl) oxy-1-thioxamimidate) was used at the recommended agricultural dosage of 2.5 liters per feddan (4200 m²). For pot experiments, a concentration of 0.3 ml/pot was applied as soil drench unless otherwise specified.

Greenhouse Experimental Design

All experiments employed a randomized complete block design (RCBD) with four replicates per treatment. Plastic pots (14 cm diameter) were filled with 1800 g of steam-sterilized soil mixture (1:1 w/w clay: sand). Thirty-day-old seedlings eggplant (*Solanum melongena* cv. Black king) were transplanted with one seedling per pot. At 7 days post-transplanting, each pot received 1000 *M. incognita* eggs suspended in 5 ml water, injected at 3 cm soil depth around the root zone. Treatments were applied at 14 days post-transplanting. Control groups included: nematode-infected untreated plants (positive control), nematode-free plants (negative control), and oxamyl-treated plants (chemical control). Plants received standard horticultural care with drip irrigation and were protected against arthropod pests.

Plant Oil Efficacy against *M. incognita* on Eggplant (soil drench application)

The experiment was conducted at 19±3°C. Essential oils of four plant species were applied as soil drench (2.5 ml/pot in 50 ml water). Treatments included: 1) Single applications: chili pepper, dill, garlic, or peppermint essential

oil; 2) Integrated applications: Half-dose essential oil (1.25 ml) combined with half-dose oxamyl (0.15 ml/pot); 3) Full-dose oxamyl control (0.3 ml/pot); 4) N alone; and 5) Healthy control.

Plant Oil Efficacy against *M. incognita* on Eggplant (Foliar application)

Under 19±3°C, foliar sprays (2.5 ml oil/L water + 0.1% Tween 20) were applied three times at 7-day intervals starting at 14 days post-transplanting. Spray volume was adjusted to achieve complete leaf coverage (~50 ml/plant). In integrated treatments, oxamyl was applied as soil drench (0.15 ml/pot).

Evaluation Parameters

Plants were harvested 45 days post-inoculation. Growth parameters (shoot height, root length, fresh/dry biomass, leaf count) were recorded. Root systems were washed, stained with 0.015% acid fuchsin in lactic acid-glycerol (Byrd *et al.*, 1983), and evaluated for gall formation and egg masses using a 0-5 index (Taylor and Sasser, 1978). Soil nematodes were extracted using sieving and modified Baermann funnel technique (Goodey, 1957) and quantified with a Hawksley counting slide. Increase percentages (Inc.%) for growth parameters were calculated relative to nematode-only controls.

Biochemical Analyses

Fresh leaf tissue (0.5 g) from each replicate was analyzed for: 1) Total chlorophyll via dimethyl sulfoxide extraction and spectrophotometry at 645/663 nm (Goodwin, 1965); 2) Total phenolics using Folin-Ciocalteu reagent at 520 nm (Slinkard and Singleton, 1977); and 3) Total flavonoids via aluminium chloride method at 510 nm (Chang *et al.*, 2002).

Statistical Analysis

Data underwent analysis of variance (ANOVA) using CoStat software v6.303 (Cohort Software, 2005). Treatment means were separated by Fisher's Least Significant Difference (LSD) test at $\alpha=0.05$.

RESULTS AND DISCUSSION

Plant oil efficacy against *Meloidogyne incognita* on eggplant (soil drench).

Table (1) provide a detailed comparative analysis of the nematicidal activity of essential oils applied through soil drench, establishing peppermint oil as the preeminent botanical solution for managing *M. incognita* in eggplant cultivation. The data reveal three-dimensional nematode suppression across juvenile populations (J_2 /pot), gall formation, and reproductive output (egg masses), with peppermint oil achieving exceptional 85.29% reduction in soil nematode juveniles (347.0 J_2 vs. 2358.25 in controls) and 86.37% suppression of egg masses – efficacy metrics approaching the synthetic standard oxamyl (96.14% and 98.71% respectively). Garlic oil demonstrated significant but secondary efficacy, achieving 53.59% J_2 reduction and 78.97% egg mass suppression, through likely due to allicin's impact on - nematode chemosensation, while dill oil's showed intermediate activity (52.32 and 77.79% reductions, respectively). The critical revelation emerges from gall formation analysis: peppermint oil achieved 64.45% gall reduction – and outperforming garlic oil's gall control (55.45%) despite lower J_2 reduction. Chili pepper oil's demonstrated limited efficacy (37.3% J_2 reduction, 32.99% galls reduction and 39.59% egg mass reduction).

Table 1. Nematode parameters of *Meloidogyne incognita* infecting eggplant plants as affected by essential oil of four plant species applied individually as soil drench under greenhouse conditions (19±3°C).

Treatments	J ₂ soil/pot (Red. %)	No. galls (Red. %)	RGI	No. egg masses/root (Red. %)	EI
Chili pepper	1478 ^b (37.3)	229.0 ^b (32.99)	5.0	140.75 ^b (39.59)	5.0
Dill	1124.4 ^{bc} (52.32)	153.25 ^{cd} (55.16)	5.0	51.75 ^{cd} (77.79)	4.0
Garlic	1094.4 ^{bcd} (53.59)	152.25 ^{cd} (55.45)	5.0	49.0 ^{cd} (78.97)	4.0
Peppermint	347 ^{fg} (85.29)	121.5 ^d (64.45)	5.0	31.75 ^{de} (86.37)	4.0
Oxamyl	91.0 ^g (96.14)	28.75 ^e (91.59)	3.0	3.0 ^f (98.71)	2.0
N alone	2358.25 ^a	341.75 ^a	5.0	233.0 ^a	5.0
LSD	407.05	39.94	-----	20.004	-----

Pi=1000 eggs of *M. incognita*

Each value is a mean of four replicates.

Means in each column followed by the same letter(s) did not differ at $p < 0.05$ according to Duncan's multiple-range test.

Reduction % = (N alone – Treatment) / N alone × 100

Root gall index (RGI) or egg mass index (EI): 0 = no galling or egg masses; 1 = 1-2 galls or egg masses; 2 = 3-10 galls or egg masses; 3 = 11-30 galls or egg masses; 4 = 31-100 galls or egg masses; 5 = more than 100 galls or egg masses.

Table (2) demonstrated how essential oils applied as soil drench fundamentally alter eggplant physiology under *M. incognita* stress. The data documented unprecedented growth as peppermint oil triggers photosynthetic hyperstimulation in healthy plants, elevating them to 58.88 cm total length and 41.52 g fresh weight – surpassing untreated healthy controls by 58.29% in biomass and generating a staggering 13.33% leaf proliferation (8.5 leaves vs. healthy controls' 7.5 leaves). Conversely, under nematode infestation, dill oil at infected plants not only recover 68.8% of architectural loss (49.38 cm length) but paradoxically develop 29.41% more leaves than infected controls. The garlic oil presents critical agricultural implications: despite moderate nematode suppression, it significantly stunts development in both systems, reducing healthy plants to stunted 40.75 cm long (38.5% below healthy controls) and collapsing infected plants to 35.75 cm. Chili pepper oil exhibits varying bioactivity, enhancing uninfected plants (49.25 cm length) but showing reduced effectiveness in infected systems (48.0 cm).

Table 2. Plant growth response of eggplant infected or uninfected with *Meloidogyne incognita* under the stress of essential oil of four plant species applied individually as soil drench under greenhouse conditions (19±3°C).

Treatments	Plant growth response							
	Length (cm)		Plant length (cm) (Inc. %)	Fresh weight (g)		Plant F. wt. (g) (Inc. /Dec. %)	Shoot dry wt. (g) (Inc. %)	No. of leaves (Inc. %)
	Shoot	Root		Shoot	Root			
Uninfected								
Chili pepper	29.5 ^{cde}	19.7 ^{def}	49.25 ^{efg} (-25.66)	30.75 ^b	2.56 ^{de}	33.31 ^{bc} (26.99)	9.74 ^c (43.66)	6.5 ^{cd} (-13.33)
Dill	32.0 ^{bc}	20.75 ^d	52.25 ^{de} (-21.13)	30.75 ^b	2.8 ^{d-g}	32.84 ^{bc} (25.20)	9.75 ^c (43.81)	6.5 ^{cd} (-13.33)
Garlic	19.5 ^h	21.25 ^{cd}	40.75 ^{hi} (-38.49)	14.25 ^d	2.7 ^d	16.95 ^{gh} (-35.38)	9.38 ^{cd} (38.35)	6.25 ^{de} (-16.67)
Peppermint	31.75 ^{bcd}	27.13 ^{ab}	58.88 ^{bc} (-11.12)	38.75 ^a	2.77 ^{cd}	41.52 ^a (58.29)	12.75 ^{ab} (88.05)	8.5 ^{ab} (13.33)
Infected								
Chili pepper	27.0 ^{ef}	21.0 ^d	48.0 ^{efg} (64.1)	14.7 ^d	3.97 ^b	18.72 ^{fg} (80.4)	7.13 ^f (181.9)	4.75 ^{gh} (11.76)
Dill	31.5 ^{bcd}	17.88 ^{d-g}	49.38 ^{efg} (68.8)	20.5 ^c	2.88 ^{cd}	23.38 ^{de} (125.3)	8.25 ^{def} (226.4)	5.5 ^{d-g} (29.41)
Garlic	18.5 ^h	17.25 ^{efg}	35.75 ^{jk} (22.22)	12.0 ^{de}	1.61 ^{e-g}	13.61 ^{hi} (31.2)	7.13 ^f (181.9)	4.75 ^{gh} (11.76)
Peppermint	29.0 ^{cde}	15.75 ^{ghi}	44.75 ^{gh} (52.99)	23.0 ^c	1.55 ^{fg}	24.55 ^{de} (136.6)	7.88 ^{ef} (211.6)	5.25 ^{e-h} (23.53)
Oxamyl	25.5 ^{ef}	16.0 ^d	41.5 ^d (41.88)	25.0 ^{de}	2.43 ^{de}	27.43 ^{fg} (164.39)	5.36 ^{ef} (112.07)	7.5 ^b (76.47)
N alone	17.0 ^g	12.25 ^c	29.25 ^e	8.75 ^g	1.63 ^e	10.38 ⁱ	2.53 ^g	4.25 ^d
Plant free of N & any treatment	37.5 ^{ab}	28.75 ^{ab}	66.25 ^a (126.5)	22.5 ^{ef}	3.725 ^c	26.23 ^{gh} (152.77)	6.78 ^{cd} (168.05)	7.5 ^b (76.47)
LSD _{p<5%}	3.1	3.71	4.95	4.05	0.98	4.37	1.49	1.01

N=1000 eggs of *M. incognita*

*Each figure is the mean of four replicates.

**Increase% = (Treatment – N alone) / N alone × 100.

Means in each column followed by the same letter(s) did not differ significantly at $P \leq 0.05$ according to Duncan's multiple-range test.

Table (3) demonstrated how essential oils fundamentally reconfigure plant biochemistry to combat *M. incognita* stress through three synergistic pathways: photosynthetic reinforcement, defense potentiation, and antioxidant management. The data revealed that dill oil plays a remarkable role in restoring photosynthesis in infected plants, driving chlorophyll levels to 2.94 mg/ml – a staggering 206.25% increase over nematode controls (0.96 mg/ml) –

while simultaneously decreasing flavonoids to 30.76 mg/ml (15.07% reduction versus 36.22 mg/ml in controls). Conversely, peppermint oil exhibited impressive antioxidant properties limiting flavonoid levels in to just 6.27% (33.95 mg/ml) in infected plants that was the smallest reduction among all treatments. The garlic oil, despite its moderate nematode suppression (Table 3), triggered catastrophic metabolic collapse in infected plants, reducing chlorophyll to

1.12 mg/ml (16.67% above devastated controls but 14.5% below healthy levels) while minimizing flavonoids by 82.83%. Chili pepper oil revealed context-dependent

efficacy, boosting chlorophyll by 86.46% and decreasing flavonoid level by 18.88% in infected plant.

Table 3. Chemical constituents of eggplant uninfected and infected with *Meloidogyne incognita* as affected by soil drench application of essential oils from four plant species under greenhouse conditions ($19 \pm 3^\circ\text{C}$).

Treatments	Chlorophyll (mg/ml)			Polyphenol (Inc. / Dec.%)	Flavonoid (Inc. / Dec.%)
	a	b	a + b(Inc.%)		
UNINFECTED					
Chili pepper	0.9	0.5	1.4 (45.83)	4.1 (83.53)	11.79 (-47.32)
Dill	0.63	0.34	0.97 (1.04)	6.9 (88.59)	8.09 (-63.85)
Garlic	0.89	0.31	1.2 (25.00)	3.8 (85.88)	20.3 (-9.29)
Peppermint	1.4	0.39	1.79 (86.46)	9.5 (78.94)	24.39 (8.98)
INFECTED					
Chili pepper	1.3	0.49	1.79 (86.46)	40.4 (375.29)	29.38 (-18.88)
Dill	1.87	1.07	2.94 (206.25)	35.8 (321.18)	30.76 (-15.07)
Garlic	0.74	0.38	1.12 (16.67)	2.8 (-67.06)	6.22 (-82.83)
Peppermint	1.57	0.54	2.11 (119.79)	4.5 (-47.06)	33.95 (-6.27)
Oxamyl	1.59	0.5	2.09 (117.71)	11.3 (75.41)	39.79 (9.89)
N alone	0.67	0.29	0.96	8.5	36.22
Plant free of N & any treatment	0.97	0.34	1.31 (36.46)	9.2 (84.59)	22.38 (38.21)

N=1000 eggs of *M. incognita*

* Increase or decrease % = (Treatment – N alone) / N alone × 100.

Integration of essential oils and chemical nematicide for the management of root-knot nematode.

Table (4) unveils a significant shift in precision nematode management, demonstrating integration of essential oils with reduced-rate chemical nematicides that achieves near-complete *M. incognita* suppression through complementary modes of action. The data revealed that peppermint oil + oxamyl each at half dose delivered exceptional juvenile control (94.4% J_2 reduction – within 1.74% of full-dose Oxamyl) while maintaining potent gall suppression (50.64% reduction). Simultaneously, garlic oil + oxamyl executed specialized reproductive disruption, achieving the highest egg mass reduction (54.36%) among botanical combinations through likely allicin-mediated inhibition of nematode oviposition. The most significant

synergy emerged from chili pepper + oxamyl, which accomplished 56.34% gall suppression – outperforming chili oil alone (32.99%, Table 1) by 23.35 percentage despite 50% less active. Dill oil + oxamyl revealed unexpected physiological insights: though showing the lowest J_2 reduction (71.3%) among combinations, it achieved disproportionate egg mass suppression (50.86%). Statistical validation through Duncan's grouping (LSD=43.36 for galls) confirmed biological significance: peppermint oxamyl (168.7^{bc} galls) aligns chemically with garlic + oxamyl (155.5^{bcd}), while dill + oxamyl (169.5^{bc}) and chili pepper + oxamyl (149.2^{bcd}) form distinct efficacy groups. Critical comparative analysis exposed that garlic + oxamyl's egg mass reduction (54.36%) surpassed both garlic oil alone (78.97%, Table 1) and Oxamyl alone (98.71%).

Table 4. Nematode parameters of *Meloidogyne incognita* infecting eggplant as affected by the combination of oil plants and oxamyl as soil drench under greenhouse conditions ($19 \pm 3^\circ\text{C}$).

Treatments	J_2 soil/pot(Red. %)	No. galls(Red. %)	RGI	No. egg masses/root(Red. %)	EI
Chili pepper + Oxamyl	357.1 ^{def} (84.9)	149.2 ^{bcd} (56.34)	5.0	111.0 ^{cd} (52.36)	5.0
Dill + Oxamyl	676.0 ^{cd} (71.3)	169.5 ^{bc} (50.4)	5.0	114.5 ^{cd} (50.86)	5.0
Garlic + Oxamyl	257.0 ^{gh} (89.1)	155.5 ^{bcd} (54.5)	5.0	106.33 ^{cd} (54.36)	5.0
Peppermint + Oxamyl	132.5 ^{gh} (94.4)	168.7 ^{bc} (50.64)	5.0	123.25 ^c (47.1)	5.0
Oxamyl	91.0 ^h (96.14)	28.75 ^e (91.59)	3.0	3.0 ^e (98.71)	2.0
N alone	2358.25 ^a	341.75 ^a	5.0	233.0 ^a	5.0
LSD	182.71	43.36	-----	27.72	-----

Pi=1000 eggs of *M. incognita*

Each value is a mean of four replicates.

Means in each column followed by the same letter(s) did not differ at $p < 0.05$ according to Duncan's multiple-range test.

Reduction % = (N alone – Treatment) / N alone × 100

Root gall index (RGI) or egg mass index (EI): 0 = no galling or egg masses; 1= 1-2 galls or egg masses; 2= 3-10 galls or egg masses; 3= 11-30 galls or egg masses; 4=31-100 galls or egg masses; 5= more than 100 galls or egg masses.

Table (5) illustrates how essential oils enhance the effectiveness of rate oxamyl (50% dosage) to achieve efficacy comparable to full-dose or exceeding those of chemical

nematicides through highly specific, complementary modes of action. The garlic oil + oxamyl treatment resulted in a total plant length of 59.25 cm, representing a 102.56% increase

over the nematode-alone treatment (29.25 cm) and achieved the highest total fresh weight (42.86 g), with an increase of 313.12% compared to N alone (10.38 g). Chili pepper oil + oxamyl also showed significant improvements, with 59.0 cm total plant length (101.71% increase) and 41.9 g total fresh weight (304.09% increase). Peppermint oil + oxamyl and dill oil + oxamyl treatments showed moderate increases in total plant length (76.07% and 68.38%, respectively) and fresh weight (280.25% and 252.09%). In contrast, the oxamyl (full

dose) treatment showed a 41.88% increase in plant length and 164.39% in fresh weight over N alone, while remaining less effective than essential oil combinations. All oil-based treatments also enhanced shoot dry weight and number of leaves, with garlic oil + oxamyl leading to a 203.8% increase in leaf number. These findings indicate that combining Oxamyl with specific essential oils significantly boosts plant growth, likely due to synergistic biostimulant and nematocidal effects.

Table 5. Impact of essential oils of four plant species in integration with oxamyl, applied as soil drench, compared to oxamyl on controlling *Meloidogyne incognita* infecting eggplant plants under greenhouse conditions (19 ± 3°C).

Treatments	* Plant growth response							
	Length (cm) Shoot Root	Plant length (cm)(Inc. %)	Fresh weight (g) Shoot Root	Plant F. wt. (g)(Inc. %)	Shoot dry wt. (g) (Inc. %)	No. of leaves (Inc. %)		
Chili pepper oil + Oxamyl	35.5 ^{ab} 23.5 ^{bc}	59.0 ^{bc} (101.71)	38.25 ^{ab} 3.67 ^{cd}	41.9 ^{b-d} (304.09)	7.1b ^c (181)	7.0 ^d (64.71)		
Dill oil + Oxamyl	29.25 ^{de} 20.0 ^{cde}	49.25 ^{ef} (68.38)	32.7 ^{bc} 3.78 ^c	36.53 ^{de} (252.09)	5.9 ^{de} (133.2)	6.5 ^{def} (52.94)		
Garlic oil + Oxamyl	30.25 ^{cde} 29.0 ^a	59.25 ^{bc} (102.56)	39.25 ^a 3.67 ^{cd}	42.86 ^{abc} (313.12)	7.68 ^b (203.8)	7.5 ^{cd} (76.47)		
Peppermint oil + Oxamyl	30.0 ^{de} 21.5 ^{bcd}	51.5 ^{de} (76.07)	35.75 ^{abc} 3.7 ^{cd}	39.45 ^{cd} (280.25)	5.3 ^e (110.16)	6.5 ^{def} (52.94)		
Oxamyl + N	25.5 ^{ef} 16.0 ^d	41.5 ^d (41.88)	25.0 ^{de} 2.43 ^{de}	27.43 ^{fg} (164.39)	5.36 ^{ef} (112.07)	7.5 ^b (76.47)		
N alone	17.0 ^g 12.25 ^e	29.25 ^e (126.5)	8.75 ^g 1.63 ^e	10.38 ⁱ (152.77)	2.53 ^g (168.05)	4.25 ^d (76.47)		
Plant free of N & any treatment	37.5 ^{ab} 28.75 ^{ab}	66.25 ^a (126.5)	22.5 ^{ef} 3.725 ^e	26.23 ^{gh} (152.77)	6.78 ^{cd} (168.05)	7.5 ^b (76.47)		
LSD _{P<5%}	3.96 3.83	5.88	5.5 0.98	5.84	1.18	1.47		

N=1000 eggs of *M. incognita*

*Each figure is the mean of four replicates.

**Increase% = (Treatment - N alone) / N alone × 100.

Means in each column followed by the same letter(s) did not differ significantly at P≤0.05 according to Duncan's multiple-range test.

Data within Table (6) showed that under *M. incognita* infection, eggplant treated with peppermint oil + oxamyl showed the highest chlorophyll (1.72 mg/ml) among botanical combinations but the lowest polyphenols (6.4 mg/ml) compared to control plants, whereas dill oil + oxamyl yielded marginally lower chlorophyll (1.71 mg/ml) than peppermint yet higher polyphenols (7.2 mg/ml). Garlic oil + oxamyl generated intermediate chlorophyll (1.65 mg/ml) but the highest polyphenols (7.7 mg/ml) among botanicals, while chili pepper oil + oxamyl produced the lowest chlorophyll (1.56 mg/ml) and polyphenols (7.0

mg/ml) but achieved the greatest flavonoid reduction (21.58 mg/ml, -40.42% vs. N alone). Contrastingly, full-dose oxamyl exceeded all botanical treatments in chlorophyll (2.09 mg/ml, +117.71% vs. N alone) and flavonoids (39.79 mg/ml), but its polyphenols (11.3 mg/ml) represented 75.41% increase over plants —the Baseline controls confirmed nematode-induced depletion: chlorophyll in infected plants (N alone: 0.96 mg/ml) was 26.72% below healthy plants (1.31 mg/ml), while flavonoids surged 61.75% (N alone: 36.22 mg/ml vs. healthy: 22.38 mg/ml).

Table 6. Chemical constituents of eggplant infected with *Meloidogyne incognita* affected by combination of oil plants and oxamyl applied at half dose under greenhouse conditions (19 ± 3°C).

Treatments	Chlorophyll (mg/ml)			Polyphenol (Inc. / Dec. %)	Flavonoid (Inc. / Dec. %)
	a	B	a + b (Inc. %)		
Chili pepper + Oxamyl	1.23	0.33	1.56 (62.50)	7 (-17.65)	21.58 (-40.42)
Dill + Oxamyl	1.22	0.49	1.71 (78.13)	7.2 (-15.29)	26.22 (-27.61)
Garlic + Oxamyl	1.29	0.36	1.65 (71.88)	7.7 (-9.41)	26.35 (-27.25)
Peppermint + Oxamyl	1.23	0.49	1.72 (79.17)	6.4 (-24.71)	28.98 (-19.99)
Oxamyl	1.59	0.5	2.09 (117.71)	11.3 (32.94)	39.79 (9.89)
N alone	0.67	0.29	0.96	8.5	36.22
Plant free of N & any treatment	0.97	0.34	1.31 (36.46)	9.2 (84.59)	22.38 (38.21)

N=1000 eggs of *M. incognita*

* Increase or decrease % = (Treatment - N alone) / N alone × 100.

Plant oil efficacy against *M. incognita* on eggplant (foliar application).

The obtained results in Table (7) revealed that chili pepper oil treatment applied as foliar spray yielded the lowest *M. incognita* J₂ density (456.2 juveniles/pot, 80.66% reduction vs. nematode-only control) among botanical oils, outperforming dill oil (788.6, 66.56% reduction), garlic oil

(711.6, 69.83% reduction), and peppermint oil (939.6, 60.16% reduction). For gall formation, chili pepper oil also showed the strongest suppression (137.25 galls, 59.84% reduction), followed by dill oil (150 galls, 56.11% reduction), garlic oil (167.25 galls, 51.06% reduction), and peppermint oil (162.5 galls, 52.45% reduction). In egg mass reduction, chili pepper oil achieved the highest decrease (22.25 masses,

90.45% reduction), exceeding dill oil (46.75 masses, 79.94% reduction), garlic oil (49 masses, 78.97% reduction), and peppermint oil (67.75 masses, 70.92% reduction). The chemical control Oxamyl consistently demonstrated superior efficacy: lowest J₂ count (91.0, 96.14% reduction), fewest galls (28.75, 91.59% reduction), and minimal egg masses (3.0, 98.71% reduction). Statistical validation via Duncan's

grouping (LSD=407.05 for J₂, 39.94 for galls, 20.004 for egg masses) confirmed significant differences: nematode-only control (2358.25^a J₂, 341.75^a galls, 233.0^a egg masses) differed markedly from all treatments, while botanical oils shared overlapping efficacy clusters (e.g., J₂: chili 456.2^{efg}, garlic 711.6^{d-f}, peppermint 939.6^{cd}).

Table 7. Nematode parameters of *Meloidogyne incognita* infecting eggplant plants as affected by four essential plant oils applied as foliar spray under greenhouse conditions (19±3°C).

Treatments	J2 soil/pot (Red. %)	No. galls (Red. %)	RGI	No. egg masses/root (Red. %)	EI
Chili pepper	456.2 ^{efg} (80.66)	137.25 ^{cd} (59.84)	5.0	22.25 ^{cd} (90.45)	3.0
Dill	788.6 ^{c-e} (66.56)	150 ^{cd} (56.11)	5.0	46.75 ^d (79.94)	4.0
Garlic	711.6 ^{d-f} (69.83)	167.25 ^c (51.06)	5.0	49.00 ^{cd} (78.97)	4.0
Peppermint	939.6 ^{cd} (60.16)	162.5 ^c (52.45)	5.0	67.75 ^c (70.92)	4.0
Oxamyl	91.0 ^g (96.14)	28.75 ^c (91.59)	3.0	3.00 ^f (98.71)	2.0
N alone	2358.25 ^a	341.75 ^a	5.0	233.00 ^a	5.0
LSD	407.05	39.94	---	20.004	---

Pi=1000 eggs of *M. incognita*

*Each value is a mean of four replicates.

Means in each column followed by the same letter(s) did not differ at p<0.05 according to Duncan's multiple-range test.

**Reduction % = (N alone – Treatment) / N alone × 100

** Root gall index (RGI) or egg mass index (EI): 0 = no galling or egg masses; 1= 1-2 galls or egg masses; 2= 3-10 galls or egg masses; 3= 11-30 galls or egg masses; 4=31-100 galls or egg masses; 5= more than 100 galls or egg masses.

Table (8) conclusively demonstrates the severe growth suppression inflicted by *Meloidogyne incognita* infection on eggplants, with (N alone) exhibiting critically stunted development: a meager total length of 29.25 cm drastically reduced fresh weight (10.38 g), minimal shoot dry weight (2.53 g), and sparse foliage (only 4.25 leaves). Against this damage, all tested plant oils foliar applied showed significant nemato-protective and growth-promoting effects.

Chili pepper oil emerged as the most potent bio-nematicide for infected plants, not only mitigating nematode damage but often exceeding the chemical control Oxamyl; it achieved the highest total length (45.75 cm, +56.41% increase over control plants), superior total fresh weight (24.88 g, +139.8%), remarkable shoot dry weight (11.63 g, +359.9%), and greatest leaf number (7.75, +82.35%), demonstrating exceptional protective properties.

Table 8. Plant growth response of eggplant infected with *Meloidogyne incognita* treated by four plant essential oils as foliar sprays compared to noninfected under greenhouse conditions (19 ± 3°C).

Treatments	Plant growth response							
	Length (cm)		Plant length (cm) (Inc. %)	Fresh weight (g)		Plant F. wt (g) (Inc./Dec. %)	Shoot dry wt. (g) (Inc. %)	No. of leaves (Inc. /Dec.%)
	Shoot	Root		Shoot	Root			
UNINFECTED								
Chili pepper	28.75 ^{de}	27.5ab	56.25 ^{cd} (-15.09)	30.0 ^b	2.44 ^{def}	32.44 ^c (23.68)	13.5 ^a (99.12)	9.0 ^a (20.00)
Dill	27.75 ^e	21.0 ^d	48.75 ^{e-g} (-26.42)	19.25 ^c	2.27 ^{d-g}	21.52 ^{cd} (-17.96)	12.4 ^{ab} (82.89)	8.25 ^{ab} (10.00)
Garlic	38.5 ^a	18.0 ^{d-g}	56.5 ^{cd} (-14.72)	30.5 ^b	2.32 ^{d-g}	32.82 ^{bc} (25.12)	9.75 ^c (41.15)	6.5 ^{cd} (-13.33)
Peppermint	31.75 ^{b-d}	20.75 ^{de}	52.5 ^{de} (-20.75)	31.75 ^b	5.38 ^a	37.13 ^b (41.75)	12.0 ^b (76.99)	8.0 ^{ab} (6.67)
INFECTED								
Chili pepper	24.25 ^{fg}	21.5 ^{cd}	45.75 ^{lg} (56.41)	23.25 ^c	1.63 ^{efg}	24.88 ^{de} (139.8)	11.63 ^b (359.9)	7.75 ^b (82.35)
Dill	19.25 ^h	12.75 ^{hi}	32.0 ^{kl} (9.4)	14.0 ^d	2.32 ^{d-g}	16.32 ^{gh} (57.3)	11.63 ^b (359.9)	7.75 ^b (82.35)
Garlic	33.25 ^b	16.5 ^{fg}	49.75 ^{cd} (70.09)	13.5 ^d	1.39 ^g	14.89 ^{gh} (43.5)	9.0 ^{cde} (256.1)	6.0 ^{d-f} (41.18)
Peppermint	23.5 ^g	16.0 ^{gh}	39.5 ^{ij} (35.04)	14.5 ^d	1.68 ^{efg}	16.18 ^{gh} (56.00)	7.5 ^f (196.7)	5.0 ^{i-h} (17.65)
Oxamyl	25.5 ^{ef}	16.0 ^d	41.5 ^d (41.88)	25.0 ^{de}	2.43 ^{de}	27.43 ^{lg} (164.39)	5.36 ^{cd} (112.07)	7.5 ^b (76.47)
N alone	17.0 ^g	12.25 ^e	29.25 ^e	8.75 ^g	1.63 ^e	10.38 ⁱ	2.53 ^g	4.25 ^d
Plant free of N & any treatment	37.5 ^{ab}	28.75 ^{ab}	66.25 ^a (126.5)	22.5 ^{ef}	3.725 ^c	26.23 ^{gh} (152.77)	6.78 ^{cd} (168.05)	7.5 ^b (76.47)
LSD _{P<5%}	3.1	3.71	4.95	4.05	0.98	4.37	1.49	1.01

N=1000 eggs of *M. incognita*

Each figure is the mean of four replicates.

Increase % = (Treatment – N alone) / N alone × 100.

Means in each column followed by the same letter(s) did not differ significantly at P≤0.05 according to Duncan's multiple-range test.

Garlic oil uniquely fostered the longest shoot growth in infected plants (33.25 cm), though its overall efficacy was

inconsistent, yielding lower root length (16.5 cm) and notably poor fresh weight (14.89 g, +43.5%). Dill and peppermint oils

provided significant but comparatively moderate nematode suppression in infected plants (Table 7), with peppermint oil showing the weakest performance in plant growth (e.g., only +35.04% total length increase). Strikingly, all oils dramatically stimulated growth in uninfected plants, far surpassing both the infected control and often the healthy untreated control (Plant free); peppermint oil was particularly exceptional here, yielding the highest absolute fresh weight (37.13 g, +257.9% over control plants shoot) and dry weight (12.0 g, +374.8%), while garlic oil produced the longest shoots (38.5 cm) and chili pepper oil generated robust roots (27.5 cm) in healthy plants. The data indicated that chili pepper oil is highly effective, naturally derived alternative for managing *M. incognita* infection in eggplants, while simultaneously highlighting garlic and peppermint oil's outstanding potential as a general plant growth enhancer in nematode-free conditions.

Data in Table (9) confirmed clear variations in chlorophyll, polyphenol, and flavonoid levels across eggplant treatments. Under infected conditions, chili pepper oil treatment yielded a total chlorophyll (a + b) value of 2.36 mg/ml, representing a 162.22% increase compared to control treatment (N). Dill oil followed with a value of 2.00 mg/ml and a 108.33% increase. Garlic oil resulted in 1.39 mg/ml (44.79% increase), while peppermint oil showed 1.61 mg/ml (67.71% increase). For polyphenols, infected plants treated

with chili pepper oil recorded 5.6 mg/ml (34.82% decrease), dill oil 4.4 mg/ml (48.24% decrease), garlic oil 3.3 mg/ml (61.18% decrease), and peppermint oil 8.8 mg/ml (3.53% increase). Regarding flavonoids, infected dill-treated plants showed 34.23 mg/ml (5.49% decrease), chili pepper 34.10 mg/ml (5.85% decrease), garlic 30.80 mg/ml (14.96% decrease), and peppermint 30.29 mg/ml (16.37% decrease) compared to control plants. In uninfected plants, garlic oil produced the highest chlorophyll content (2.01 mg/ml; 53.44% increase), followed by chili pepper (1.74 mg/ml; 32.82% increase). Dill and peppermint oils showed decreases (14.85% and 22.14%, respectively). Polyphenol levels for uninfected plants were highest with garlic oil (14.30 mg/ml; 55.43% decrease) and chili pepper oil (11.05 mg/ml; 20.11% increase). Flavonoid reductions were most notable with dill oil (18.23 mg/ml; 18.45% decrease) and least with garlic oil (33.75 mg/ml; 50.8% increase). The Oxamyl treatment recorded chlorophyll at 2.09 mg/ml (117.71% increase), polyphenols at 11.30 mg/ml (32.94% increase), and flavonoids at 39.79 mg/ml (9.89% increase). N alone showed baseline values of 0.96 mg/ml chlorophyll, 8.50 mg/ml polyphenols, and 36.22 mg/ml flavonoids. Untreated plants had 1.31 mg/ml chlorophyll, 9.20 mg/ml polyphenols, and 22.38 mg/ml flavonoids. These numerical outcomes demonstrated distinct treatment-specific differences across all tested parameters.

Table 9. Chemical constituents of eggplant uninfected and infected with *Meloidogyne incognita* as affected by foliar spray application of essential oils under greenhouse conditions (19 ± 3 °C).

Treatments	Chlorophyll (mg/ml)		Polyphenol (Inc./ Dec.%)	Flavonoid (Inc./ Dec.%)
	a	b a + b(Inc./ Dec.%)		
UNINFECTED				
Chili pepper	1.39	0.35 1.74 (32.82)	11.05 (20.11)	30.71 (36.60)
Dill	0.71	0.34 1.05 (-19.85)	3.6 (-60.87)	18.23 (-18.54)
Garlic	1.64	0.37 2.01 (53.43)	14.3 (55.43)	33.75 (50.80)
Peppermint	0.69	0.33 1.02 (-22.14)	5.3 (-42.39)	30.57 (36.60)
ININFECTED				
Chili pepper	1.7	0.66 2.36 (145.83)	5.6 (-34.82)	34.1 (-5.85)
Dill	1.44	0.56 2.00 (108.33)	4.4 (-48.24)	34.23 (-5.49)
Garlic	0.89	0.5 1.39 (44.79)	3.3 (-61.18)	30.8 (-14.96)
Peppermint	1.22	0.39 1.61 (76.71)	8.8 (-3.53)	30.29 (-16.37)
Oxamyl	1.59	0.5 2.09 (117.71)	11.3 (32.94)	39.79 (9.89)
N alone	0.67	0.29 0.96 0.00	8.5 (88.71)	36.22 0.00
Plant free of N & any treatment	0.97	0.34 1.31 (36.46)	9.2 (84.59)	22.38 (38.21)

N=1000 eggs of *M. incognita*

Increase or decrease % = (Treatment – N alone) / N alone × 100.

Efficacy of integrated essential oils of four plant species with oxamyl, at half dose, on *M. incognita* infection.

The obtained results in Table (10) revealed that the nematode-only control treatment recorded the highest population of second-stage juveniles (J₂), with 2,358.25 J₂ per pot, alongside the highest number of root galls at 341.75 and egg masses at 233.0. All foliar oil treatments reduced J₂ populations relative to the nematode-only control. Peppermint oil resulted in 216.9 J₂ (90.8% reduction), garlic oil yielded 297.6 J₂ (87.4% reduction), chili pepper oil

produced 471.5 J₂ (80.0% reduction), and dill oil showed 831.6 J₂ (64.7% reduction). The synthetic oxamyl treatment achieved the lowest J₂ count at 91.0 (96.14% reduction). For gall formation, oxamyl demonstrated the strongest suppression (28.75 galls; 91.59% reduction). Among oils, peppermint oil + oxamyl reduced galls to 150.0 (64.45% reduction), followed by garlic oil+ oxamyl (134.5 galls; 55.16% reduction), dill oil + oxamyl (158.75 galls; 55.45% reduction), and chili pepper oil+ oxamyl (127.25 galls; 32.99% reduction). The galling index (RGI) was 5 for all oil

treatments and the nematode control, while oxamyl lowered it to 3. In egg mass reduction, peppermint oil decreased counts to 31.25 (86.59% reduction), chili pepper oil to 40.5 (82.62% reduction), dill oil to 53.0 (77.25% reduction), and garlic oil to 62.0 (73.39% reduction). Oxamyl achieved near-complete suppression (3.0 egg masses; 98.71% reduction). The egg

mass index (EI) was 4.0 for oil treatments and 5.0 for control, whereas oxamyl reduced it to 2. The least significant difference (LSD) values were 182.71 for J2 counts, 43.36 for gall numbers, and 27.72 for egg mass counts, indicating statistical thresholds for comparing treatment effects.

Table 10. Nematode parameters of *Meloidogyne incognita* infecting eggplant as affected by the combination of oil plants as foliar spray and oxamyl each applied at half dose under greenhouse conditions ($19 \pm 3^\circ\text{C}$)

Treatments	J2 soil/pot(Red. %)	No. galls(Red. %)	RGI	No. egg masses/root(Red. %)	EI
Chili pepper + Oxamyl	471.5 ^{de} (80.0)	127.25 ^{cd} (32.99)	5.0	40.5 ^{ef} (82.62)	4.0
Dill + Oxamyl	831.6 ^b (64.7)	158.75 ^{b-d} (55.45)	5.0	53.0 ^{ef} (77.25)	4.0
Garlic + Oxamyl	297.6 ^{e-g} (87.4)	134.5 ^{b-d} (55.16)	5.0	62.0 ^e (73.39)	4.0
Peppermint + Oxamyl	216.9 ^{f-h} (90.8)	150.0 ^c (64.45)	5.0	31.25 ^f (86.59)	4.0
Oxamyl	91.0 ^h (96.14)	28.75 ^e (91.59)	3.0	3.0 ^g (98.71)	2.0
N alone	2358.25 ^a	341.75 ^a	5.0	233.0 ^a	5.0
LSD	182.71	43.36	-----	27.72	-----

Pi=1000 eggs of *M. incognita*

Each value is a mean of four replicates.

Means in each column followed by the same letter(s) did not differ at $p < 0.05$ according to Duncan's multiple-range test.

Reduction % = (N alone – Treatment) / N alone $\times 100$

Root gall index (RGI) or egg mass index (EI): 0 = no galling or egg masses; 1= 1-2 galls or egg masses; 2= 3-10 galls or egg masses; 3= 11-30 galls or egg masses; 4=31-100 galls or egg masses; 5= more than 100 galls or egg masses.

The results in Table (11) showed that the nematode-only control treatment (only nematode) recorded the lowest values across all growth parameters: shoot length at 17.0 cm, root length at 12.25 cm, total plant length at 29.25 cm, shoot fresh weight at 8.75 g, root fresh weight at 1.63 g, total fresh weight at 10.38 g, shoot dry weight at 2.53 g, and leaf count at 4.25 leaves. In contrast, the plant-free control (no nematodes or treatments) showed the highest total plant

length (66.25 cm) and total fresh weight (26.23 g), with shoot length at 37.5 cm, root length at 28.75 cm, shoot fresh weight at 22.5 g, root fresh weight at 3.73 g, shoot dry weight at 6.78 g, and leaf count at 7.5 leaves. Among integrated oil treatments, peppermint oil + oxamyl (half dose) produced the highest shoot length (38.0 cm), total fresh weight (47.79 g), and leaf count (11.0 leaves; 158.82% increase).

Table 11. Plant growth response of eggplant infected with *Meloidogyne incognita* to essential oils of four plant species as foliar spray in integration with oxamyl each at half dose under greenhouse conditions ($19 \pm 3^\circ\text{C}$).

Treatments	Plant growth response							
	Length (cm)		Plant length cm (Inc. %)	Fresh weight (g)		Plant F. wt. g (Inc. %)	Shoot dry wt. (g)(Inc. %)	No. of leaves (Inc. %)
	Shoot	Root		Shoot	Root			
Chili pepper + oxamyl	28.5 ^{de}	18.75 ^{de}	47.25 ^{ef} (61.54)	17.75 ^{de}	3.36 ^{cde}	21.11 ^{fg} (103.45)	3.05 ^{fg} (20.71)	9.5 ^b (123.53)
Dill + oxamyl	31.0 ^{cd}	16.75 ^{ef}	47.75 ^{ef} (63.25)	23.0 ^d	2.38 ^{fg}	25.38 ^f (144.63)	3.77 ^f (48.98)	8.5 ^b (100)
Garlic + oxamyl	29.0 ^{de}	16.38 ^{ef}	45.38 ^{fg} (55.13)	16.25 ^e	3.29 ^{cdf}	19.54 ^g (88.33)	2.57 ^g (1.6)	7.75 ^{cd} (82.35)
Peppermint + oxamyl	38.0 ^a	18.5 ^{def}	56.5 ^{cd} (93.16)	39.75 ^a	8.04 ^a	47.79 ^a (360.6)	7.55 ^{bc} (198.74)	11.0 ^a (158.82)
Oxamyl	25.5 ^{ef}	16.0 ^d	41.5 ^d (41.88)	25.0 ^{de}	2.43 ^{de}	27.43 ^{fg} (164.39)	5.36 ^{ef} (112.07)	7.5 ^b (76.47)
N alone	17.0 ^g	12.25 ^e	29.25 ^e	8.75 ^g	1.63 ^e	10.38 ⁱ	2.53 ^g	4.25 ^d
Plant free of N &any treatment	37.5 ^{ab}	28.75 ^{ab}	66.25 ^a (126.5)	22.5 ^{ef}	3.725 ^c	26.23 ^{gh} (152.77)	6.78 ^{cd} (168.05)	7.5 ^b (76.47)
LSD _{P<5%}	3.96	3.83	5.88	5.5	0.98	5.84	1.18	1.47

N=1000 eggs of *M. incognita*

*Each figure is the mean of four replicates.

**Increase % = (Treatment–N alone)/N alone $\times 100$.

Means in each column followed by the same letter(s) did not differ significantly at $P \leq 0.05$ according to Duncan's multiple-range test.

It also achieved the greatest shoot fresh weight (39.75 g; inducing 360.6% increase in fresh weight) and root fresh weight (8.04 g). Dill oil + oxamyl resulted in a total plant length of 47.75 cm (63.25% increase), shoot fresh weight of 23.0 g, and shoot dry weight of 3.77 g (48.98% increase). Chili pepper oil + oxamyl yielded a total plant length of 47.25 cm (61.54% increase), total fresh weight of 21.11 g (103.45% increase), and leaf count of 9.5 leaves (123.53% increase). Garlic oil + oxamyl showed more

modest improvements, with a leaf count increase of only 82.35% (7.75 leaves) and total fresh weight of 19.54 g (88.33% increase). The oxamyl treatment (full dose) generated a total plant length of 41.5 cm (41.88% increase), total fresh weight of 27.43 g (164.39% increase), shoot dry weight of 5.36 g (112.07% increase), and leaf count of 7.5 leaves (76.47% increase). Least Significant Difference (LSD) values provided statistical thresholds for parameter comparisons.

The results in Table (12) stated that control treatment (N alone) recorded baseline values of 0.67 mg/ml for chlorophyll a, 0.29 mg/ml for chlorophyll b, and 0.96 mg/ml for total chlorophyll (a + b), alongside polyphenol levels of 8.5 mg/ml and flavonoid content of 36.22 mg/ml. All integrated oil treatments increased total chlorophyll relative to the nematode control. Chili pepper oil + oxamyl (half dose) achieved the highest total chlorophyll (2.43 mg/ml; 153.13% increase), followed by oxamyl (2.09 mg/ml; 117.71% increase), peppermint oil + oxamyl (1.99 mg/ml; 107.29% increase), dill oil + oxamyl (1.73 mg/ml; 80.21% increase), and garlic oil + oxamyl (1.62 mg/ml; 68.75% increase). For polyphenols, dill oil + oxamyl reduced levels to 4.8 mg/ml (43.53% decrease), chili pepper oil + oxamyl to 4.6 mg/ml (45.88% decrease), and peppermint oil + oxamyl to 7.2 mg/ml (15.29% decrease). The oxamyl

treatment showed 11.3 mg/ml polyphenols (732.94% decrease). Flavonoid content was decreased across all treatments compared to the nematode control (36.22 mg/ml). Dill oil + oxamyl resulted in 26.91 mg/ml flavonoids (25.70% decrease), garlic oil + oxamyl in 28.36 mg/ml (21.70% decrease), and both chili pepper oil + oxamyl and peppermint oil + oxamyl in 30.23 mg/ml (16.54% decrease). Oxamyl alone recorded 39.79 mg/ml flavonoids (9.89% increase). The plant-free control (no nematodes/treatments) showed total chlorophyll at 1.31 mg/ml (36.46% increase over control plants), polyphenols at 9.2 mg/ml (84.59% decrease relative to N alone), and flavonoids at 22.38 mg/ml (38.21% decrease). Percent change values for the plant-free control were calculated against the control plants baseline.

Table 12. Chemical constituents of eggplant infected with *Meloidogyne incognita* affected by combination of oil plants and oxamyl each applied at half dose under greenhouse conditions ($19 \pm 3^\circ\text{C}$).

Treatments	Chlorophyll (mg/ml)			Polyphenol (Inc./ Dec%)	Flavonoid (Inc./ Dec.%)
	a	b	a + b(Inc.%)		
Chili pepper + Oxamyl	1.77	0.66	2.43 (153.13)	4.6 (-45.88)	30.23 (-16.54)
Dill + Oxamyl	1.2	0.53	1.73 (80.21)	4.8 (-43.53)	26.91 (-25.70)
Garlic + Oxamyl	1.27	0.35	1.62 (68.75)	3.1 (-63.53)	28.36 (-21.70)
Peppermint + Oxamyl	1.43	0.56	1.99 (107.29)	7.2 (-15.29)	30.23 (-16.54)
Oxamyl	1.59	0.5	2.09 (117.71)	11.3 (32.94)	39.79 (9.89)
N alone	0.67	0.29	0.96	8.5	36.22
Plant free of N & any treatment	0.97	0.34	1.31 (36.46)	9.2 (8.2)	22.38 (-38.21)

N=1000 eggs of *M. incognita*

Increase or decrease % = (Treatment – N alone) / N alone × 100.

The experimental data reported that botanical oils exert multi-tiered control over *M. incognita* through direct nematode suppression, host physiological reprogramming, and metabolic restructuring. Peppermint oil's exceptional nematode suppression (85.29% J_2 reduction, 86.37% egg mass reduction) stems from the rhizospheric persistence of its monoterpenes (menthol >60%; menthone >20%), which penetrate nematode cuticles to disrupt mitochondrial complexes I/III, inducing oxidative stress and neurotoxicity via acetylcholinesterase inhibition (Caboni *et al.*, 2013). Its disproportionate gall reduction (64.45% vs. 85.29% J_2 suppression) implies systemic acquired resistance (SAR) activation, likely through jasmonic acid (JA) pathway induction enhancing phenylpropanoid biosynthesis and cell wall lignification – a defense mechanism independent of initial penetration blocking (Khalil *et al.*, 2021). This efficacy originates from essential oil neurotoxic disruption of nematode chemoreception: it binds TRPA-1 (Transient Receptor Potential Ankyrin 1) ion channels in amphidial neurons, paralyzing host-finding behaviors by inhibiting Ca^{2+} -dependent signaling pathways (Jardim *et al.*, 2020). Concurrently, peppermint orchestrated unprecedented recovery of infected plants, biomass accumulation outperforming the synthetic nematicide oxamyl. This results from menthol-induced jasmonoyl-isoleucine (JA-Ile) accumulation, which degrades JAZ (JASMONATE ZIM-DOMAIN) repressor proteins, liberating MYC2 transcription factors to suppress auxin signaling genes (IAA19, ARF8) within giant cells (Grunewald *et al.*, 2009), thereby restoring

photoassimilate partitioning to aerial tissues and reversing nematode-induced growth inhibition.

Garlic oil's moderate efficacy (53.59% J_2 reduction) aligns with allicin's (diallyl thiosulfinate) thiol-modifying activity, which irreversibly inhibits nematode chemosensory receptors and glutathione-S-transferases critical for detoxification (Oka *et al.*, 2000; Zhou *et al.*, 2021). Garlic oil + oxamyl achieved gall reduction, surpassing additive effects. This synergy arises from Allicin-enhanced oxamyl bioavailability: Sulfur compounds increase cuticular permeability, accelerating carbamate uptake (Doshi *et al.*, 2021). Dual neurotoxicity: Allicin inhibits acetylcholinesterase (AChE) 3.2-fold more potently than oxamyl (Ntalli *et al.*, 2016). Garlic oil emulsion was more effective as natural nematicides on *M. incognita*, and in enhancing eggplant growth parameters (Osman *et al.*, 2025). The antimicrobial efficacy of garlic extract has been extensively examined and is primarily attributed to organosulfur compounds present in its essential oils, including ajoene, dithiines, diallyl sulfide (DADS), diallyl trisulfide (DATS), and allyl methyl trisulfide. These compounds are recognized for their nematicidal properties, with their mechanisms of action and probable cellular targets being closely associated with various reactive sulfur species (Jardim *et al.*, 2020). Studies have demonstrated the nematicidal potential of different garlic-derived formulations against *Meloidogyne* spp., exhibiting comparable effectiveness to conventional synthetic nematicides (El-Saedy *et al.*, 2014). Furthermore, garlic-based pesticides have been developed, registered, and

commercialized for managing nematodes and other pests, though their success rates vary. Given that *Meloidogyne* spp. are endoparasitic nematodes residing within plant roots, there is a growing demand for a translatable compound capable of targeting these organisms in situ. Essential oils from garlic represent a promising source for such compounds, as they encompass a range of antimicrobial components that function via diverse mechanisms of action (Osman *et al.*, 2025). The chlorophyll increase and flavonoid surge in infected plants further confirm allicin-induced upregulation of phenylpropanoid pathways (Phenylalanine ammonia lyase, chalcone synthase) and ROS-scavenging enzymes (Superoxide dismutase, Catalase) (Khalil *et al.*, 2021; Molinari and Leonetti, 2019).

Chili pepper (*Capsicum frutescens*) contains phytochemicals such as capsaicin and capsaicinoids, which are used to control plant diseases (Soumya and Nair, 2012) and storage insects (Oni, 2011) and were found highly effective to them. In this study, *C. frutescens* was identified as having low nematocidal activities against *M. incognita* on eggplant plants. Kepenekci *et al.* (2016) applied *C. frutescens* extracts against *M. javanica* on tomato and found low nematocidal activity against nematode. Our study supports this finding.

Dill oil's variable performance (52.32–77.79% reductions) reflects rapid β -hydroxylation of carvone by soil microbiota, reducing its bioavailability (Ntalli *et al.*, 2010). The synergistic interaction of peppermint + Oxamyl (94.4% J₂ reduction) arises from terpene-enhanced nematicide solubility and xylem translocation via increased membrane fluidity (Doshi *et al.*, 2021), while garlic + Oxamyl 54.51% egg mass suppression (exceeding solo components) demonstrates allicin-mediated potentiation of carbamate toxicity through acetylcholinesterase saturation (Abd-Elgawad, 2020). This integrated approach achieves >90% target efficacy with 50% chemical reduction, fulfilling the FAO's sustainable nematode management framework.

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الإمكانية القاتلة لبعض الزيوت النباتية المطبقة في التربة أو رشاً على النبات ضد نيماتودا تعقد الجذور التي تصيب الباذنجان تحت ظروف الصوبة السلكية.

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الملخص

أظهرت التجارب المنفذة في الصوبة الزراعية عند درجة حرارة $23 \pm 19^\circ\text{C}$ على نباتات الباذنجان (صنف Black King) أن الزيوت العطرية الأربعة - النعناع (*Mentha piperita*)، الثوم (*Allium sativum*)، الفلفل الحار (*Capsicum annum*)، والشبث (*Anethum graveolens*) - تمتلك فعالية ملحوظة في مكافحة نيماتودا تعقد الجذور *M. incognita*. سقى التربة (Soil Drench): عند اختبار الزيوت العطرية على الباذنجان عبر سقي التربة، تفوق زيت النعناع كأقوى معاملة، حيث خفض تعداد اليرقات بنسبة ٨٥,٢٩٪ والعقد النيماتودية (٦٤,٤٥٪) وكثرت البيض بنسبة ٨٦,٣٧٪، مقترباً من فعالية الأوكساميل (٩٦,١٤٪) خفض في اليرقات). كما جاء زيت الفلفل الحار في المرتبة الأخيرة (٣٧,٣٪) خفض في اليرقات). على المستوى الفسيولوجي، حفز زيت النعناع المجموع الخضري في النباتات السليمة، حيث حقق زيادة في الطول وصلت إلى ٥٨,٨٨ سم ووزنها الطازج إلى ٤١,٥٢ جم. وفي النباتات المصابة، تفوق زيت النعناع وحقق زيادة في الوزن الطازج بمقدار ١٣٦,٦٪. بالمقابل، سجل زيت الثوم - رغم فعاليته المتوسطة ضد النيماتودا - في سمية نباتية حادة، حيث خفض طول النباتات السليمة إلى ٤٠,٧٥ سم (- ٣٨,٥٪) والنباتات المصابة إلى ٣٥,٧٥ سم. الرش الورقي (Foliar Spray): عند تطبيق الزيوت بالرش الورقي تحت نفس الظروف، اختلفت ترتيب الفعالية الإيجابية للمركبات تحت الدراسة حيث هيمن زيت الفلفل الحار بنتائج مرتفعة: ٨٠,٦٦٪ انخفاض في عدد اليرقات و ٩٠,٤٥٪ في عدد كتل البيض. في حين كان زيت النعناع الأقل فعالية (٦٠,١٦٪) خفض في عدد اليرقات). سجل الرش بزيت الفلفل الحار زيادة في عدد أوراق النباتات المصابة بنسبة ٨٢,٣٥٪ بينما سجل زيادة في أطوال وأوزان النباتات المصابة بنسبة ٥٦,٤١٪ و ١٣٩,٨٠٪ على التوالي. في حين رفع زيت الفلفل الكلوروفيل بنسبة ١٤٥,٨٣٪ في النباتات المصابة لكنه استنزف البوليفينولات بشكل حاد (٣٤,٨٢٪). أظهرت المعاملات المزوجة تفاعل تنشيطي حيث انخفضت أعداد النيماتودا في التربة عند استخدام زيت النعناع والأوكساميل (٩٤,٤٪) يليه المعاملة بزيت الثوم والأوكساميل (٨٩,١٪) مقارنة بالمعاملات الفردية للزيوت.