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Pakistan Journal of Nematology

Research Article

Open-Field Evaluation of Jojoba (*Simmondsia chinensis*) Oil Emulsion and Its Seed Cake for Biological Control of Root-Knot Nematode (*Meloidogyne incognita*) in Hybrid Watermelon (Giza Type)

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Abstract | Root-knot nematodes (*Meloidogyne incognita*) are a major constraint to watermelon production. This study evaluated the nematicidal potential of jojoba (*Simmondsia chinensis*) oil emulsion (JOE) and seed cake (JSC) under open-field conditions. Physicochemical analysis confirmed the high quality and stability of the oil, with trace levels of heavy metals. Field application of JOE significantly reduced nematode infection, including galling (by 38–55%), egg masses (40–60%), and juvenile soil population (35–50%), in a concentration-dependent manner. The combined application of JSC with JOE exhibited superior efficacy, achieving the highest reductions across all nematode indices. Treatments also enhanced vegetative growth, increasing vine length by 18–25%, shoot biomass by 15–22%, and root development by 20–28% compared to untreated controls. These findings indicate that jojoba-based products, especially in combination, are effective and eco-friendly alternatives to synthetic nematicides, offering practical solutions for sustainable watermelon cultivation.

Received | January 24, 2026; **Accepted** | March 04, 2026; **Published** | April 14, 2026
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Citation | Ghareeb, R.Y., S.M. Eid and S.A. Omran. 2026. Open-field evaluation of jojoba (*Simmondsia chinensis*) oil emulsion and its seed cake for biological control of root-knot nematode (*Meloidogyne incognita*) in hybrid watermelon (Giza type). *Pakistan Journal of Nematology*, 44(1): 48-57.
DOI | https://dx.doi.org/10.17582/journal.pjn/2026/44.1.48.57
Keywords | *Simmondsia chinensis*, *Meloidogyne incognita*, Nematicide, Biological control, Watermelon productivity

Introduction

Watermelon (*Citrullus lanatus*) is one of the most economically important cucurbit crops cultivated worldwide due to its high nutritional value and market demand. However, its production is severely constrained by soil borne pathogens, particularly root-knot nematodes (RKNs), *Meloidogyne incognita*, which cause substantial yield and quality losses in cucurbit crops (Sharma *et al*., 2004; Jones *et al*., 2013). In heavily infested soils, yield losses attributed to *M. incognita* may exceed 30–50%, posing a serious threat to sustainable watermelon production.

Meloidogyne incognita is among the most destructive plant-parasitic nematodes affecting vegetable crops, including watermelon. Its infection results in characteristic gall formation on roots, leading to impaired water and nutrient uptake, disruption of vascular tissues, reduced photosynthetic efficiency, and overall stunted plant growth (Baloch *et al*., 2013; Sikandar *et al*., 2025). These physiological disturbances ultimately compromise plant vigor and fruit productivity.

Despite extensive breeding and screening efforts, no commercially available watermelon cultivars with stable resistance to *M. incognita* have been developed. As a result, chemical nematicides and cultural practices remain the primary management strategies (Boyhan *et al*., 2003; Thies *et al*., 2010). Although chemical nematicides are effective, their continuous and indiscriminate use has raised serious environmental and public health concerns, including toxicity to non-target organisms, groundwater contamination, and the emergence of resistant nematode populations (Chen *et al*., 2020; Silva *et al*., 2025). Consequently, increasing regulatory restrictions and growing demand for sustainable agricultural practices have intensified the search for safer and environmentally friendly alternatives (Ahmad *et al*., 2021).

In recent years, botanical oils and plant-derived products have gained considerable attention as eco-friendly nematicidal agents due to their biodegradability, low environmental persistence, and rich composition of bioactive secondary metabolites (Ntalli *et al*., 2010, 2023). Several essential and fixed oils have demonstrated strong nematicidal activity by disrupting nematode cuticle integrity, inhibiting egg hatching, reducing juvenile mobility, and limiting host root penetration (Ntalli *et al*., 2010; Baazeem *et al*., 2022).

Among plant-derived oils, jojoba oil, extracted from *Simmondsia chinensis*, is distinctive because of its unique wax ester composition, which confers exceptional chemical stability and prolonged biological activity. Jojoba oil has been widely reported for its insecticidal, acaricidal, antifungal, and antimicrobial properties, highlighting its broad-spectrum bioactivity (Al-Obaidi *et al*., 2017). Moreover, plant oil emulsions have been shown to enhance nematode control efficiency by improving oil dispersion, increasing contact with target organisms, and reducing phytotoxicity.

In addition to their direct nematicidal effects, botanical oils may indirectly enhance plant tolerance to nematode infection by improving physiological performance and activating plant defense-related mechanisms under biotic stress conditions (Pavela and Benelli, 2016). Such dual action combining pest suppression with plant growth promotion makes plant oil emulsions particularly attractive for integrated nematode management programs.

Despite these promising attributes, information regarding the efficacy of jojoba oil emulsion against *Meloidogyne incognita*, especially on watermelon under greenhouse or semi-field conditions, remains limited. Therefore, the present study aimed to evaluate the potential of jojoba oil emulsion as a sustainable nematicidal agent for suppressing *M. incognita* infection and enhancing Hybrid watermelon (Giza type) growth performance, offering an environmentally safe alternative to conventional chemical nematicides.

Materials and Methods

Jojoba oil extraction, emulsion preparation, and seed cake utilization

Jojoba oil was obtained by mechanical cold pressing of jojoba (*Simmondsia chinensis* L.) seeds. Green jojoba seeds were purchased from Al-Khaligia Company, New Alamein City, Egypt, and mechanically cold-pressed at the oil presses of Top Chemical Company, Alexandria, Egypt, using a screw-type press system. The extraction temperature was maintained below 40 °C to preserve oil quality and bioactive constituents. The extracted oil was allowed to settle for 24 h to facilitate sedimentation of insoluble materials, then filtered and stored in dark glass bottles at 4 °C until formulation.

Jojoba oil emulsions were prepared according to Shahin *et al*. (2011), with minor modifications. Tween 20 was used as a non-ionic surfactant, and triethanolamine was used as a co-emulsifier. Three oil-in-water (O/W) emulsions were formulated at different jojoba oil concentrations as follows:

- JOEc–5: Emulsion containing 5% (v/v) jojoba oil, 1.5% (v/v) Tween 20, and 0.5% (v/v) triethanolamine, with distilled water added to complete the final volume to 100%.
- JOEc–10: Emulsion containing 10% (v/v) jojoba oil, 2.0% (v/v) Tween 20, and 1.0% (v/v) triethanolamine, adjusted to 100% with distilled water.
- JOEcm–15: Emulsion containing 15% (v/v) jojoba oil, 2.5% (v/v) Tween 20, and 1.5% (v/v) triethanolamine, with distilled water added to complete the volume to 100%.

For all formulations, Tween 20 was first blended with the jojoba oil under continuous stirring for 10 min, followed by gradual addition of triethanolamine. Distilled water was then added dropwise under constant agitation, and the mixtures were stirred for 30 min at room temperature until homogeneous and physically stable emulsions were obtained. The prepared jojoba oil emulsions were stored for 48 hours at room temperature on the laboratory bench to assess their visual stability. Prior to application, the emulsions were inspected for homogeneity and absence of phase separation or creaming. Only stable emulsions were used for treatment to ensure consistency across all experimental units.

The residual solid material obtained after cold pressing, hereafter referred to as jojoba seed cake, was collected, air-dried, and finely ground to obtain a uniform powder. The seed cake was stored under dry conditions until application as a soil amendment treatment to evaluate its nematicidal potential against *Meloidogyne incognita*.

GC analysis of fatty acid composition of jojoba oil

The fatty acid composition of jojoba oil was determined by gas chromatography (GC) at the Central Laboratories, Special Units, Agricultural Research Center (ARC), Giza, Egypt. Prior to analysis, oil samples were converted to fatty acid methyl esters (FAMEs) according to the AOAC official method (AOAC, 2019). GC analysis was performed using a gas chromatograph equipped with a flame ionization detector (FID) and a capillary column (HP-88, 100 m × 0.25 mm i.d., 0.20 µm film thickness). The oven temperature program was set from 140 °C (held for 5 min) to 230 °C at a rate of 4 °C min^{-1}, with a final hold of 10 min. Injector and detector temperatures were maintained at 250 °C. Helium was used as the carrier gas at a constant flow rate of 1.0 mL min^{-1}.

Individual fatty acids were identified by comparing their retention times with those of certified FAME standards. The relative percentage of each fatty acid was calculated based on peak area normalization.

Physicochemical characterization of jojoba oil

The physicochemical properties of jojoba oil were determined following standard analytical procedures. All analyses were carried out at the Central Laboratories, Special Units, Agricultural Research Center (ARC), Giza, Egypt.

Acid value

The acid value of jojoba oil was determined and expressed as percentage free fatty acids (% FFA) according to standard titrimetric methods, as described by AOAC (2019).

Peroxide value

The peroxide value (meq O_2 kg^{-1} oil) was measured to assess the extent of primary oxidation products in the oil following the AOCS official method Cd 8b-90.

Iodine value

The iodine value was determined as an indicator of the degree of unsaturation of jojoba oil according to AOCS official method Cd 1-25.

Refractive index

The refractive index of the oil was measured at 25 °C using a digital refractometer following AOAC standard procedures.

Mineral and heavy metal analysis of jojoba oil for environmental safety evaluation (AAS)

To evaluate the environmental safety and potential toxicological risks associated with the agricultural application of jojoba oil, the mineral and heavy metal contents were determined using Atomic Absorption Spectroscopy (AAS). The mineral and heavy metal contents of jojoba oil were determined using Atomic Absorption Spectroscopy (AAS) at the Center of Materials Analysis, Nanjing University, China, following the standard analytical procedure GB/T 9723-2007. Prior to analysis, oil samples were subjected to appropriate digestion to ensure complete mineralization. The concentrations of macro- and micro-elements, including K, Na, Ca, Mg, Al, Cd, Cr, Cu, Fe, Mn, Ni, Zn, and Pb, were quantified. Elemental contents were expressed as mg kg^{-1} of oil. All measurements were performed under calibrated instrumental conditions to ensure analytical accuracy and reproducibility.

Field application of jojoba oil emulsion and seed cake on watermelon for nematode control and growth assessment

Open-field experiments were conducted on hybrid watermelon (*Citrullus lanatus*) cultivar Giza type, naturally infested with root-knot nematodes (*Meloidogyne incognita*) at a research farm located in Housh Eissa District, El-Beheira Governorate, North Delta, Egypt (31.1983° N, 30.4141° E). Standard field management practices, including irrigation, fertilization, and weeding, were maintained throughout the experimental period.

The experiment was arranged in a randomized complete block design (RCBD) with 10 replicates per treatment. Each replicate consisted of three watermelon plants grouped together as one experimental unit. Jojoba oil emulsions at three concentrations (JOE–5, JOE–10, and JOE–15) and jojoba seed cake were applied either individually or in combination to evaluate their effectiveness in suppressing nematode infestation and improving watermelon growth and yield under natural field conditions. Jojoba oil emulsions were applied as soil drenches around the root zone of watermelon plants, while jojoba seed cake was incorporated into the soil prior to transplanting. Treatments were applied uniformly to all plants within each experimental unit. Care was taken to ensure that each plant received an equal amount of treatment solution, and applications were performed under the same environmental conditions to maintain consistency across replicates.

After 85 days from transplanting, watermelon plants were carefully uprooted, and root systems were gently washed and examined for nematode infection. Nematode eggs and second-stage juveniles (J2s) were extracted according to (Hussey and Barker, 1973) as modified by Boneti and Ferraz (1981). The number of root galls, eggs per egg mass, and J2s per 250 g of soil and root samples were counted to assess nematode infestation levels.

Following nematode assessment, plant growth parameters including vine length, number of leaves per plant, and shoot fresh and dry weights were recorded. At harvest, yield parameters were determined by measuring fruit number per plant, average fruit weight, and total yield per experimental plot.

Statistical analysis

All recorded data were subjected to statistical analysis using analysis of variance (ANOVA) appropriate for a randomized complete block design (RCBD). Data were tested for normality and homogeneity of variance prior to analysis. When significant differences among treatments were detected, mean comparisons were performed using the least significant difference (LSD) test at $P \leq 0.05$. All statistical analyses were carried out using SAS software (Version 9.4; SAS Institute Inc., Cary, NC, USA). Percentage reductions in nematode parameters and percentage increases in plant growth and yield were calculated relative to the untreated control to assess treatment efficacy.

Results

Preparation and characterization of jojoba seeds, oil, and emulsion for nematicidal assessment

Figure 1 illustrates the various jojoba-derived materials utilized in this study for nematicidal evaluation. Fresh green jojoba seeds are shown alongside naturally dried seeds, highlighting the initial raw material. The residual seed cake obtained after mechanical cold-press extraction of the oil is presented, demonstrating its finely ground form suitable for soil amendment applications. The extracted jojoba oil appears as a clear, light-yellow liquid, while the prepared oil-in-water emulsions at defined concentrations were visually confirmed to be homogeneous and physically stable, ensuring uniform application across all experimental units.

Figure 1: *Preparation and characterization of jojoba-derived materials used for nematicidal assessment. (A) Fresh green jojoba seeds, (B) naturally dried seeds, (C) finely ground seed cake obtained after cold-press oil extraction, (D) extracted jojoba oil, and (E) formulated oil-in-water emulsion. These materials were applied in open-field trials to evaluate their efficacy against root-knot nematode infestation and their effects on watermelon growth.*

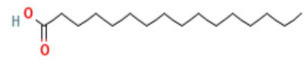
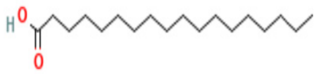
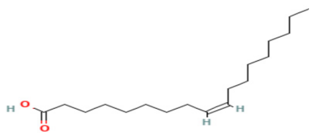
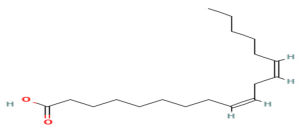
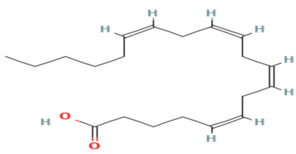
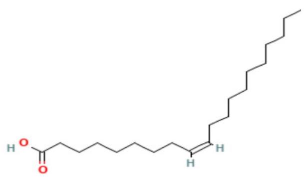
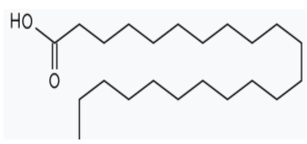
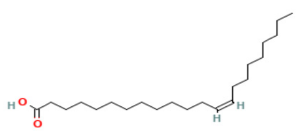
Physicochemical properties of jojoba oil emulsion

The physicochemical properties of jojoba oil are presented in Table 1. The oil exhibited a low acidity value (0.64%), indicating minimal free fatty acid content and good oil quality. The peroxide value was 5.74 mEq O_2/kg oil, reflecting a low level of primary oxidation products and confirming the oxidative stability of the extracted oil. The iodine value reached 80.89, suggesting a relatively high degree of unsaturation, which is characteristic of jojoba oil and contributes to its biological activity. The refractive index measured at 25 °C was 1.4565, which falls within the typical range reported for high-quality jojoba oil and further supports its purity and stability.

Table 1: *Physicochemical properties of jojoba oil indicating its quality and suitability for emulsion preparation.*

No.	Parameters	Average value
1	Acidity (%)	0.64±0.23
2	Peroxide value (mEq/Kg)	5.74±0.42
3	Iodine value	80.89±2.9
4	Refractive index	1.4565

Table 2: *Fatty acid composition of jojoba oil as determined by gas chromatography (GC) analysis.*

Fatty acid	Molecular formula	Area %	Chemical structure
Palmitic acid (C16:0)	C16H32O2	3.23	
Stearic acid (C18:0)	C18H36O2	1.36	
Oleic acid (C18:1)	C18H34O2	18.80	
Linoleic acid (C18:2)	$C_{18}H_{32}O_2$	4.88	
Arachidonic acid (C20:0)	$C_{20}H_{32}O_2$	3.48	
Gadoleic acid (C20:1)	$C_{20}H_{38}O_2$	47.83	
Behenic acid (C22:0)	$C_{22}H_{44}O_2$	2.29	
Erucic acid (C22:1)	$C_{22}H_{42}O_2$	4.55	
Lignoceric acid (C24:1)	$C_{24}H_{48}O_2$	13.58	

GC analysis of fatty acid composition

Table 2 presents the fatty acid composition of jojoba oil as determined by GC analysis. The results show the presence of both saturated and unsaturated fatty acids with varying proportions. Gadoleic acid (C20:1) was the predominant fatty acid, followed by oleic acid (C18:1) and lignoceric acid (C24:1). Saturated fatty acids such as palmitic (C16:0), stearic (C18:0), arachidonic (C20:0), and behenic acids (C22:0) were detected in lower percentages. Minor amounts of linoleic (C18:2) and erucic acids (C22:1) were also identified. The relative percentages of individual fatty acids were calculated based on peak area normalization.

Mineral and heavy metal profile (safety assessment)

Table 3, shows the concentrations of mineral elements detected in jojoba oil using atomic absorption spectroscopy. The analysis revealed the presence of macro- and micro-elements including K, Na, Ca, Mg, Al, Fe, Zn, Mn, Cu, and Ni at low concentrations. Trace levels of heavy metals such as Cd, Cr, and Pb were also detected, with lead (Pb) recorded in µg/kg. All values are presented as quantitative measurements of elemental content in the oil sample.

Table 3: *Mineral content of jojoba oil determined by atomic absorption spectroscopy (AAS). Results are expressed as mg/kg oil, except for Pb which is expressed as µg/kg.*

Elements detection	Q. (mg/Kg)
K	0.57
Na	9.55
Ca	0.85
Mg	1.40
Al	0.84
Cd	0.12
Cr	0.23
Cu	0.64
Fe	1.06
Mn	0.25
Ni	0.24
Zn	1.16
Pb	1.77 (µg/Kg)

Effect of jojoba-based treatments on root-knot nematode infection under open-field conditions

As shown in Table 4 and Figure 2, all evaluated treatments induced statistically significant reductions ($P \leq 0.05$) in root-knot nematode infection parameters compared with the infected control. The magnitude of suppression increased in a concentration-dependent manner across all tested treatments. Application of jojoba oil emulsion alone caused a substantial decrease in gall formation, egg masses, J2s population in soil, and number of females per root, achieving reduction percentages ranging from 63.72 to 87.53% for galls, 66.54 to 90.12% for egg masses, 76.00 to 92.23% for J2s/250 g soil, and 70.5 to 84.2% for females per root as the concentration increased from 5 to 15%.

Notably, the combined treatments of jojoba seed cake (JSC) with JOE exhibited a significantly higher suppressive effect on all nematode parameters than either treatment applied alone, as reflected by distinct statistical groupings. The reduction percentages progressively increased with JOE concentration, reaching maximum values of 95.03% for galls, 96.30% for egg masses, 98.61% for J2 population in soil, and 94.73% for females per root under the JSC + JOE-15 treatment. Intermediate combined treatments (JSC + JOE-5 and JSC + JOE-10) also showed consistently high and statistically significant reduction levels, exceeding 87% across most parameters.

Overall, the results clearly demonstrate a strong positive correlation between treatment intensity and nematode suppression, with the integration of JSC and JOE resulting in significantly enhanced reduction efficiency, as confirmed by the higher reduction percentages and clear statistical separation among treatments in all assessed nematode indices.

Figure 2: *Representative photographs showing the effect of different treatments on root galling symptoms caused by Meloidogyne incognita in Hybrid watermelon (Giza type) plants. (A) Infected control showing severe galling symptoms; (B) Jojoba oil emulsion (JOE, 5%)–treated plants; (C) Jojoba oil emulsion (JOE, 10%)–treated plants; (D) Jojoba oil emulsion (JOE, 15%)–treated plants; (E) Jojoba seed cake (JSC)–treated plants; (F) Combined treatment of jojoba seed cake with jojoba oil emulsion (JSC + JOE, 15%) showing the highest reduction in gall formation.*

Effect of jojoba-based treatments on growth parameters of watermelon plants infected with Meloidogyne incognita

As shown in Table 5, all jojoba-based treatments resulted in significant improvements in vegetative growth parameters of watermelon plants compared with nematode-infected plants, as confirmed by statistical analysis ($P \leq 0.05$). Significant differences among treatments were observed for vine length, fresh shoot weight, fresh root weight, and root length, with clear statistical separation indicated by different letters. Application of jojoba oil emulsion (JOE) alone

Table 4: *Influence of jojoba-based treatments on Meloidogyne incognita infection parameters and reduction percentages (R %).*

Treatment	Nematode parameters							
	Galls	R%	Eggmasses	R%	J2s/250 g soil	R%	Female/Root	R%
Control (*M. incognita*)	782^{a}	–	813^{a}	–	1300^{a}	–	19^{a}	–
JOE-5 + *M. incognita*	202.6^{c}	74.09	233.8^{bc}	71.24	297^{c}	77.15	5.6^{b}	70.5
JOE-10 + *M. incognita*	127.3^{cd}	83.72	105.4^{cd}	87.03	185^{cd}	85.76	4^{bc}	78.9
JOE-15 + *M. incognita*	97.5^{d}	87.53	80.3^{d}	90.12	101^{d}	92.23	3^{c}	84.2
JSC only + *M. incognita*	283.7^{b}	63.72	272^{b}	66.54	312^{b}	76.00	4^{bc}	78.9
JSC + JOE-5 + *M. incognita*	94.6^{d}	87.90	90.4^{d}	88.90	112.2^{d}	91.36	2^{c}	89.47
JSC + JOE-10 + *M. incognita*	65.6^{e}	91.61	62.2^{e}	92.34	83.4^{e}	93.58	2^{c}	89.47
JSC + JOE-15 + *M. incognita*	38.8^{f}	95.03	30^{f}	96.30	18.0^{f}	98.61	1^{d}	94.73

Reduction % = [total number J2s in control - number of J2s in treatment / total number of juveniles J2s in control] × 100

Means within each column followed by the same letter(s) are not significantly different according to the LSD test at $P \leq 0.05$.

induced a concentration-dependent enhancement in all measured growth parameters. Increasing the JOE concentration from 5 to 15% progressively improved vine elongation, shoot biomass, and root development, with the highest concentration (JOE-15) showing significantly higher values than the lower concentrations. In contrast, treatment with jojoba seed cake (JSC) alone resulted in moderate but significant improvements, suggesting partial alleviation of nematode-induced growth suppression. The most pronounced growth promotion was observed under combined applications of JSC and JOE. In particular, the JSC + JOE-15 treatment recorded the highest values for all assessed growth parameters and was statistically superior to all other treatments. The intermediate combined treatments (JSC + JOE-5 and JSC + JOE-10) also showed significant improvements compared with single applications, indicating an additive enhancement of plant growth under combined treatment conditions. These quantitative findings are consistent with the visual assessments of shoot vigor and root architecture presented in Figures 3, where plants subjected to combined treatments exhibited healthier root systems and more vigorous shoot growth than nematode-infected plants.

Table 5: *Effects of jojoba oil emulsion (JOE) alone and in combination with jojoba seed cake (JSC) on vegetative growth parameters of Hybrid watermelon (Giza type) plants infected with Meloidogyne incognita.*

Treatment	Growth parameters			
	Vine length (cm)	Fresh shoot wt.(gm)	Fresh root wt. (gm)	Root length (cm)
Control	166^{c}	3500^{c}	220^{c}	40^{a}
JOE-5 + *M. incognita*	114^{e}	3000^{d}	200^{d}	48^{h}
JOE-10 + *M. incognita*	126^{d}	3300^{cd}	215^{cd}	49^{fg}
JOE-15 + *M. incognita*	170^{c}	3600^{c}	230^{c}	62^{e}
JSC only + *M. incognita*	160^{c}	2900^{d}	185^{e}	51^{d}
JSC + JOE-5 + *M. incognita*	185.4^{b}	3800^{b}	245^{b}	68^{c}
JSC + JOE-10 + *M. incognita*	195.1^{b}	4100^{b}	255^{b}	75^{b}
JSC + JOE-15 + *M. incognita*	205.3^{a}	4300^{a}	275^{a}	95^{a}

Values represent means of three replicates (n = 10). Means within each column followed by different letters are significantly different according to Duncan's multiple range test at P ≤ 0.05.

Discussion

The present study provides an integrated evaluation of jojoba-based products as eco-friendly nematicidal agents by linking chemical quality, safety profile, and biological performance under open-field conditions. The physicochemical characterization of jojoba oil confirmed its high quality and stability, which are essential prerequisites for consistent biological activity in field applications. The low acidity and peroxide values indicate minimal hydrolytic and oxidative degradation, respectively, supporting the suitability of the oil for agricultural formulation and long-term use (Wisniak, 1987, AOAC, 2019). Similar physicochemical ranges have been reported for high-quality jojoba oil intended for industrial and biological applications (Miwa, 1971).

Figure 3: *Representative photograph of a harvested Hybrid watermelon (Giza type) fruit obtained from treated plants.*

The fatty acid composition of jojoba oil, dominated by gadoleic acid followed by oleic and lignoceric acids, is in agreement with previous reports describing jojoba oil as a liquid wax rich in long-chain monounsaturated fatty acids (Wisniak, 1987; El-Bassam, 2011). These compounds have been shown to disrupt membrane integrity and interfere with metabolic processes in plant-parasitic nematodes, contributing to reduced mobility, impaired development, and suppressed reproduction (Oka, 2010; Ntalli and Caboni, 2012). The presence of minor saturated and unsaturated fatty acids may further enhance bioactivity through additive or synergistic effects rather than reliance on a single active component (Ntalli and Caboni, 2012). In addition to chemical quality, safety assessment represents a critical aspect of botanical nematicides. The mineral and heavy metal profile of jojoba oil revealed only trace levels of Cd, Cr, and Pb, comparable to or lower than those reported for other plant-derived oils used in agricultural and food-related contexts (Codex Alimentarius Commission 2019; Isman, 2006). These levels fall within internationally accepted safety limits and indicate that the extraction and formulation processes did not introduce environmentally hazardous contamination. Such findings support the safe integration of jojoba oil emulsions into sustainable nematode management programs (Isman, 2006).

The nematicidal activity observed under open-field conditions reflects the combined influence of chemical composition and formulation stability. Application of jojoba oil emulsion alone resulted in significant, concentration-dependent reductions in gall formation, egg masses, juvenile populations, and females per root. Similar dose-dependent suppressive effects have been reported for other essential and fixed plant oils against Meloidogyne species, where increased concentrations enhance cuticular disruption and inhibit egg hatching and juvenile survival (Oka, 2010; Chitwood, 2002).

Notably, the combined application of jojoba seed cake with jojoba oil emulsion produced markedly greater suppression of nematode infection parameters than either treatment alone. This enhanced efficacy can be attributed to complementary mechanisms of action: rapid contact and repellent effects from the oil emulsion, combined with slower, soil-mediated effects of seed cake decomposition, including the release of bioactive compounds and stimulation of antagonistic soil microflora (Akhtar and Malik, 2000; Abbasi *et al*., 2015). Previous studies on oilseed cakes, including neem and other botanical residues, have demonstrated similar synergistic suppression of root-knot nematodes when used in combination with liquid botanical formulations (Thoden *et al*., 2011; Khan *et al*., 2008).

Beyond nematode suppression, jojoba-based treatments significantly improved vegetative growth parameters of watermelon plants. Root-knot nematode infection is known to impair root function, limiting water and nutrient uptake and ultimately reducing plant growth and vigor (Perry and Moens, 2013). The observed increases in vine length, shoot biomass, and root development indicate effective alleviation of nematode-induced stress, particularly under combined treatments. Comparable growth recovery has been reported following botanical nematicide applications that successfully reduced nematode pressure while maintaining soil health (Bridge and Starr, 2007).

Importantly, the growth-promoting effects observed in this study are consistent with the favorable safety profile of the applied materials. The absence of excessive heavy metal accumulation and the stability of the jojoba oil emulsion suggest that plant growth stimulation was not associated with phytotoxic risks. Visual assessments of root architecture and shoot vigor further corroborated the quantitative data, reinforcing the reliability of jojoba-based treatments under open-field conditions (Akhtar and Malik, 2000; Bridge and Starr, 2007).

Overall, the integration of physicochemical characterization, safety assessment, nematicidal efficacy, and plant growth response provides a coherent framework supporting the use of jojoba oil emulsion, particularly in combination with jojoba seed cake, as a sustainable alternative to synthetic nematicides. These findings align with current trends toward environmentally safe nematode management strategies that rely on multi-target botanical inputs rather than single-mode chemical control (Oka, 2010; Thoden *et al*., 2011).

Conclusion and Recommendations

This study demonstrates that jojoba-based products, particularly the combination of jojoba oil emulsion and seed cake, provide an effective and environmentally safe strategy for managing *Meloidogyne incognita* in watermelon under open-field conditions. Treatments significantly reduced nematode infection and enhanced vegetative growth, reflecting both rapid nematicidal action and longer-term soil-mediated effects. The findings highlight the potential of these botanical products as a sustainable alternative to synthetic nematicides, supporting crop productivity while minimizing environmental impact. It is recommended that jojoba-based treatments be integrated into field management practices to improve nematode control and overall plant vigor in watermelon cultivation.

Acknowledgement

No specific acknowledgements are applicable for this study.

Novelty Statement

For the first time, jojoba (*Simmondsia chinensis*) oil emulsion and seed cake are shown to effectively control *Meloidogyne incognita* in watermelon, reducing nematode infection and enhancing plant growth as an eco-friendly alternative to chemical nematicides.

Author's Contribution

R.Y. Ghareeb conceived and designed the study, supervised the research work, performed data analysis and interpretation, and prepared and revised the manuscript as the corresponding author. S.M. Eid contributed to data analysis and participated in reviewing the manuscript. S.A. Omran assisted in some analyses and contributed to manuscript revision. All authors read and approved the final version of the manuscript.

Generative AI and AI assisted technology statement

The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Statement of conflict of interest

The authors have declared no conflict of interest.

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