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Research Article

Radionics-Assisted Detection and Quantitative Assessment of Root-Knot Nematodes (*Meloidogyne* spp.) Before and After Soil Solarization in Protected Vegetable Cultivation in Kuwait

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ABSTRACT

Root-knot nematodes (*Meloidogyne* spp.) are among the most destructive soil-borne pathogens limiting greenhouse vegetable production worldwide. This study evaluated the effectiveness of soil solarization for suppressing *Meloidogyne* spp. in greenhouse soils and assessed the utility of a Radionics Computer as a rapid tool for nematode detection and population estimation. Soil samples collected from three commercial greenhouses were examined before and after six weeks of soil solarization. Prior to treatment, nematodes were the only detectable soil-borne organisms, while fungi, bacteria, viruses, insects, and weeds were absent. Among 29 nematode genera screened, only *Meloidogyne* was detected. Species identification revealed the presence of *M. hapla* in all greenhouses, with *M. incognita* occurring in greenhouses 3 and 5 and *M. javanica* in greenhouse 4. Larvae constituted the predominant developmental stage, followed by adults and eggs. Radionic analysis indicated considerable variation in nematode densities among greenhouses, with *M. javanica* exhibiting the highest populations (365-595), followed by *M. incognita* (275-545), whereas *M. hapla* occurred at comparatively low densities (45-100). The estimated total *Meloidogyne* population ranged from 103 to 7,107 individuals kg⁻¹ soil, with a mean of 1,832 ± 2,478. Following solarization, no soil organisms, including *Meloidogyne* spp., were detected in any greenhouse. Subsequent cultivation of pepper, bean, and eggplant resulted in vigorous plant growth without root galling or other nematode-associated symptoms. These findings demonstrate that soil solarization can effectively eliminate *Meloidogyne* populations under greenhouse conditions and highlight the potential of radionic detection as a rapid approach for estimating nematode populations prior to disease management interventions.

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Introduction

Cucumber (*Cucumis sativus* L.), eggplant (*Solanum melongena* L.), and tomato (*Solanum lycopersicum* L.) are among the most economically important vegetable crops cultivated worldwide and contribute substantially to food security, nutritional quality, and

farm income. However, their production is severely constrained by a range of soil-borne diseases and pests that cause significant yield and quality losses. Among these constraints, root rot, vascular wilt, and root-knot diseases are particularly destructive and are responsible for substantial economic losses in

vegetable-growing regions. These diseases are caused by diverse groups of pathogens, including fungi, bacteria, and plant-parasitic nematodes, either individually or in disease complexes that exacerbate plant damage (Jones et al., 2013; Nicol et al., 2011).

Root-knot nematodes (*Meloidogyne* spp.) are considered among the most damaging plant-parasitic nematodes worldwide because of their extensive host range and ability to predispose plants to secondary infections by fungal and bacterial pathogens. Annual global crop losses attributed to plant-parasitic nematodes are estimated to exceed US\$170 billion, posing a serious threat to sustainable agricultural production and food security (Jones et al., 2013). Conventionally, management of soil-borne pathogens and nematodes has relied heavily on synthetic pesticides and fumigants. However, indiscriminate and prolonged use of chemical pesticides has resulted in environmental contamination, deterioration of soil health, loss of beneficial soil microorganisms, development of pesticide resistance, and potential risks to animal and human health through the accumulation of toxic residues in agricultural ecosystems (Aktar et al., 2009; Sharma et al., 2020). Furthermore, chemical control measures are often expensive and economically impractical for many vegetable production systems, particularly in developing countries.

Consequently, increasing emphasis is being placed on environmentally sustainable and non-chemical disease management strategies. Among these, soil solarization has emerged as an effective, eco-friendly, and economically viable method for suppressing a wide range of soil-borne pathogens, weeds, and nematodes (Katan and Gamliel, 2009; Katan, 2012; Katan, 2015; Gamliel et al., 2000; DeVay and Katan, 2024; Katan and DeVay, 2024). Soil solarization is a hydrothermal disinfection technique that involves covering moist soil with transparent polyethylene sheets during the hottest months of the year, thereby trapping solar radiation and increasing soil temperatures to levels lethal or suppressive to many soil-borne pests (Katan, 1981). Stapleton and DeVay (1986) demonstrated that soil solarization effectively reduces populations of numerous plant pathogens while improving soil health and crop productivity. Subsequent studies have confirmed its efficacy against root-knot nematodes and other economically important nematode species in protected and open-field cultivation systems (Giannakou

et al., 2007; Katan, 2017).

The technology was introduced in Kuwait during the summer of 2000 through the technical support and guidance of the International Center for Agricultural Research in the Dry Areas (ICARDA). Gebreegziher, (2024) reported that soil solarization represents a simple, environmentally safe, pollution-free, and ecologically sound approach for managing soil-borne pathogens. Root-knot nematodes were identified as a major production constraint at Faisal Al-Ayyar Farm located in the Abdali Agricultural Area of Kuwait. To evaluate the effectiveness of soil solarization under commercial production conditions, experiments were conducted in Greenhouses No. 3, 4, and 5 following the harvest of pepper, eggplant, and tomato crops, respectively.

Accurate assessment of nematode populations is essential for evaluating disease severity and management efficacy. Traditionally, nematode extraction from soil samples has been performed using the Baermann funnel technique, originally described by Baermann (1917). This method remains one of the most widely used procedures for recovering motile nematodes from soil and plant tissues and continues to be employed in modern nematological investigations (Cesarz et al., 2019). Despite its effectiveness, the technique is labor-intensive, time-consuming, and requires specialized expertise for subsequent nematode identification. Conventionally, nematode identification relies heavily on morphological and morphometric characteristics, although molecular and biochemical approaches have increasingly been incorporated to improve diagnostic accuracy. Nevertheless, these methods often require considerable technical expertise, laboratory infrastructure, and processing time.

To address these limitations, alternative rapid diagnostic approaches have been explored. Riaz et al. (2024a) introduced a novel methodology referred to as radionics, which was proposed as a rapid and time-saving technique for biological diagnosis and assessment. In the present study, the potential application of a Radionics Computer is evaluated for the estimation of nematode population density and preliminary identification of nematode infestations. Recent reports by Riaz et al. (2021a, b; 2024a, b; Riaz et al., 2025a, b), Riaz and Al-Kandari (2025), Riaz and Kareem (2025) have described the use of Radionics Computer technology in addressing various plant pest-related problems. However, rigorous scientific validation and comparative evaluation against

established nematological methods remain necessary to determine its reliability, accuracy, and practical applicability in plant disease diagnostics.

The present study was designed to evaluate the effectiveness of soil solarization in suppressing plant-parasitic nematodes, particularly *Meloidogyne* spp., in greenhouse soils following the cultivation of pepper, eggplant, and tomato. In addition, the study assessed the potential of a novel Radionics Computer as a rapid diagnostic tool for the detection and quantitative estimation of nematode populations.

Materials and Methods

Study site and experimental materials

The study was conducted at Faisal Al-Ayyar Farm, located in the Abdali Agricultural Area of Kuwait. The experimental materials used for soil solarization included greenhouse facilities, transparent polyethylene sheets, well-decomposed organic manure, peat moss, a drip irrigation system, soil sampling equipment, plastic bags for sample collection, and a Radionics Computer with associated accessories for diagnostic investigations.

Selection of experimental greenhouses

Three commercial greenhouses, designated as greenhouse 3 (GH-3), greenhouse 4 (GH-4), and greenhouse 5 (GH-5), were selected following the harvest of pepper (*Capsicum annuum* L.), eggplant (*Solanum melongena* L.), and tomato (*Solanum lycopersicum* L.), respectively, at the end of the cropping season. These greenhouses had a documented history of root-knot nematode infestation and were selected to evaluate the effectiveness of soil solarization under protected cultivation conditions.

Soil preparation prior to solarization

Following crop removal, all plant residues and roots were carefully uprooted and removed from the greenhouses. The soil was thoroughly loosened through cultivation to improve aeration and facilitate uniform heat penetration during solarization. Well-decomposed organic manure and peat moss were incorporated into the soil to improve soil structure and moisture-holding capacity. The soil surface was subsequently leveled to ensure close contact between the soil and plastic covering material. A drip irrigation system was installed throughout each greenhouse before the commencement of solarization treatments.

Soil sampling

Initial soil samples were collected before solarization to

determine the baseline population density of soil-borne nematodes. Three sampling locations were selected randomly within each greenhouse. At each location, soil was collected from a depth of approximately 30 cm using a soil auger. The samples from each greenhouse were properly labeled, placed in plastic bags, and transported to the laboratory for analysis.

Following completion of the solarization treatment, soil samples were collected again from the same greenhouses using identical sampling procedures. These post-treatment samples were used to assess the impact of solarization on nematode populations and to compare nematode densities before and after treatment.

Soil solarization procedure

Soil solarization was carried out during the hottest period of the summer season (July-August), when maximum solar radiation and ambient temperatures prevailed. After collection of the initial soil samples, the drip irrigation system was thoroughly tested and operated to bring the soil near field capacity.

The entire soil surface within each greenhouse was covered with transparent polyethylene sheets. The edges of the sheets were buried in soil to create an airtight seal and minimize heat loss and moisture evaporation. Moisture was maintained throughout the treatment period by applying irrigation through the drip system twice weekly. Irrigation was sufficient to wet the soil profile to a depth of approximately 30 cm. The solarization treatment was maintained continuously for six weeks.

The combination of elevated soil temperatures and adequate moisture was expected to suppress soil-borne pathogens and plant-parasitic nematodes through thermal inactivation and biological changes within the soil ecosystem, consistent with established solarization protocols (Katan, 1981; Stapleton and DeVay, 1986; Katan, 2017).

Materials for diagnostic studies using the radionics computer

The following materials were utilized for experimental diagnostic investigations using the Radionics Computer:

1. Radionics device with associated accessories,
2. Transparent glass test tubes,
3. Reference lists of genera of plant-parasitic nematodes,
4. Reference lists of *Meloidogyne* species and
5. Numerical reference sheets (1-100) used for estimation of nematode population density.

Preparation of soil samples for diagnostic evaluation

Each soil sample was thoroughly homogenized before

analysis. From each greenhouse sample, 100 g of soil was weighed using an electronic balance and transferred into three separate glass test tubes designated as replicate 1 (R1), replicate 2 (R2), and replicate 3 (R3). Accordingly, samples were coded as follows: GH-3 R1, GH-3 R2, GH-3 R3, GH-4 R1, GH-4 R2, GH-4 R3 and GH-5 R1, GH-5 R2, GH-5 R3. These coded samples were used for subsequent diagnostic assessments.

Detection of soil-borne nematodes before solarization

Prior to solarization treatment, each soil sample was evaluated using the Radionics Computer. The responses generated by the device were recorded systematically for each replicate. The observations were tabulated to determine the occurrence of soil-borne nematodes within each greenhouse before treatment.

Estimation of nematode population density and identification

For diagnostic evaluation, a test tube containing a soil sample (e.g., GH-3 R1) was placed in the sample holder located on the right side of the Radionics device. The device sensor was sequentially positioned over reference lists containing the names of different genera of plant-parasitic nematodes. Responses indicated by pendulum movement were observed and recorded.

For samples exhibiting positive responses, the procedure was repeated using reference lists of *Meloidogyne* species to determine the probable species identity. Population density estimates were obtained by placing the sensor over a numerical reference scale ranging from 1 to 100. Numbers producing positive pendulum responses were recorded as the estimated nematode population values for the corresponding samples.

All observations were recorded in tabular form and subsequently compared among greenhouses and between pre- and post-solarization samples to evaluate

the effectiveness of soil solarization and the diagnostic capability of the Radionics-based approach.

Data analysis

Nematode occurrence, estimated population density, and species identification data obtained before and after soil solarization were compiled and summarized descriptively. Changes in nematode populations following solarization were assessed by comparing pre-treatment and post-treatment observations for each greenhouse. The effectiveness of soil solarization was determined based on the reduction in nematode incidence and population density after the six-week treatment period.

Results

Detection of soil-borne organisms before solarization

The occurrence of soil-borne organisms in the three selected greenhouses prior to soil solarization is presented in Table 1. Analysis of soil samples revealed that nematodes were the only detectable soil organisms in greenhouses 3, 4, and 5. No fungi, bacteria, viruses, insects, or weeds were detected in any of the samples. The presence of nematodes in all three greenhouses indicated that plant-parasitic nematodes were the predominant biological constraint in the experimental soils.

Identification of nematode genera

The nematode populations detected in the soil samples were identified to the generic level. Among the 29 nematode genera screened, only the genus *Meloidogyne* was detected in all three greenhouses. All other genera were absent from the soil samples. The detailed results for greenhouses 3, 4 and 5 are presented in Table 2. The exclusive detection of *Meloidogyne* spp. confirmed that root-knot nematodes were the dominant plant-parasitic nematodes present at the experimental site.

Table 1. Occurrence of soil organisms in greenhouses 3, 4, and 5 before soil solarization.

Pest	Greenhouse No. 3		Greenhouse No. 4		Greenhouse No. 5	
	Indication by Computer	Remarks	Indication by Computer	Remarks	Indication by Computer	Remarks
Fungi	Negative	No	Negative	No	Negative	No
Bacteria	Negative	No	Negative	No	Negative	No
Viruses	Negative	No	Negative	No	Negative	No
Nematodes	Positive	Yes	Positive	Yes	Positive	Yes
Insects	Negative	No	Negative	No	Negative	No
Weeds	Negative	No	Negative	No	Negative	No

Table 2. Comparative occurrence of nematode genera in greenhouses 3, 4, and 5.

Sr. No.	Nematode genus	Occurrence of nematode spp.		
		Greenhouse No. 3	Greenhouse No. 4	Greenhouse No. 5
1	Anguina	Absent	Absent	Absent
2	Aphelenchoides	Absent	Absent	Absent
3	Atylenchus	Absent	Absent	Absent
4	Belonolaimus	Absent	Absent	Absent
5	Circonema	Absent	Absent	Absent
6	Criconemoides	Absent	Absent	Absent
7	Ditylenchus	Absent	Absent	Absent
8	Dolichdorus	Absent	Absent	Absent
9	Dorylaimus	Absent	Absent	Absent
10	Helicotylenchus	Absent	Absent	Absent
11	Hemicyclophora	Absent	Absent	Absent
12	Hemicirconemoides	Absent	Absent	Absent
13	Heterodera	Absent	Absent	Absent
14	Hoplolaimus	Absent	Absent	Absent
15	Longidorus	Absent	Absent	Absent
16	Meloidodera	Absent	Absent	Absent
17	<i>Meloidogyne</i>	<i>Present</i>	<i>Present</i>	<i>Present</i>
18	Neccobus	Absent	Absent	Absent
19	Paratylenchus	Absent	Absent	Absent
20	Pratylenchus	Absent	Absent	Absent
21	Rodopholus	Absent	Absent	Absent
22	Rotylenchulus	Absent	Absent	Absent
23	Rotylenchus	Absent	Absent	Absent
24	Spraeronema	Absent	Absent	Absent
25	Trichodolrs	Absent	Absent	Absent
26	Tylenchorhynchus	Absent	Absent	Absent
27	Tylenchulus	Absent	Absent	Absent
28	Tylenchus	Absent	Absent	Absent
29	Xiphinema	Absent	Absent	Absent

Identification of Meloidogyne species

Species-level identification of root-knot nematodes revealed differences among the greenhouse soils. In greenhouse 3, *M. hapla* and *M. incognita* were detected. Similarly, greenhouse 5 contained both *M. hapla* and *M. incognita*. In contrast, greenhouse 4 was infested with *M. hapla* and *M. javanica* (Table 3). These results demonstrated that *M. hapla* was common to all three greenhouses, whereas *M.*

incognita and *M. javanica* showed greenhouse-specific distributions.

Population density of Meloidogyne species before solarization

The population density and developmental stages of *M. hapla*, *M. incognita* and *M. javanica* in greenhouse 3, 4 and 5 are presented in Tables 4, 5 and 6, respectively. It is clear from the tables that the larvae represented the largest proportion, followed by adults and eggs.

Table 3. Species composition of *Meloidogyne* in greenhouses 3, 4, and 5 before soil solarization.

Sr. No.	<i>Meloidogyne</i> spp.	Occurrence		
		Greenhouse No. 3	Greenhouse No. 4	Greenhouse No. 5
1	<i>M. arenaria</i>	Absent	Absent	Absent
2	<i>M. arenaria-thamsii</i>	Absent	Absent	Absent
3	<i>M. hapla</i>	Present	Present	Present
4	<i>M. incognita</i>	Present	Absent	Present
5	<i>M. incognita</i> var. <i>acrida</i>	Absent	Absent	Absent
6	<i>M. javonica</i>	Absent	Present	Absent

Table 4. Population density and developmental stages of *M. hapla* in greenhouses 3, 4 and 5 before soil solarization.

Developmental stage	Greenhouse No. 3		Greenhouse No. 4		Greenhouse No. 5	
	Average No. per 100 g of soil	% age	Average No. per 100 g of soil	% age	Average No. per 100 g of soil	% age
Eggs	9	18.75	14.3	42.19	7.3	27.2
Larvae	21	43.75	12.3	36.28	8.7	32.5
Adults	18	37.5	7.3	21.53	10.7	40.3
Total population	48	100	33.9	100	26.7	100

Table 5. Population density and developmental stages of *M. incognita* in greenhouses 3, 4 and 5 before soil solarization.

Developmental stage	Greenhouse No. 3		Greenhouse No. 4		Greenhouse No. 5	
	Average No. per 100 g of soil	% age	Average No. per 100 g of soil	% age	Average No. per 100 g of soil	% age
Eggs	2.7	23.90	-	-	3.3	18.3
Larvae	6.3	55.70	-	-	9.0	50.0
Adults	2.3	20.40	-	-	5.7	31.7
Total population	13.3	100	-	-	18	100

Table 6. Population density and developmental stages of *M. javonica* in greenhouses 3, 4 and 5 before soil solarization.

Developmental stage	Greenhouse No. 3		Greenhouse No. 4		Greenhouse No. 5	
	Average No. per 100 g of soil	% age	Average No. per 100 g of soil	% age	Average No. per 100 g of soil	% age
Eggs	-	-	7.0	26.6	-	-
Larvae	-	-	11.0	41.8	-	-
Adults	-	-	8.3	31.6	-	-
Total population	-	-	26.3	100	-	-

Pre-solarization population densities of *Meloidogyne* spp.

Pre-treatment radionic assays revealed species- and site-specific variations in nematode densities across greenhouses. *M. javonica* was consistently the most abundant species in all three greenhouses (ranging 365-595), while *M. hapla* remained the lowest (45-100). Greenhouse 5 recorded the highest overall populations (*M. javonica*: 595; *M. incognita*: 545), followed by

greenhouse 4 (*M. javonica*: 581; *M. incognita*: 455) and greenhouse 3 (*M. javonica*: 365; *M. incognita*: 275). These elevated pre-solarization densities, particularly of *M. javonica* and *M. incognita*, indicate a high initial inoculum potential, which is critical for interpreting subsequent solarization efficacy (Figure 1).

Pre-solarization population density of *Meloidogyne* spp. in soil

The radionically estimated population density

of *Meloidogyne* spp. (combined eggs, juveniles, and adults) per kilogram of soil prior to solarization ranged from 103 to 7,107 individuals, with a mean value of

$1,832 \pm 2,478$ (SD). The data exhibited high variability across samples, as indicated by the broad range and standard deviation (Figure 2).

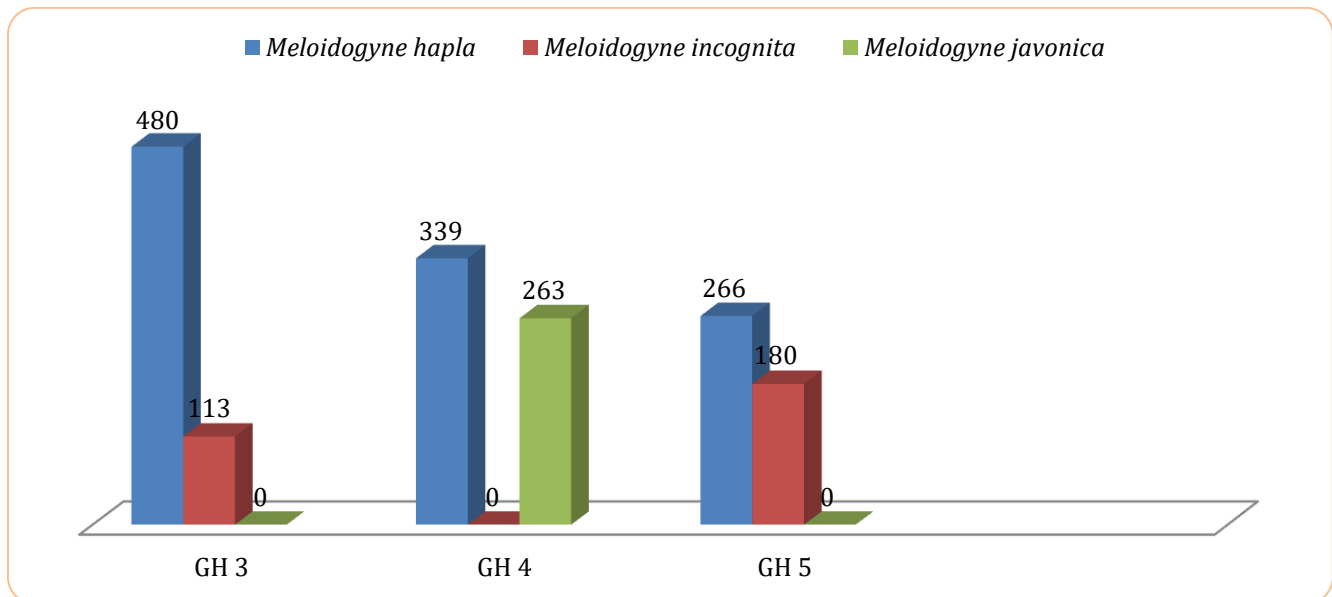


Figure 1. Comparative population densities of *M. hapla*, *M. incognita*, and *M. javanica* in greenhouses 3, 4, and 5, as determined using a radionic computer prior to solarization.

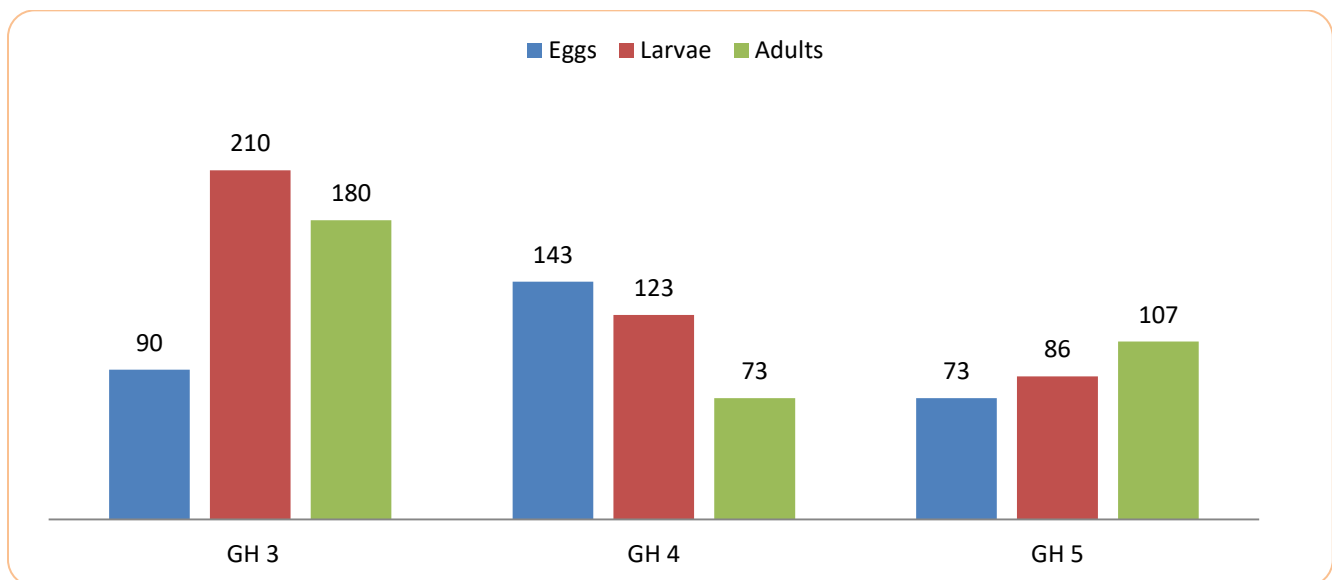


Figure 2. Pre-solarization population density of *Meloidogyne* spp. (eggs, juveniles, and adults) per kilogram of soil, estimated using a radionic computer.

Effect of soil solarization on soil organisms

Following six weeks of soil solarization, soil samples from the three greenhouses were re-examined for the presence of soil organisms. The results presented in Table 7 showed complete absence of fungi, bacteria,

viruses, nematodes, insects, and weeds in all treated soils. The complete elimination of *Meloidogyne* spp. following solarization indicated the effectiveness of this treatment in suppressing root-knot nematode populations under greenhouse conditions.

Table 7. Occurrence of soil organisms in greenhouses 3, 4, and 5 after soil solarization.

Parameter	Greenhouse No. 3		Greenhouse No. 4		Greenhouse No. 5	
	Indication by Computer	Remarks	Indication by Computer	Remarks	Indication by Computer	Remarks
Fungi	Negative	No	Negative	No	Negative	No
Bacteria	Negative	No	Negative	No	Negative	No
Viruses	Negative	No	Negative	No	Negative	No
Nematodes	Negative	No	Negative	No	Negative	No
Insects	Negative	No	Negative	No	Negative	No
Weeds	Negative	No	Negative	No	Negative	No

Crop response following soil solarization

After removal of the polyethylene sheets, pepper, bean, and eggplant crops were planted in greenhouses 3, 4, and 5, respectively. Regular monitoring throughout the growing season revealed healthy crop establishment and vigorous plant growth. Root examination of randomly uprooted plants showed no evidence of root galling or other symptoms associated with root-knot nematode infestation. These observations confirmed the successful suppression of *Meloidogyne* spp. through soil solarization and demonstrated the effectiveness of the treatment in producing nematode-free growing conditions.

Discussion

The present study demonstrated that plant-parasitic nematodes were the only detectable soil-borne organisms in the investigated greenhouse soils before soil solarization, with *Meloidogyne* being the sole nematode genus identified. This finding indicates that root-knot nematodes constituted the principal biological constraint under the protected cultivation system. Greenhouse production often favors the development and persistence of *Meloidogyne* spp. because continuous monocropping, intensive irrigation, high soil moisture, and moderate soil temperatures create ideal conditions for nematode survival and reproduction while reducing opportunities for natural population decline. Such production systems frequently experience a gradual shift towards the dominance of root-knot nematodes, particularly where crop rotation is limited and chemical fumigants are no longer widely used (Sikora and Fernández, 2005; Jones et al., 2013). The absence of detectable fungal, bacterial, viral, insect, and weed problems further suggests that nematodes represented the major soil health challenge in these greenhouses before treatment.

The exclusive detection of *Meloidogyne* among the 29 nematode genera screened further highlights the ecological dominance of root-knot nematodes in intensively cultivated greenhouse soils. Members of the genus *Meloidogyne* possess an exceptionally wide host range, infecting more than 3,000 plant species, and are regarded as the most economically important plant-parasitic nematodes worldwide (Trudgill and Blok, 2001; Jones et al., 2013). Their ability to complete multiple generations annually under protected cultivation allows populations to increase rapidly, particularly in vegetable production systems where susceptible hosts are continuously available (Moens et al., 2009). Similar predominance of *Meloidogyne* over other plant-parasitic nematodes has been reported from greenhouse vegetables in Mediterranean, Asian and subtropical production systems where environmental conditions remain favorable throughout the growing season (Sikora and Fernández, 2005).

Species identification revealed the occurrence of *M. hapla* in all three greenhouses, whereas *M. incognita* occurred in greenhouses 3 and 5 and *M. javanica* was detected only in greenhouse 4. The coexistence of multiple *Meloidogyne* species within greenhouse production systems has been widely documented and reflects differences in host preference, temperature adaptation, cropping history, and local environmental conditions (Karssen and Moens, 2006; Perry et al., 2009). The widespread occurrence of *M. hapla* suggests that this species has successfully established under the prevailing environmental conditions, while the more restricted distribution of *M. incognita* and *M. javanica* may be associated with differences in previous cropping patterns or localized soil characteristics. Mixed infestations of root-knot nematode species are common in commercial vegetable production and often

complicate management because different species may vary in pathogenicity, host range, and response to resistant cultivars (Jones et al., 2013).

The developmental stage analysis showed that second-stage juveniles (J2) constituted the largest proportion of the nematode populations, followed by adults and eggs. This distribution is biologically consistent with the life cycle of root-knot nematodes because J2 represents the infective stage responsible for host invasion and is therefore commonly recovered in soil samples (Perry and Moens, 2011). Higher juvenile populations generally indicate active reproduction and substantial infection potential, whereas the presence of eggs and adults confirms the completion of successive life cycles within the greenhouse environment. Similar population structures have been reported in naturally infested vegetable fields where continuous host availability supports overlapping generations throughout the growing season (Moens et al., 2009).

Considerable variation in nematode population density among greenhouses indicates differences in infestation intensity despite similar production conditions. Greenhouse 5 supported the highest populations of *M. incognita* and *M. javanica*, whereas *M. hapla* remained comparatively less abundant. Such spatial variation is expected because nematode population dynamics are influenced by previous crop history, host susceptibility, irrigation practices, soil texture, organic matter, and microclimatic conditions within protected structures (Bridge and Starr, 2007; Perry et al., 2009). High initial inoculum densities are particularly important because pre-plant nematode populations strongly influence subsequent disease severity and crop losses. Previous studies have consistently demonstrated positive relationships between initial *Meloidogyne* population density and reductions in vegetable yield (Jones et al., 2013). Consequently, the relatively high pre-solarization populations observed in the present study provided a rigorous test of soil solarization efficacy.

The substantial variability observed in pre-solarization population density among soil samples further reflects the aggregated spatial distribution that characterizes plant-parasitic nematodes in agricultural soils. Root-knot nematodes typically occur in localized patches because their dispersal depends largely on root growth, irrigation water, cultivation practices, and movement of infested soil (Nicol et al., 2011). Such heterogeneous distribution explains the wide range of population

estimates obtained before treatment and highlights the importance of adequate soil sampling when evaluating nematode management strategies.

Following six weeks of soil solarization, no soil organisms, including *Meloidogyne* spp., were detected in any greenhouse soil. Soil solarization is a well-established, environmentally sustainable technique that relies on trapping solar radiation beneath transparent polyethylene sheets, thereby increasing soil temperatures to levels lethal for many soil-borne pathogens, nematodes, weed seeds, and certain insects (Katan, 1981; Katan and DeVay, 1991). Elevated temperatures disrupt cellular metabolism, denature proteins, impair membrane integrity, and reduce egg viability, ultimately resulting in mortality of nematode eggs, juveniles, and adults (Stapleton, 2000). Numerous investigations have demonstrated significant reductions in *Meloidogyne* populations following solarization under greenhouse and field conditions, particularly in regions receiving high solar irradiance during summer months (Katan, 1981; Pullman et al., 1981; Stapleton and DeVay, 1986). Therefore, the complete suppression observed in the present study is consistent with the established effectiveness of soil solarization when sufficient temperature and treatment duration are achieved.

The excellent crop performance observed after solarization provides practical evidence that suppression of *Meloidogyne* translated directly into improved crop health. Pepper, bean and eggplant plants established vigorously, and no root galling or other symptoms of root-knot nematode infection were observed throughout the growing period. Root gall formation is the characteristic symptom of *Meloidogyne* infection and results from the induction of giant cells that interfere with normal water and nutrient transport (Williamson and Hussey, 1996). The absence of galling therefore indicates successful protection of the root system from nematode invasion. Previous studies have consistently shown that effective solarization not only reduces nematode populations but also enhances plant growth, increases nutrient uptake, and improves crop yield through the combined effects of pathogen suppression and favorable changes in soil physical, chemical, and biological properties (Katan and DeVay, 1991; Stapleton, 2000).

Although the present investigation demonstrated complete elimination of detectable nematodes after soil solarization, these findings should be interpreted with

appropriate consideration of the detection methodology employed. Confirmation of nematode suppression using conventional nematode extraction techniques, microscopic identification, and molecular diagnostics would further strengthen future investigations and facilitate direct comparison with established phytopathological studies. Nevertheless, the observed absence of root galling together with vigorous crop growth strongly supports the conclusion that soil solarization substantially reduced the disease pressure imposed by root-knot nematodes under the experimental greenhouse conditions.

Overall, the present study reinforces the importance of soil solarization as an effective, environmentally friendly, and non-chemical strategy for managing root-knot nematodes in protected vegetable production systems. Given increasing restrictions on soil fumigants and the global emphasis on sustainable agriculture, soil solarization represents an important component of integrated nematode management programmes. When combined with crop rotation, resistant cultivars, biological control agents, and organic soil amendments, solarization can contribute significantly to long-term suppression of *Meloidogyne* populations while reducing reliance on synthetic nematicides.

Author Contributions

Both authors equally conceptualized and designed the experiment, conducted the field investigations, and executed the experimental work. They jointly prepared the initial manuscript draft, including structuring the content, compiling results, and integrating preliminary interpretations. Both authors critically reviewed the manuscript, contributed to its intellectual refinement, cross-checked the data and analyses, and approved the final version for submission.

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Conflict of Interest

The authors declare no conflict of interest.

Sustainable Development Goals Targeted

SDG 2: Zero Hunger

SDG 12: Responsible Consumption and Production

SDG 15: Life on Land

Policy Addressed

The study supports policies on sustainable protected agriculture and IPM by promoting soil solarization as a non-chemical nematode management strategy. It also aligns with soil health and pesticide reduction policies and supports plant health monitoring and diagnostic innovation for more sustainable greenhouse production.

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