BIODIVERSITAS
Volume 27, Number 2, February 2026
Pages: 11

ISSN: 1412-033X
E-ISSN: 2085-4722
https://doi.org/10.13057/biodiv/d270235

Nematode diversity in tomato and cucumber agroecosystems of Fergana Valley and control of root-knot nematodes, Uzbekistan

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Manuscript received: 10 February 2026. Revision accepted: 27 February 2026.

Abstract. *Kambarov S, To'xtasinov F, Yakhyoyev A, Eshova K, Khabibullaev F, Mamurov K, Qoraboyev K, Abduqayumova S. 2026. Nematode diversity in tomato and cucumber agroecosystems of Fergana Valley and control of root-knot nematodes, Uzbekistan. Biodiversitas 27 (2): d270235. https://doi.org/10.13057/biodiv/d270235.* Plant-parasitic nematodes, particularly root-knot nematodes (*Meloidogyne* spp.), cause substantial yield losses in vegetable crops and threaten the sustainability of agroecosystems. This study assessed nematode diversity in tomato (*Solanum lycopersicum*) and cucumber (*Cucumis sativus*) agroecosystems of the Fergana Valley (Uzbekistan) and evaluated the field efficacy of the nematicides Nematorin (fosthiazate) and Nematozin (mebendazole) during the 2025 growing season. Nematodes were extracted using modified Baermann and flotation techniques and identified based on morphological characters. In total, 60 nematode species belonging to 22 genera, 11 families, and 5 orders were recorded, with soil showing the highest diversity (S: 20, H′: 2.706, 1-D: 0.916), followed by roots (S: 9, H′: 1.779) and the stem-leaf compartment (S: 4, H′: 1.257). Bacterivorous nematodes were the dominant trophic group. Both nematicides significantly reduced the density of invasive second-stage juveniles (J2) and root galling compared with the untreated control ($p<0.001$). Nematozin achieved 90.1% and 90.4% biological efficacy in tomato and cucumber, respectively, whereas Nematorin reached 85.7% and 87.9%. These reductions were accompanied by yield increases from 6.5 t ha^{-1} in the control to 10.8 t ha^{-1} (Nematozin) and 8.7 t ha^{-1} (Nematorin) in tomato, and to 10.2 t ha^{-1} in treated cucumber plots. Identification of *Meloidogyne* was based on morphological criteria; therefore, species-level resolution remains limited and future studies should incorporate molecular markers for confirmation. Overall, integrating nematode community assessment with chemical control measures can contribute to improved management of root-knot nematodes in vegetable agroecosystems of the Fergana Valley.

Keywords: Agroecosystem, *Meloidogyne* spp., nematode diversity, Nematorin, Nematozin

INTRODUCTION

Plant-parasitic nematodes are considered among the most important biotic constraints limiting agricultural crop productivity worldwide. The annual economic losses they cause to agricultural production are estimated to exceed USD 150 billion (Nicol et al. 2011; Jones et al. 2013). Their impact is particularly pronounced in intensive farming systems, especially in irrigated and warm-climate regions. Among plant-parasitic nematodes, root-knot nematodes (*Meloidogyne* spp.) are recognized as one of the most destructive groups due to their wide host range, high reproductive potential, and remarkable adaptability to diverse ecological conditions (Moens et al. 2009; Perry et al. 2009).

Parasitism by *Meloidogyne* spp. leads to the formation of galls in the plant root system, which disrupts the uptake of water and nutrients, reduces photosynthetic activity, and impairs metabolic processes. As a consequence, both vegetative and reproductive development of plants are suppressed, resulting in a significant decline in yield quantity and quality (Sasser and Freckman 1987; Jones et al. 2013). Studies have shown that root-knot nematodes can cause yield losses of up to 30-50% in certain crops (Perry et al. 2009; Sikora et al. 2018).

Tomato (*Solanum lycopersicum*) and cucumber (*Cucumis sativus*), which are of major importance in vegetable production systems, are highly susceptible to *Meloidogyne* spp. Gall formation induced by nematodes in the root systems of these crops disrupts water relations and mineral nutrition, leading to reduced growth rates and deterioration of fruit quality (Moens et al. 2009; Sikora et al. 2018). The severity of infestation is largely determined by nematode population density, the physicochemical properties of the soil, agronomic practices, and crop rotation systems (Jones et al. 2013).

Although Integrated Pest Management (IPM) strategies against plant-parasitic nematodes are increasingly being developed, chemical control methods remain among the most effective and widely used approaches. This is particularly true in regions where resistant cultivars or reliable biological control agents are not sufficiently available, as nematicides

allow for the rapid suppression of nematode populations and provide protection to plants during their early developmental stages (Chitwood 2003; Ntalli and Caboni 2017; Desaeger et al. 2020). At the same time, the efficacy of chemical treatments can vary considerably depending on the active ingredient, application rate, agroclimatic conditions, and soil properties.

In Central Asia, including Uzbekistan, vegetable production represents one of the key sectors of agricultural production. In particular, several studies conducted in the country have demonstrated that the composition and structure of nematode fauna are closely associated with crop species, agronomic management practices, and soil properties (Narzullayev et al. 2024). However, most existing studies have been carried out on individual crops or within limited geographic areas and have often been restricted mainly to faunistic descriptions (Kambarov et al. 2025).

The Fergana Valley is characterized by extensive irrigated areas, favorable agroclimatic conditions, and the repeated cultivation of susceptible host crops, which together create optimal conditions for the development of root-knot nematodes. Nevertheless, systematic and long-term studies on the distribution and population dynamics of *Meloidogyne* spp. as well as on the comparative field efficacy of modern nematicides in this region, remain insufficient. Most of the available data are based on laboratory or short-term experiments, which limits their applicability under real agroecosystem conditions (Kambarov et al. 2025).

Despite the importance of vegetable production in the Fergana Valley, comprehensive data on the species composition and community structure of nematodes in tomato and cucumber agroecosystems remain scarce. In addition, information on the field-level and seasonal dynamics of *Meloidogyne* populations under open-field conditions is limited, and comparative evaluations of Nematorin and Nematozin under local agroecological conditions are lacking. Therefore, this study addresses these gaps by simultaneously assessing nematode community structure and providing one of the first comparative evaluations of the efficacy of these two nematicides under local open-field conditions in the Fergana region. Accordingly, this study aimed to conduct a comparative evaluation of the biological efficacy of the nematicides Nematorin and Nematozin against root-knot nematodes in tomato and cucumber crops under open-field conditions in the Fergana region. The results were analyzed based on reductions in nematode population density, the degree of root damage, and yield parameters, and are intended to contribute to the development of scientifically sound and environmentally acceptable management strategies under regional conditions.

MATERIALS AND METHODS

Experimental design

Field experiments were conducted during the spring-autumn growing season of 2025 in open-field vegetable farms in the Oltiariq District, Fergana Valley, Uzbekistan, using a Randomized Complete Block Design (RCBD) (Figure 1). The experiment included three treatments: Nematorin, Nematozin and an untreated control. Each treatment was replicated five times, and replicates were established as independent plots within each block. Treatments were randomly assigned within each block to minimize spatial bias. Individual plot size was 10 × 5 m, and plots were separated by buffer zones of at least 1.5 m to reduce cross-contamination between treatments. The spacing between adjacent blocks was 2 m.

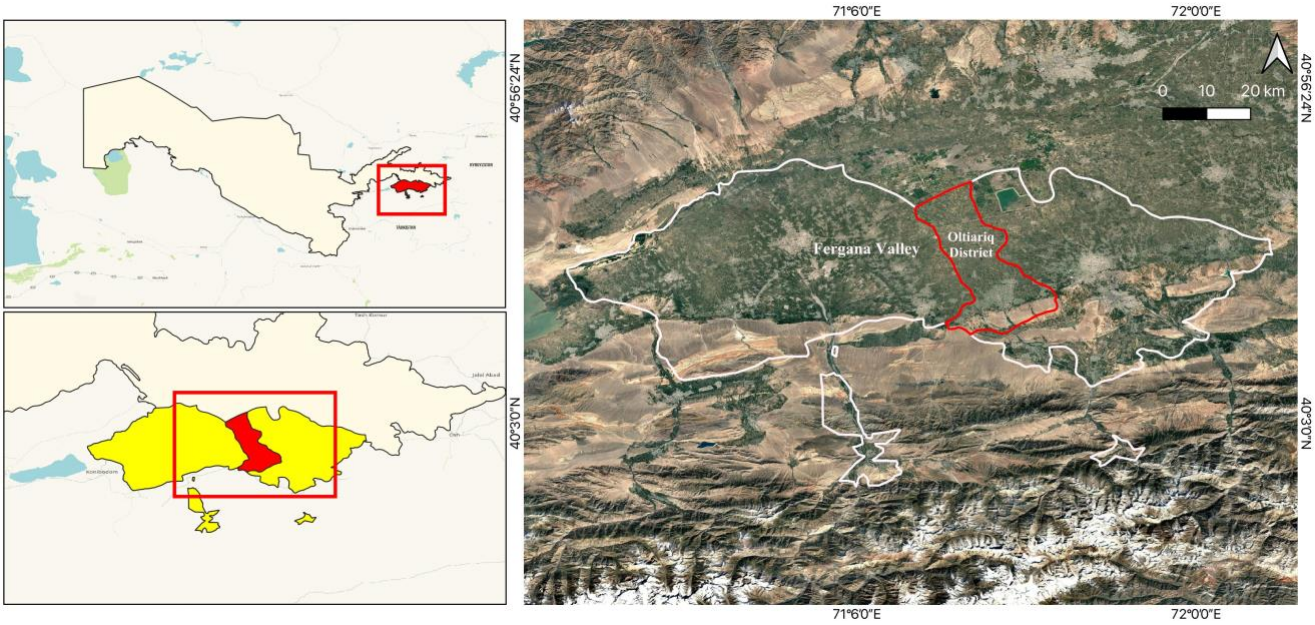

Figure 1. Map of the sampling sites and field experiment in Oltiariq District, Fergana Valley, Uzbekistan

Agronomic management

Tomato and cucumber were grown using locally recommended cultivars widely used in the region. All agronomic practices, including land preparation, planting density, irrigation, and fertilization regimes, were standardized across all treatments to ensure that differences among treatments were attributable only to nematicide application. Irrigation was performed according to local practice using furrow irrigation, and fertilization was applied uniformly based on regional recommendations for vegetable crops.

The field had previously been cultivated with vegetable crops (primarily tomato and cucumber) in rotation, a common agronomic practice in the region that favors the natural build-up of root-knot nematode populations. To prevent cumulative treatment effects across years, separate experimental plots were established in each growing season within the same farm. The selected plots were comparable in soil type, previous cropping history, irrigation regime, and agronomic management practices.

A randomized plot arrangement was applied within each season, and uniform pre-treatment soil conditions were confirmed prior to experiment establishment. This design ensured true replication, minimized environmental variability among treatments, and enhanced the reliability and reproducibility of the experimental results.

Nematode diversity

Soil sampling and nematode extraction

The study area is characterized by irrigated agriculture and a warm, arid climate, which provides favorable conditions for the development of root-knot nematodes (*Meloidogyne* spp.). The experimental fields were naturally infested with root-knot nematodes, and the density of invasive second-stage juveniles (J2) in the soil was determined before the initiation of the experiments.

Soil samples were collected from each experimental plot at two defined timepoints: at the beginning of the growing season (early vegetative stage) and at the end of the season (harvest stage). Within each plot, five soil cores were taken from random positions in the rhizosphere zone of different plants using a soil auger (0-20 cm depth, 3 cm diameter). The five cores from each plot were thoroughly mixed to obtain one composite sample per plot. From each composite sample, a 500 cm^3 subsample was used for nematode extraction and quantitative analysis.

The density of invasive second-stage juveniles (J2) was calculated per 100 cm^3 of soil. Nematodes were extracted from rhizosphere soil and plant root samples using sugar flotation and a modified Baermann funnel technique. The Baermann method was based on nematode motility, with samples placed on filter material and incubated in water at 25°C for 24 h to ensure optimal extraction efficiency. During incubation, active nematodes migrated into the water and accumulated at the bottom of the container. The flotation procedure followed van Bezooijen (2006) and was performed using a sugar solution with a density of 1.18 g cm^{-3}. Samples were centrifuged at 3000 rpm for 5 min to separate nematodes, eggs, and cysts from soil debris. This method enabled efficient recovery of cyst-forming and egg-laying phytonematodes. The organisms floating on the surface were collected and transferred to counting dishes. All extracted nematodes were examined under a light microscope. Identification was performed to the genus level using standard taxonomic keys. The combined application of both methods ensured reliable, comprehensive, and reproducible assessment of nematode populations.

For root sampling, five plants were randomly selected from each plot at each sampling time. Their root systems were carefully excavated, washed free of soil, and used for the assessment of root damage. The degree of galling was evaluated visually using a five-point scale. Roots were also inspected for the presence of nematodes; however, nematode numbers were not expressed per unit root mass, and population density was primarily assessed based on soil J2 counts.

After collection, soil and root samples were placed in labeled plastic bags, stored in insulated containers, and transported to the laboratory. To avoid changes in nematode activity and density, all samples were processed within 24 h after sampling. Nematodes extracted from soil and roots were fixed in 4% formalin solution. Subsequently, both temporary and permanent microscope slides were prepared. For temporary preparations, several drops of glycerin were placed on a glass slide, the fixed nematodes were mounted, and the preparation was covered with a coverslip. For permanent slides, nematodes were isolated using an entomological needle, collected in a watch glass, and immersed in 15-20 drops of a glycerin-ethanol mixture (1:1) for 18-20 h. During this process, the cuticle became transparent and acquired light-transmitting properties. Thereafter, a glycerin-gelatin medium was added, and 5-10 nematodes were mounted on each slide for microscopic examination. The permanent slides are stored in the Zoological Research Laboratory of Fergana State University.

Nematode analysis

The nematodes isolated from plant and soil samples and fixed in 4% formalin solution were examined to determine species composition and the number of individuals. For this purpose, all samples were studied using MBC-9 or MBC-10 series and Olympus CH binocular microscopes (Olympus Optical, Tokyo, Japan). The nematodes were collected, and temporary glycerin or permanent glycerin-gelatin microslides were prepared. Species identification was primarily based on adult female individuals (rarely male individuals were used).

For taxonomic analysis, both classical and modern phylogenetic classification systems were applied (Chitwood 1958; De Ley and Blaxter 2004). The nematodes identified during the study were classified based on their trophic relationships, and their feeding types were assigned according to the classification proposed by Yeates (1993). Accordingly, they were grouped into five main categories: bacterivores (BF), fungivorous (FF), plant feeders (PP), plant phytoparasites (PPp), and predators (PR). omnivores (O). Bacterivores primarily feed on soil bacteria and play a crucial ecological role in regulating soil microflora. Fungivorous consume fungi and filamentous microscopic organisms, thereby contributing to the stability of soil ecosystems. Plant-parasitic nematodes feed on the roots,

stems, or leaves of plants and may cause damage to agricultural crops. Omnivores are capable of consuming bacteria, fungi, and other nematodes, exhibiting a versatile feeding strategy. Predators feed on other nematodes or microscopic soil organisms, supporting the natural biological control mechanisms within the soil.

Nematode diversity analysis

Alpha diversity of nematode communities across biotopes was assessed using species richness (S), Shannon diversity index (H′), and Simpson diversity index (1-D). Species richness (S) was defined as the total number of species recorded within each biotope.

Shannon diversity (H′) was calculated according to the formula:

$$H' = -\sum (pi \ln pi)$$

Where, pi represents the proportional abundance of the i-th species relative to the total number of individuals in the corresponding sample.

Simpson diversity was calculated as:

$$1 - D, \text{ where } D = \sum (pi^2)$$

Both indices incorporate species abundance and evenness; higher values of H′ and 1-D indicate greater diversity and lower dominance within the community. All diversity indices were computed using the PAST software package (Hammer et al. 2001) based on abundance data aggregated for each biotope.

Control of root-knot nematodes

Field experiment treatments

The experiment included three treatments: i) untreated control (no chemical application), ii) Nematorin 10% G, and iii) Nematozin 30% SC. Nematorin 10% G (formulation: granules; active ingredient: fosthiazate; chemical group: organophosphates; manufacturer (Belgium) was applied at a rate of 30 kg ha^{-1}. The product was evenly distributed over the soil surface before transplanting and incorporated into the soil to a depth of 15-20 cm, followed by soil leveling.

Nematozin 30% SC (formulation: suspension concentrate; active ingredient: mebendazole; chemical group: benzimidazoles; manufacturer (Iran) was applied as a soil drench at a concentration of 0.3% (300 mL per 100 L of water), with 100 mL of the working solution applied per plant. The first application was carried out 5-6 days after transplanting and was repeated at 15-day intervals for a total of three applications, resulting in a cumulative dose of 0.3 g active ingredient per plant.

The selected application rates and treatment schedules followed the manufacturers' label recommendations for vegetable crops and were further supported by previous field studies on the control of root-knot nematodes. The same application rates and treatment schedules were used for both tomato and cucumber in each experimental year, as no crop-specific differences in label rates were indicated. The timing of applications was aligned with early plant developmental stages, particularly seedling establishment and root growth phases (Uzbekistan Republic Agency for Plant Quarantine and Protection 2022). Field trials were conducted under the agroecological conditions of the Oltiariq District.

Yield was measured from a predefined harvest area within each plot, excluding border rows to avoid edge effects. All marketable fruits from the harvest area were collected and weighed, and yields were converted to t ha^{-1} based on the harvested area. Yield values were standardized to a uniform fresh-weight (moisture) basis before analysis.

Assessment parameters

To evaluate the efficacy of the treatments, the following parameters were measured: i) the number of invasive juveniles in the soil (per 100 cm^3 of soil); ii) the degree of root damage, assessed on a 5-point scale; and iii) crop yield (t ha^{-1}). Soil samples were collected from the 0-20 cm layer around the plants at the beginning and at the end of the growing season. The degree of root damage was determined by visual assessment and expressed as a mean score.

The average level of root infection by *Meloidogyne* spp. was assessed using a five-point scale according to Kiryanova (1969), as follows: score 1: one or two galls observed on the roots, with up to 10% of the root system affected; score 2: 10-35% of the root system affected; score 3: 35-70% of the root system affected, with partial deformation of the roots; score 4: more than 70% of the root system covered with galls, with most roots deformed; score 5: nearly the entire root system affected by nematodes.

Statistical analysis

All statistical analyses were performed using the PAST (Paleontological Statistics Software) software package (Hammer et al. 2001). Differences among treatments were evaluated by One-Way Analysis of Variance (ANOVA). Homogeneity of variances was assessed using Levene's test (Levene 1960). When the assumption of homogeneity was violated, Welch's ANOVA was applied (Welch 1951). Pairwise comparisons among treatments were conducted using Tukey's HSD post hoc test (Zar 2010). Because the degree of root damage was assessed using an ordinal scale, this parameter was additionally analyzed using the non-parametric Kruskal-Wallis test followed by Dunn's post hoc test (Dunn 1964). Statistical significance was accepted at $p<0.05$. Biological efficacy (%) was calculated according to the following formula:

$$\text{Biological efficacy (\%)} = ((C - T) / C) \times 100$$

Where, C is the mean juvenile density (J2 per 100 cm^3 of soil) in the untreated control at the end of the growing season, and T is the corresponding mean juvenile density in the treated plots at the same timepoint.

RESULTS AND DISCUSSION

Nematode diversity

A total of 60 nematode species recorded in the tomato and cucumber agroecosystem of the Oltiariq District during the 2025 growing season were assigned, according to the classification of De Ley and Blaxter (2004), to 2 classes, 5 orders, 11 families, and 22 genera (Table 1).

Table 1. Nematode species recorded in tomato and cucumber agroecosystems

Nematode species	Ecological (trophic) group (Yeates)	Stem-leaf	Root	Soil
Acrobeloides buetschlii de Man, 1884	Bacterivore	-	+	+
Acrobeloides emarginatus de Man, 1880	Bacterivore	+	+	-
Acrobeloides tricornus Thorne, 1925	Bacterivore	-	-	+
Aglenchus agricola de Man, 1884	Plant parasite	-	+	+
Aphelenchoides angusticaudatus de Man, 1880	Fungivore	+	+	+
Aphelenchoides blastophthorus Franklin, 1957	Fungivore	+	+	+
Aphelenchoides clarolineatus Steiner, 1936	Fungivore/parasite	-	+	+
Aphelenchoides composticola Franklin, 1957	Fungivore	-	+	+
Aphelenchoides limberi Steiner, 1936	Fungivore	+	+	+
Aphelenchoides macronucleatus Steiner, 1932	Fungivore	-	-	+
Aphelenchoides bicaudatus Imamura, 1931	Fungivore	+	+	+
Aphelenchoides parietinus Bastian, 1865	Fungivore	+	+	+
Aphelenchoides saprophilus Franklin, 1957	Fungivore	+	-	-
Aphelenchoides scalacaudatus Steiner, 1945	Fungivore	-	+	+
Aphelenchoides subparietinus Andrássy, 1958	Fungivore	+	-	+
Aphelenchoides subtenuis Andrássy, 1958	Fungivore	+	-	+
Aphelenchus avenae Bastian, 1865	Fungivore	+	+	+
Bitylenchus dubius (Bütschli, 1873)	Plant parasite	-	+	-
Cephalobus persegnis Bastian, 1865	Bacterivore	-	+	-
Cephalobus quadrileniatus de Man, 1880	Bacterivore	-	+	+
Cervidelus insubricus Steiner, 1914	Bacterivore	+	-	+
Chiloplacus bibigulae Andrássy, 1954	Bacterivore	-	-	+
Chiloplacus minimus Thorne, 1925	Bacterivore	-	+	-
Chiloplacus propinquus de Man, 1880	Bacterivore	-	-	+
Chiloplacus sclerovaginatus Andrássy, 1954	Bacterivore	-	+	-
Chiloplacus soosi Andrássy, 1958	Bacterivore	-	-	+
Chiloplacus symmetricus Thorne, 1925	Bacterivore	-	+	+
Clarkus papillatus Bastian, 1865	Predator	-	-	+
Diphtherophora communis de Man, 1880	Plant parasite	-	-	+
Diphtherophora obesus Thorne, 1925	Plant parasite	-	-	+
Diplogaster coronata Cobb, 1893	Omnivore/predator	+	+	+
Diplogaster rhizophilus de Man, 1880	Omnivore/predator	-	+	-
Ditylenchus dipsaci Kühn, 1857	Plant parasite	-	+	+
Enchodelus macrodorus de Man, 1880	Predator	-	-	+
Eucephalobus cornis Thorne, 1937	Bacterivore	-	+	+
Eucephalobus oxyuroides de Man, 1876	Bacterivore	-	+	+
Eucephalobus striatus Bastian, 1865	Bacterivore	-	+	+
Eudorylaimus monohystera de Man, 1880	Predator	-	-	+
Eudorylaimus obtusicaudatus de Man, 1880	Predator	-	-	+
Eudorylaimus pratensis de Man, 1880	Predator	-	-	+
Filenchus filiformis Bütschli, 1873	Plant parasite	-	-	+
Helicotylenchus dihystera Cobb, 1893	Plant parasite	-	-	+
Helicotylenchus multicinctus Cobb, 1893	Plant parasite	-	-	+
Helicotylenchus nannus Steiner, 1945	Plant parasite	-	-	+
Heterocephalobus elongatus de Man, 1880	Bacterivore	-	-	+
Lelenchus discrepans Andrássy, 1954	Plant parasite	-	-	+
Meloidogyne spp. Chitwood, 1949	Plant parasite	-	+	+
Mesorhabditis monhystera Bütschli, 1873	Bacterivore	-	+	+
Panagrolaimus armatus Thorne, 1937	Bacterivore	-	-	+
Panagrolaimus rigidus Schneider, 1866	Bacterivore	+	+	+
Panagrolaimus subelongatus Andrássy, 1958	Bacterivore	+	+	+
Paraphelenchus tritici Mishra & Edward, 1971	Fungivore	-	+	+
Paratylenchus hamatus Thorne & Allen, 1950	Plant parasite	+	+	-
Plectus parietinus Bastian, 1865	Bacterivore	-	+	-
Pratylenchus pratensis de Man, 1880	Plant parasite	+	+	+
Prismatolaimus dolichurus de Man, 1880	Bacterivore	-	-	+
Prismatolaimus intermedius de Man, 1880	Bacterivore	-	-	+
Rhabditis brevispina Claus, 1862	Bacterivore	+	+	+
Rhabditis filiformis Bastian, 1865	Bacterivore	-	+	+
Tylenchus davainei Bastian, 1865	Plant parasite	-	+	-

In terms of species richness, the class Chromadorea was dominant, comprising approximately 70% of the total recorded species. Within this class, the orders Rhabditida, Tylenchida, Aphelenchida, Diplogastrida, and Plectida were represented. Among these, Rhabditida was the most species-rich order, with 23 identified species. The second class, Enoplea, comprised nearly 30% of the total fauna and was mainly represented by the orders Dorylaimida and Plectida. Among these, Dorylaimida was dominant, comprising three families and 12 species.

At the family level, the highest species richness was observed in Tylenchidae (8 species), Dorylaimidae (7 species), Aphelenchidae (6 species), and Rhabditidae (5 species). The order Tylenchida was particularly well represented in root-associated communities and contained the highest number of phytoparasitic species, suggesting that this order may serve as an important indicator group for assessing phytosanitary conditions in vegetable agroecosystems.

As a result of our study, a total of 60 nematode species were identified, some of which were found to occur on both of the selected host plants. According to the diagram, 24 species were exclusive to cucumber, whereas 11 species were exclusive to tomato. The number of species shared by both crops was 22. These results indicate that the nematode fauna of cucumber and tomato agroecosystems is partially overlapping. At the same time, species richness was higher in cucumber than in tomato (Figure 2).

Quantitative analysis of alpha diversity across biotopes revealed clear structural differences in nematode community composition. All diversity indices were calculated using pooled abundance data for each biotope across all plots and both crops. Species richness (S) was highest in soil (S: 20; N: 210 individuals), followed by roots (S: 9; N: 86) and the stem-leaf compartment (S: 4; N: 44).

Shannon diversity (H') was highest in soil (H': 2.706), intermediate in roots (H': 1.779), and lowest in the stem-leaf compartment (H': 1.257). Similarly, Simpson diversity (1-D) reached its maximum in soil (0.9161), indicating greater evenness and lower dominance compared to root and stem-leaf compartments. The total of 60 species represents the pooled species list recorded across all biotopes and both crops during the 2025 growing season. Crop-level species counts (e.g., cucumber soil) were calculated separately and therefore are not directly comparable to the pooled biotope-level values presented here.

In this study, *Meloidogyne* spp. were identified based on morphological characteristics only; therefore, taxonomic resolution is limited to the genus level. Molecular markers such as internal transcribed spacer (ITS) or cytochrome c oxidase subunit I (COI) would allow more precise species-level discrimination in future investigations.

Structure of the nematode fauna in the cucumber agrocenosis

Faunistic surveys conducted during the 2025 growing season in cucumber fields revealed a total of 46 nematode species. Species richness varied across biotopes, with the rhizosphere soil representing the principal habitat (36 species), followed by roots (23 species) and the stem-leaf compartment (14 species) (Figure 3).

Alpha diversity patterns presented in Figure 3 confirmed that the soil biotope supported the highest diversity, whereas the stem-leaf compartment exhibited the lowest diversity, indicating a strong edaphic structuring of the cucumber-associated nematode community.

Faunistic analysis of cucumber nematodes by plant organs (biotopes)

The rhizosphere soil harbored the richest assemblage both in terms of species number and individual abundance. Dominant species, defined here in terms of numerical abundance, included *Panagrolaimus rigidus*, *Chiloplacus symmetricus*, *Mesorhabditis monhystera*, and *Aphelenchus avenae*. Their prevalence reflects active microbial processes and intensive organic matter decomposition in the soil environment (Figure 3).

The nematode fauna associated with roots was comparatively less diverse than that of soil. No single species exhibited overwhelming numerical dominance. The assemblage consisted primarily of subdominant taxa, including both free-living and phytoparasitic forms. The intermediate diversity observed in roots suggests a transitional community structure between the highly diverse soil habitat and the simplified aboveground compartment (Figure 3).

The stem-leaf compartment supported a comparatively simplified nematode assemblage. *Panagrolaimus rigidus* was the most abundant species in this biotope, whereas phytoparasitic taxa were rare. The reduced diversity in this compartment likely reflects limited ecological niches and lower habitat heterogeneity compared to soil. In total, 14 species were recorded only in cucumber fields within the present sampling framework. However, this exclusivity reflects the scope of the current sampling design and should not be interpreted as strict crop specificity (Figure 3).

According to the trophic classification of Yeates et al. (1993), the cucumber-associated nematode fauna included bacterivores (BF), fungivorous (FF), plant feeders (PP), true phytoparasites (PPp), and predators (PR). Bacterivores were the most widespread group, particularly in the rhizosphere soil, indicating strong microbial-driven trophic pathways. Fungivorous were also well represented, confirming the importance of fungal energy channels. True phytoparasites were present but did not dominate the assemblage, suggesting relatively balanced trophic interactions during the 2025 growing season.

Structure of the nematode fauna in tomato agrocenosis

Faunistic surveys conducted in tomato fields during the 2025 growing season revealed a total of 36 nematode species associated with tomato plants and their rhizosphere soil. Because both plant-parasitic and free-living taxa were included in the survey, the term “nematode fauna associated with tomato” is used here rather than “nematode fauna”. The nematode community was unevenly distributed among plant-associated biotopes: 28 species were recorded in the rhizosphere soil, 21 species in the roots, and 14 species in the stems and leaves (Figure 4). 6 species were common to both plant tissues and rhizosphere soil.

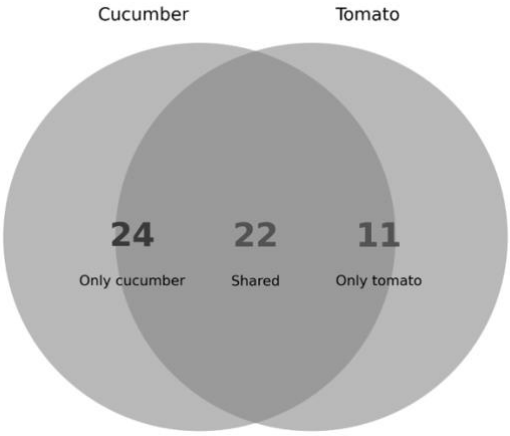

Figure 2. Venn diagram illustrating the overlap in nematode species composition between cucumber and tomato agroecosystems

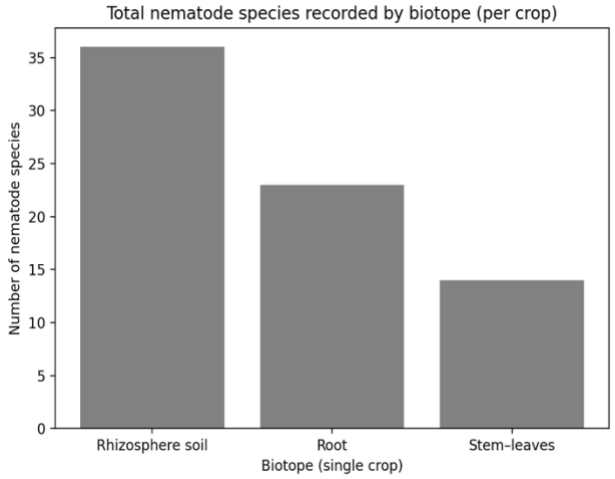

Figure 3. Distribution of nematode species across different biotopes in cucumber agrocenosis

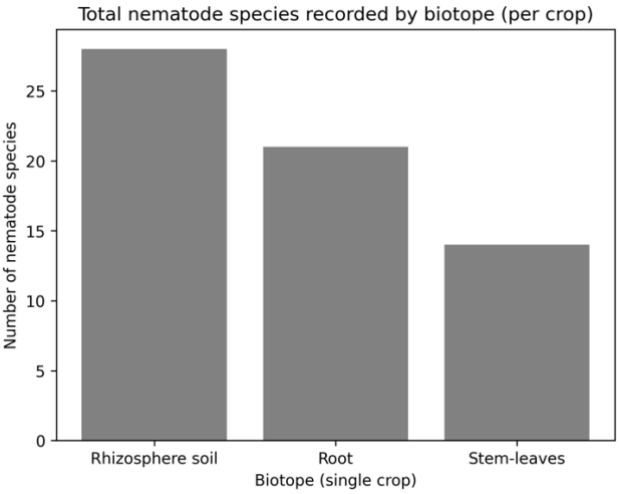

Figure 4. Distribution of nematode species across different biotopes in tomato agrocenosis

Faunistic analysis of tomato nematodes by plant organs (biotopes)

A total of 28 species were recorded in the rhizosphere soil. This biotope exhibited high species richness. Species dominance categories (dominant, subdominant, recedent, subrecedent) were assigned according to relative abundance within each biotope, based on proportional representation of individuals in the total sample. No single species exhibited overwhelming numerical dominance in the soil compartment, indicating a relatively even distribution among taxa. *Aphelenchoides clarolineatus* occurred as a subdominant species, whereas *Panagrolaimus rigidus* and *Aphelenchus avenae* were classified as recedent species. Subrecedent taxa comprised 25 species. This pattern indicates that bacterivorous and fungivorous nematodes predominate in the rhizosphere soil, participating actively in trophic pathways associated with organic matter decomposition and fungal biomass.

A total of 21 nematode species were recorded in tomato roots, and this compartment exhibited the highest abundance of individuals. The dominant species in terms of numerical abundance was *Meloidogyne* spp., while subdominant species included *Panagrolaimus rigidus*, *Helicotylenchus nannus*, and *Pratylenchus pratensis*. Recedent species included *Eucephalobus cornis* and *Aphelenchoides composticola*.

In several individual root samples, the density of *Meloidogyne* spp. reached 200-250 individuals; however, these values represent localized sample-level observations rather than overall mean abundance. High densities of *Meloidogyne* spp. were associated with gall formation and visible root deformation. Although elevated local densities were observed, broader phytosanitary implications should be interpreted cautiously within the limits of the present sampling framework.

A total of 14 species were recorded in stems and leaves. This compartment was characterized by comparatively low abundance and simplified species composition. *Panagrolaimus rigidus* was the most numerically abundant species, whereas most other taxa occurred at low frequencies. The reduced diversity and abundance in this biotope suggest limited ecological suitability of aboveground tissues for nematode colonization. During the study, 8 species (*Clarcus papillatus*, *Eudorylaimus pratensis*, *Diplogaster rhizophilus*, *Tylenchus davainei*, *Aphelenchoides macronucleatus*, *Helicotylenchus nannus*, *Pratylenchus pratensis*, and *Meloidogyne* spp.) were recorded only in tomato fields. This apparent exclusivity reflects the current sampling design and does not necessarily imply strict host specificity.

Ecological groups of nematodes in the tomato agrocenosis according to Yeates

Bacterivorous nematodes (BF) were widely represented, particularly in rhizosphere soil and roots. Their presence reflects active bacterial decomposition processes and nutrient cycling within the soil environment. Fungivorous nematodes (FF), mainly species of *Aphelenchus* and *Aphelenchoides*, were also recorded in soil and plant tissues, indicating the importance of fungal-based trophic channels. Predatory nematodes (PR), including representatives of *Clarcus*, *Eudorylaimus*, and *Diplogaster*, occurred in

low numbers, mainly in soil. The relatively low abundance of predatory taxa may indicate a simplified trophic structure typical of intensively managed agroecosystems. Non-plant-feeding nematodes were recorded primarily in soil and occurred at low densities in plant organs. True plant-parasitic nematodes (PP) included *Helicotylenchus multicinctus*, *H. dihystera*, *H. nannus*, *Ditylenchus dipsaci*, *Pratylenchus pratensis*, and *Meloidogyne* spp. Among these, *Meloidogyne* spp. represented the most phyto-sanitarily significant species in root tissues during the 2025 season. Saprobiont and semi-saprobiont nematodes were primarily recorded in rhizosphere soil and are considered indicators of biological activity and organic matter turnover.

Distribution of root-knot nematodes in tomato and efficacy of treatments

Prior to treatment application, the density of invasive juveniles (J2) in tomato fields did not differ significantly among treatments and averaged approximately 32 individuals per 100 cm³ of soil. Baseline densities were compared using one-way ANOVA and showed no significant differences among treatments ($F(2,12)$: 0.36, p: 0.704), confirming initial homogeneity of experimental plots. Each treatment consisted of five independent plots (n: 5), and the plot was considered the experimental unit in all statistical analyses.

At the end of the growing season, significant differences among treatments were detected (Table 2). One-way ANOVA performed on the same dataset indicated a strong treatment effect on juvenile density ($F(2,12)$: 8334, p: 1.386×10^{-19}). Because Levene's test revealed heterogeneity of variances (p: 0.01365), Welch's ANOVA was conducted on the same data and confirmed the significance of the treatment effect (Welch's $F(2, 7.315)$: 4356, p: 5.607×10^{-12}). The effect size was very large (ω^2: 0.9991), indicating that treatment explained most of the variation in juvenile density under the experimental conditions. Juvenile counts were derived from one composite 500 cm³ soil sample per plot. Therefore, variability reflects between-plot differences rather than within-plot subsampling variation. Tukey's post hoc test showed that both Nematozin and Nematorin significantly reduced juvenile densities compared to the control (Nematozin vs control: p: 2.809×10^{-14}; Nematorin vs control: p: 2.809×10^{-14}), and Nematozin was significantly more effective than Nematorin (p: 0.019). The high control values represent plot-level means and do not reflect measurement truncation.

Root damage index

The Kruskal-Wallis test indicated significant differences in root damage index among treatments (H: 12.5; $p<0.01$). Dunn's post hoc test showed significantly lower damage in treated plots compared to the control. Nematozin achieved 90.1% biological efficacy and produced a yield of 10.8 t ha^{-1}. Nematorin achieved 85.7% efficacy with a yield of 8.7 t ha^{-1}, while the control produced 6.5 t ha^{-1} (Figure 5). These results demonstrate strong suppression of root-knot nematodes in tomato under the conditions of the 2025 growing season, with Nematozin showing comparatively higher efficacy.

Distribution of root-knot nematodes in cucumber and efficacy of treatments

Before treatment application, juvenile densities in cucumber plots did not differ significantly among treatments (mean ≈ 32.0 individuals per 100 cm³; $p>0.05$). As in tomato, five independent plots per treatment were used (n: 5), and statistical analyses were conducted using plot-level means. By the end of the growing season, significant treatment effects were observed (Table 3). One-way ANOVA revealed a highly significant difference among treatments (F: 8334; $p<0.001$). Because Levene's test indicated unequal variances (p: 0.013), Welch's ANOVA was additionally applied and confirmed treatment differences (Welch's F: 4356; $p<0.001$). The effect size was extremely large (ω^2: 0.999), indicating strong treatment influence on nematode density. Tukey's post hoc comparisons showed that both Nematozin and Nematorin resulted in significantly lower juvenile densities than the untreated control at the end of the growing season ($p<0.001$). Nematozin was significantly more effective than Nematorin (p: 0.019).

The root galling index differed significantly among treatments (Kruskal-Wallis $H(2)$: 12.57; p: 0.0019). Treated plots exhibited significantly lower galling severity compared with the untreated control according to Dunn's post hoc test. Biological efficacy, calculated based on end-season juvenile densities using the formula $((C - T) / C) \times 100$, reached 87.9% in the Nematorin treatment and 90.4% in Nematozin-treated plots.

Although similar treatment trends were observed in both crops, formal crop × treatment interaction was not modeled; therefore, cross-crop comparisons should be interpreted within the single-season framework of this study. Overall, both nematicides substantially reduced root-knot nematode populations and increased yield under the agroecological conditions of the 2025 season. Yield was higher in treated plots (10.2 t ha^{-1}) compared with the control (6.5 t ha^{-1}) (Figure 6).

Table 2. Effect of nematicides on invasive juveniles in tomato (n: 5 plots per treatment)

Treatment	Mean±SE (J2 per 100 cm³)	Group
Nematozin	25.0±0.7	a
Nematorin	33.5±0.9	b
Control	250.0±2.3	c

Note: Different letters indicate significant differences among treatments according to Tukey's test ($p<0.05$)

Table 3. Effect of nematicides on invasive juveniles in cucumber (n: 5 plots per treatment)

Treatment	Mean±SE (J2 per 100 cm³)	Group
Nematozin	24.0±0.7	a
Nematorin	30.5±0.7	b
Control	250.0±2.2	c

Note: Different letters indicate significant differences among treatments according to Tukey's test ($p<0.05$)

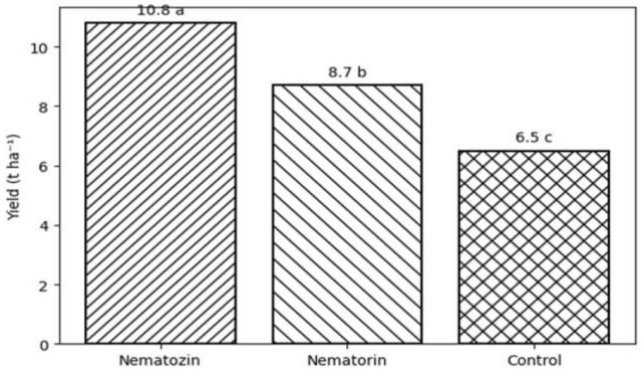

Figure 5. Effect of nematicide treatments on tomato yield (t ha^{-1}). Different letters indicate significant differences among treatments ($p<0.05$)

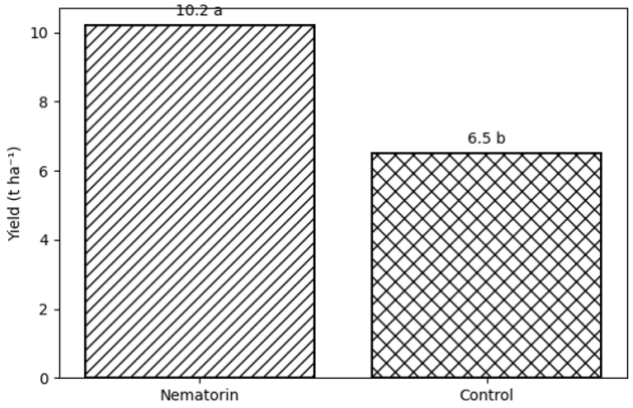

Figure 6. Effect of nematicide treatment on cucumber yield (t ha^{-1}). Different letters indicate significant differences between treatments ($p<0.05$)

Discussion

The present study demonstrated that nematodes belonging to the class Chromadorea, particularly representatives of the order Rhabditida and the family Tylenchidae, were numerically dominant in tomato and cucumber agroecosystems of the Fergana Valley during the 2025 growing season. The dominance of these taxa reflects the structural organization of soil food webs in cultivated vegetable systems, where enrichment opportunists and bacterial feeders typically prevail under conditions of regular disturbance and nutrient input.

Bacterivorous nematodes constituted a substantial component of the recorded fauna. Their ecological role is closely linked to regulation of bacterial biomass, stimulation of microbial turnover, and acceleration of nutrient mineralization processes. By grazing on bacteria, these nematodes may enhance nitrogen release and indirectly contribute to improved plant nutrient availability. Similar patterns have been documented in intensively managed agricultural soils, where bacterivores frequently represent the dominant trophic group (Salas and Achinelly 2020; Furmanczyk et al. 2025).

The relatively high representation of bacterivorous and fungivorous taxa in the rhizosphere suggests active microbial-driven decomposition processes typical of irrigated vegetable production systems receiving nutrient inputs. Although phytoparasitic nematodes represented a smaller proportion of total species richness compared with free-living taxa, their agronomic importance was substantial. In particular, root-knot nematodes of the genus *Meloidogyne* spp. were recorded as dominant phytoparasites in root tissues of both crops. Species identification was based on morphological characteristics observed under light microscopy; therefore, molecular confirmation would be required to achieve definitive species-level resolution. Accordingly, the present results should be interpreted at the genus level (*Meloidogyne* spp.) unless supported by additional diagnostic evidence.

The presence of *Meloidogyne* spp. is consistent with numerous studies identifying this genus as one of the most destructive groups affecting vegetable crops worldwide (Hallmann and Kiewnick 2018; Geldenhuys 2023). High localized densities in root tissues were associated with gall formation and visible impairment of root systems, which likely contributed to reduced nutrient uptake and growth suppression in untreated plots.

The distribution of nematodes among biotopes revealed pronounced ecological differentiation. The rhizosphere soil supported the highest species richness, indicating that this compartment functioned as the primary reservoir of nematode biodiversity within the studied fields. In contrast, phytoparasitic taxa were concentrated mainly in root tissues, reflecting their direct trophic dependence on living plant cells.

This spatial structuring is consistent with the concept of habitat filtering in plant-soil systems, where root exudates, microbial communities, and microenvironmental gradients selectively favor particular nematode assemblages. Previous research has demonstrated compositional differences between rhizosphere soil, root tissues, and bulk soil environments (Gols et al. 2023; Teshita et al. 2024). The comparatively low abundance of nematodes in stems and leaves further supports the notion that aboveground plant organs provide limited ecological opportunities for nematode colonization.

The field experiments demonstrated that both Nematozin and Nematorin significantly reduced densities of invasive juveniles (J2) in the soil and decreased the severity of root damage compared with the untreated control. These results indicate that chemical control played a major role in suppressing nematode populations under the specific experimental conditions. However, the magnitude of these treatment effects should be interpreted with caution, as the study was conducted over a single growing season and relied on plot-level replication.

Nematozin consistently showed higher biological efficacy than Nematorin in both tomato and cucumber. Yield increases observed in treated plots further support the functional linkage between nematode suppression and crop productivity. Reduction of root damage likely improved water uptake, mineral nutrition, and overall plant vigor, contributing to enhanced yield performance. These findings are broadly consistent with previous studies reporting

suppressive effects of chemical nematicides against root-knot nematodes under field conditions (Desaeger and Watson 2019; Loffredo et al. 2024). However, direct comparison with other regions should be made cautiously due to differences in soil type, climate, and agronomic practices.

The observed yield response reinforces the agronomic relevance of effective nematode management strategies under local production conditions. Although comparable efficacy trends were observed in both crops, crop × treatment interaction was not explicitly modeled; therefore, cross-crop comparisons should be interpreted cautiously within the context of this single-season study. From a management perspective, the results indicate that targeted nematicide application can substantially reduce phytosanitary pressure in vegetable agroecosystems of the Fergana Valley. However, exclusive reliance on chemical control may not be sustainable in the long term.

In our field experiments, Nematozin and Nematorin showed strong efficacy in reducing J2 densities and root damage, indicating that chemical control can be highly effective under the tested conditions. However, these results also highlight the need to carefully consider environmental safety and regulatory aspects, particularly given the use of organophosphate-based products and compounds such as mebendazole. While the observed treatment effects demonstrate short-term benefits, potential risks to non-target soil organisms, residue persistence, and long-term ecological impacts cannot be excluded and should be addressed in future studies. Therefore, integrating these chemical treatments with crop rotation, resistant cultivars, organic amendments, and biological control agents would represent a more sustainable IPM-based strategy, reduce environmental risks and help to delay the development of nematicide resistance.

This study was conducted in a single district (Oltiariq) during the 2025 growing season and evaluated two crops and two nematicides. Therefore, extrapolation of the findings beyond the studied agroecological and temporal context should be undertaken with caution. Future investigations should include multi-year trials, expanded geographic coverage, molecular confirmation of *Meloidogyne* spp. explicit modeling of crop × treatment interactions, and assessment of integrated pest management strategies to provide a more comprehensive understanding of nematode dynamics in regional agroecosystems. Overall, the present research provides a structured evaluation of nematode community composition and demonstrates the field performance of Nematozin and Nematorin under local production conditions, contributing baseline data for regional phytosanitary management planning.

In conclusion, this study assessed the composition and distribution of nematode communities and evaluated the field efficacy of Nematorin and Nematozin in tomato and cucumber agroecosystems of the Fergana region during the 2025 growing season. The results showed that bacterivorous nematodes represented the most species-rich trophic group within the recorded fauna, while phytoparasitic nematodes of the genus *Meloidogyne* spp. were dominant in root tissues. Both nematicides significantly reduced densities of invasive juveniles (J2) compared with the untreated control. Statistical analyses based on plot-level means (n: 5) confirmed significant treatment effects in both crops. Nematozin demonstrated significantly higher biological efficacy than Nematorin under the conditions of the present study. Yield increases observed in treated plots indicate a functional relationship between nematode suppression and crop productivity. Because the study was conducted in a single district and during one growing season, extrapolation of the findings should be made with caution. Future research should include multi-site and multi-year trials, evaluation of additional management strategies, and molecular confirmation of *Meloidogyne* spp. to strengthen the evidence base for regional nematode management.

ACKNOWLEDGEMENTS

The authors sincerely acknowledge Fergana State University, Uzbekistan, for providing the scientific equipment and institutional support required for this study. The authors also extend their appreciation to the staff of the Laboratory of the Department of Zoology and General Biology for their valuable assistance with sample processing and analysis.

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