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Plant-parasitic nematode fauna in potato production areas of Erzurum Province, Türkiye and evaluation of fluopyram efficacy against economically important species

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Summary – Potato (*Solanum tuberosum* L.) is an important food crop worldwide, but plant-parasitic nematodes can adversely affect yield and tuber quality. This study characterised the plant-parasitic nematode fauna associated with potato production areas in Erzurum Province, Türkiye and assessed the efficacy of fluopyram against *Pratylenchus neglectus* and *Ditylenchus destructor* under field conditions. A total of 213 soil samples were collected from potato fields in 14 districts from 2021-2023. Nematodes were identified using morphological and morphometric characters and the three target species were identified by species-specific PCR primers. Plant-parasitic nematodes were detected in 186 soil samples. Seventeen species belonging to ten genera and seven families were identified; cyst nematodes were not detected. *Pratylenchus neglectus*, *P. thornei* and *D. destructor* were confirmed by PCR. Two-year field trials were conducted in Ebsemce village, Pasinler district, using cultivars 'Agria', 'Granola' and 'Marfona' in a split-plot arrangement within a randomised complete block design. Based on the nematode reproduction factor (RF), fluopyram-treated plots had RF values below 1 for *P. neglectus* in every cultivar-year combination. By contrast, *D. destructor* had RF values above 1 in all fluopyram-treated plots in 2022 and below 1 in 2023. These results identify *P. neglectus*, *P. thornei* and *D. destructor* as relevant targets for regional monitoring and indicate that fluopyram may contribute to *P. neglectus* management, whereas *D. destructor* requires an integrated approach.

Keywords – *Ditylenchus destructor*, molecular diagnostics, morphological identification, population density, *Pratylenchus neglectus*, *Pratylenchus thornei*, reproduction factor, SCAR primers, taxonomic diversity, tuber rot.

Potato (*Solanum tuberosum* L.) is one of the major food crops worldwide and contributes substantially to food security and sustainable agricultural production because of its wide adaptation, high yield potential, nutritional value and diverse uses (Lima *et al*., 2018; Devaux *et al*., 2021). Potato production is affected by several biotic constraints, including fungal, bacterial and viral pathogens, insect pests, weeds and plant-parasitic nematodes (Brodie *et al*., 1993; Jones *et al*., 2013; Lima *et al*., 2018). Plant-parasitic nematodes can feed on roots, stolons and tubers, restrict water and nutrient uptake and facilitate the entry of secondary pathogens through feeding wounds (Jones *et al*., 2013; Lima *et al*., 2018).

Root-lesion nematodes (*Pratylenchus* spp.) are migratory endoparasites that feed within the root cortex, causing necrotic lesions, impaired root function and reduced plant growth (Castillo & Vovlas, 2007; Orlando *et al*., 2020). Among them, *P. neglectus* (Rensch, 1924) is important because of its wide host range, occurrence in diverse cropping systems and adaptation to different ecological conditions (Olthof, 1990; Thompson *et al*., 2008; Orlando *et al*., 2020). *Pratylenchus thornei* (Sher & Allen, 1953) is also associated with many field crops and should be considered in rotation systems (Thompson *et al*., 2008; Orlando *et al*., 2024).

Ditylenchus destructor Thorne, 1945, commonly known as the potato rot nematode, is another important species associated with potato, particularly because it causes tuber discolouration, cracking, spongy tissue, necrosis and rot, leading mainly to tuber quality and storage losses

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(Mwaura *et al*., 2015; EPPO, 2017; CABI, 2021; Song *et al*., 2023). Its ability to be disseminated through infested tubers makes healthy seed tubers and storage hygiene important components of nematode management (EPPO, 2017; Cheng *et al*., 2019).

In Türkiye, previous studies on nematodes associated with potato production areas have reported *D. destructor* from potato in Erzurum Province (Yüksel, 1978), plant-parasitic nematode genera including *Pratylenchus* spp. in potato fields of Bolu Province (İmren, 2018) and *Meloidogyne* spp. and *Globodera* spp. from İzmir and other production regions (Özarslandan *et al*., 2009; Demirbaş Pehlivan *et al*., 2020; Evlice, 2021). However, information remains limited for high-altitude and cool-climate potato production regions such as Erzurum, particularly regarding species-level nematode fauna, distribution of economically important species and locally applicable management options.

The objectives of this study were: *i*) to determine the plant-parasitic nematode species associated with potato production areas in Erzurum Province using morphological and morphometric methods; *ii*) to confirm selected economically important species using species-specific molecular markers; *iii*) to determine the frequency and population density of these species; and *iv*) to evaluate the effect of fluopyram on population development of *P. neglectus* and *D. destructor* in the potato cultivars 'Agria', 'Granola' and 'Marfona' under field conditions.

Materials and methods

Survey and soil sampling

The survey material consisted of soil samples collected from potato production areas in Erzurum Province, Türkiye, during 2021-2023. A total of 213 soil samples were collected from 14 potato-growing districts; the district-level sample distribution and the number of samples positive for plant-parasitic nematodes are presented in Supplementary Table S1. The survey fields were selected based on location and coordinate information on potato-growing areas obtained from the Erzurum Provincial Directorate of Agriculture and Forestry. Soil samples were collected following a Z-shaped sampling pattern within each field. Sampling was conducted between June and September, covering different developmental stages of potato plants. Wheat, sunflower and sugar beet are commonly grown in rotation with potato in the study region.

Soil samples were taken from 0-30 cm depth to represent the feeder-root zone of potato plants. In each field, 15-25 subsamples were collected and combined to form an approximately 1 kg composite soil sample. Soil samples were placed in labelled polyethylene bags and transported to the laboratory on the day of collection. Nematode extraction was initiated within 24 h and completed by the end of the third day. The nematodes recovered following extraction were stored at 4°C for approximately 2 weeks.

Soil properties of the field trial site

A soil sample from the field trial site was analysed to determine physical and chemical properties. Selected soil properties of the field site are presented in Supplementary Table S2. The soil had a clay loam texture, pH 7.5 and electrical conductivity of 0.48 mS cm^{-1}. These properties were used as supporting environmental information for interpreting nematode population development and field performance of fluopyram.

Nematode extraction

Mobile plant-parasitic nematodes were extracted from 100 g soil using the modified Baermann funnel technique for 48 h (Hooper *et al*., 2005). To recover sedentary forms, including cyst nematodes, a separate 250 g soil subsample was processed by Cobb sieving (Cobb, 1918) through 18-, 50-, 100- and 200-mesh sieves, corresponding to nominal aperture sizes of 1000, 300, 150 and 75 μm, respectively; the material retained on the 200-mesh sieve was collected for examination. Nematode suspensions were adjusted to a known volume and counted under a microscope. Population densities of vermiform nematodes were expressed as individuals per 100 g soil.

Morphological and morphometric identification

Permanent nematode slides were prepared using the TAF-glycerol method (Seinhorst, 1959; De Grisse, 1969). Morphological and morphometric observations were made using a ZEISS Scope A1 research microscope. Depending on specimen availability and condition, two to ten adult females were measured per species. For the three target species, eight *P. neglectus*, seven *P. thornei* and ten *D. destructor* females were measured. Species identification was based on diagnostic characters including body shape, lip region, stylet, pharyngeal region, lateral lines,

vulva and tail morphology, together with morphometric measurements (Siddiqi, 2000; Castillo & Vovlas, 2007).

Molecular identification

Among the morphologically identified species, populations of *P. neglectus*, *P. thornei* and *D. destructor* were subjected to species-specific PCR assays because of their economic importance. DNA was extracted from morphologically identified specimens using the High Pure PCR Template Preparation Kit. Species-specific SCAR primers used for molecular identification are listed in Supplementary Table S3. Molecular confirmation has been shown to improve identification reliability in *Pratylenchus* species (Waeyenberge *et al*., 2000; Oliveira *et al*., 2017; Orlando *et al*., 2024).

The primer pairs PNEG-F1/D3B5, PTHO/D3B and D1/D2 were used for *P. neglectus*, *P. thornei* and *D. destructor*, respectively (Al-Banna *et al*., 2004; Liu *et al*., 2007; Yan *et al*., 2008; Song *et al*., 2023). Each 20 μl PCR reaction contained 4 μl of 5X PCR Master Mix (Solis BioDyne), 2 μl of DNA template, 0.5 μl of forward primer, 0.5 μl of reverse primer and 13 μl of nuclease-free water. The same thermal cycling programme was used for the three target species, with conditions adapted from published molecular identification methods (Al-Banna *et al*., 2004; Liu *et al*., 2007; Yan *et al*., 2008; Subbotin *et al*., 2011). Amplification involved initial denaturation at 95°C for 3 min, followed by 35 cycles including denaturation at 95°C for 30 s and annealing at 57°C for 40 s, with a final extension at 72°C for 7 min.

Amplification products were separated by electrophoresis on 1.5% agarose gels prepared in 1× TAE buffer and run at 80 V for 45 min, stained with ethidium bromide and evaluated using a 100 bp DNA Ladder (Invitrogen, Thermo Fisher Scientific). Species assignments were supported only when the morphological and morphometric diagnosis agreed with a species-specific amplicon of the expected size.

Field trials and fluopyram application

Field trials were conducted during the 2022 and 2023 growing seasons in a potato field in Ebsemce village, Pasinler district, Erzurum Province, where *P. neglectus* and *D. destructor* were detected at relatively high population densities. The potato cultivars 'Agria', 'Granola' and 'Marfona' were selected because they are commonly cultivated in Erzurum Province and represent local potato production practices. Certified seed tubers of all three potato cultivars were used in the field trials.

The experiment was established as a split-plot arrangement within a randomised complete block design with three cultivars, two treatments (control and fluopyram) and five replications, giving a total of 30 plots. Fluopyram and control were assigned to main plots and the three cultivars were arranged as subplots within each block. The location of the field trial site in Ebsemce village, Pasinler district, Erzurum Province, together with the split-plot experimental layout and a general view of the field trial area, is shown in Figure 1.

Planting was performed on 10 May 2022 and 28 May 2023 and harvest was carried out in October in both growing seasons. Each plot was 14 m^2, consisted of four rows and each row contained 14 tubers. Row spacing was 70 cm and intra-row spacing was 35 cm. Seed potato tubers were placed manually into planting holes approximately 15 cm deep, maintaining a spacing of 35 cm between consecutive tubers within each row. The total experimental area was 999 m^2.

Two treatments were included: fluopyram and control. The commercial nematicide Velum Prime® SC 400 was applied directly to the soil before planting the seed potato tubers, using an 18 l backpack sprayer at a dose of 120 ml da^{-1}. A total of 18 l of spray solution was applied to 15 treated plots, each measuring 14 m^2, corresponding to a spray volume of 85.7 l da^{-1}. Control plots received water only. Initial (P_i) and final (P_f) nematode population densities were determined using the soil sampling and extraction procedures described previously. Soil samples for P_i determination were collected prior to fluopyram application, whereas those for P_f determination were collected 14 days before tuber harvest to avoid potential disturbance of nematode distribution associated with harvesting.

The nematode reproduction factor (RF) was calculated as the ratio of the final (P_f) to the initial (P_i) population density ($RF = P_F/P_i$), with $RF > 1$ indicating population increase and $RF < 1$ indicating population decline. Weeds were removed manually throughout the experimental period and no disease control treatments were applied. The experimental field was irrigated using surface (flood) irrigation. Tuber yield and the incidence or severity of visible tuber symptoms were not quantitatively assessed in this trial.

Data evaluation and statistical analysis

Survey results were evaluated based on occurrence, frequency and population density of plant-parasitic nema-

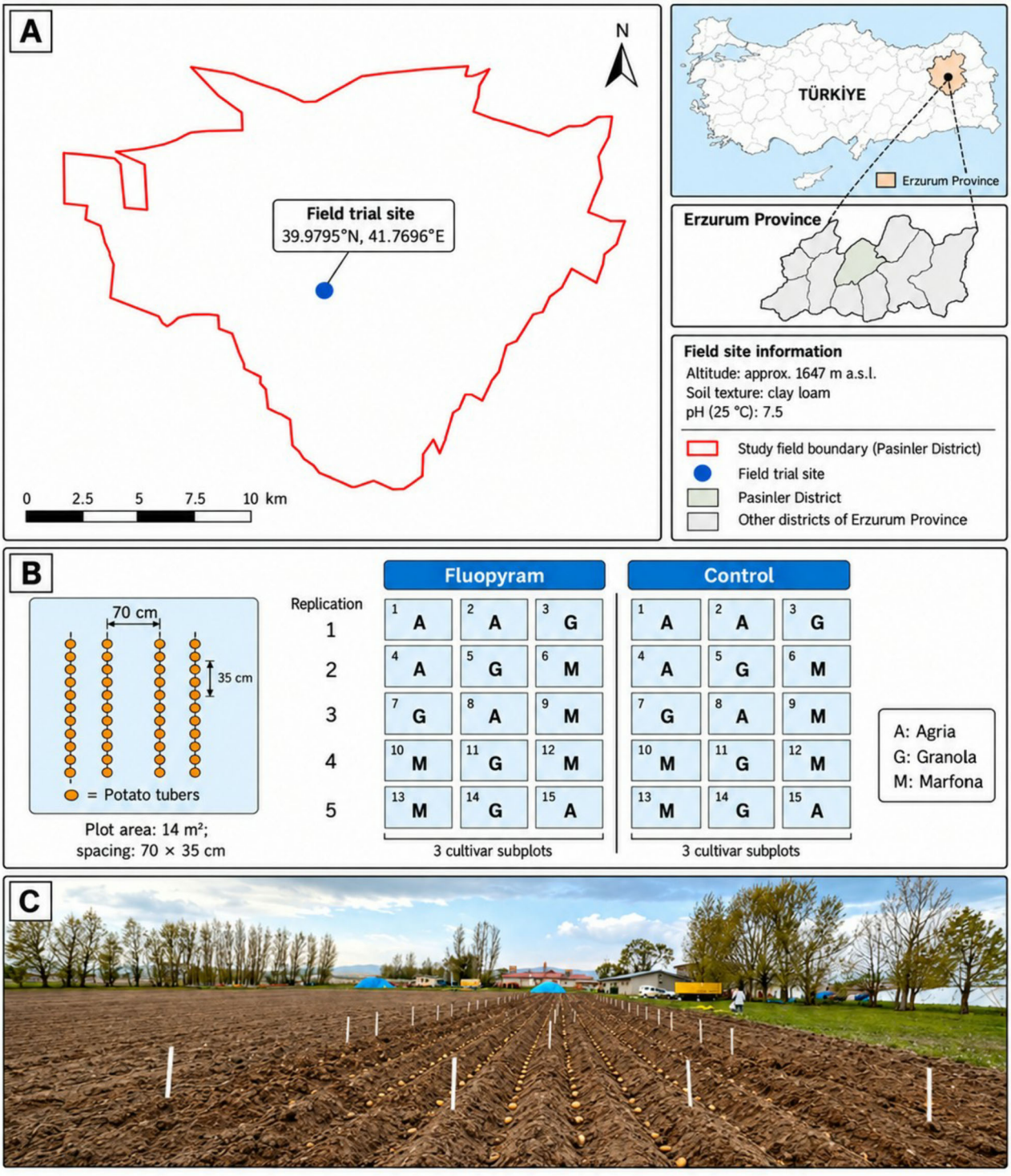

Fig. 1. Location and experimental layout of the potato field trial in Ebsemce village, Pasinler district, Erzurum Province, Türkiye. A: Geographic location of the field trial site; B: Split-plot arrangement of three potato cultivars under control and fluopyram treatments with five replications. C: General view of the experimental field area.

tode species. Frequency (%) was calculated as the number of samples in which a species was detected divided by the total number of samples examined, multiplied by 100. Population densities were expressed as individuals (100 g soil)$^{-1}$.

The 2022 and 2023 data were analysed separately by analysis of variance in accordance with the split-plot design, with treatment as the main-plot factor, cultivar as the subplot factor and block as the replication term. Statistical analyses were conducted using SPSS version 16.0. To account for plots with zero initial nematode populations (P_i), changes in nematode populations were analysed using the logarithmic transformation $\ln((P_f + 1)/(P_i+1))$ (Wang *et al*., 2000; Kessler & Koehler, 2023). For each treatment-cultivar combination, the nematode RF was calculated as the ratio of the mean final population density (P_f) to the mean initial population density (P_i).

Results

Plant-parasitic nematode species detected in potato production areas of Erzurum Province

Plant-parasitic nematodes were detected in 186 of the 213 soil samples collected from potato production areas of Erzurum Province. The distribution of samples by district and the number of positive samples are given in Supplementary Table S1.

Morphological and morphometric examinations identified 17 plant-parasitic nematode species belonging to ten genera and seven families within Tylenchida. Cyst nematodes were not detected in the examined samples. The species detected are listed in Table 1 and morphometric measurements of the three focal species are presented in Table 2. Diagnostic morphological characters of the focal species are shown in Supplementary Figure S1 and those of the remaining species are shown in Supplementary Figure S2.

Table 1. Plant-parasitic nematode species detected in potato production areas of Erzurum Province, Türkiye.

Genus	Species detected
Pratylenchus	*P. neglectus*, *P. thornei*
Ditylenchus	*D. destructor*, *D. myceliophagus*
Pratylenchoides	*P. alkani*, *P. erzurumensis*, *P. leiocauda*
Paratylenchus	*P. projectus*
Paratrophurus	*P. acristylus*, *P. striatus*
Helicotylenchus	*H. digonicus*, *H. pseudorobustus*
Merlinius	*M. brevidens*, *M. microdorus*
Rotylenchus	*R. cypriensis*
Trophurus	*T. imperialis*
Zygotylenchus	*Z. guevarai*

Because of their economic importance, *P. neglectus*, *P. thornei* and *D. destructor* were evaluated in detail. Their morphological characters and morphometric ranges were consistent with the diagnoses used in this study (Suppl. Fig. 1; Table 2). Species-specific PCR products of the expected sizes provided an independent line of support (Fig. 2) and further population-level amplification results are shown in Supplementary Figure S3.

Frequency and population density of economically important species

In the current survey, the highest frequency of *Pratylenchus neglectus* (87.5%) and its highest population density were recorded in Yakutiye district (Fig. 3). *Pratylenchus thornei* showed a more limited distribution but reached notable frequency and density values in Palandöken district. *Ditylenchus destructor* was most frequent in Pasinler district, whereas the highest population density was recorded in Yakutiye district. The district-level occurrence frequencies and population densities of *P. neglectus*, *P. thornei* and *D. destructor* across the 14 surveyed districts are presented in Figure 3. These findings indicate that *P. neglectus*, *P. thornei* and *D. destructor* should be considered in regional nematode management in potato production areas of Erzurum Province.

Photographs of symptomatic potato tubers collected during the field trial are provided in Supplementary Figure S4. Internal tissue discolouration, necrotic lesions and white mealy areas were observed in symptomatic tuber tissues. These symptoms were observed in tubers collected from the experimental field in Ebsemce village, Pasinler district; their incidence was not quantified and the photographs alone do not establish causation by a particular nematode species.

Effect of fluopyram on *P. neglectus* and *D. destructor* populations

The RF-based field assessment showed a consistent treatment pattern for *P. neglectus*. In control plots, RF values were above 1 in all cultivar-year combinations. In fluopyram-treated plots, RF values remained below 1 in every combination, indicating that population increase was not sustained under the treated conditions. Year- and cultivar-specific RF values are shown in Figure 4A, B. In Figure 4, descriptive year-specific values are presented as

Table 2. Morphometric measurements of adult females of the three focal plant-parasitic nematode species from Erzurum Province, Türkiye.

Character	*Pratylenchus neglectus*	*Pratylenchus thornei*	*Ditylenchus destructor*
n	8	7	10
L (μm)	395.5 ± 28.3 (365-452)	515.9 ± 61.2 (414-595)	930.7 ± 107.5 (753-1030)
a	24.2 ± 1.8 (21.9-26.6)	29.6 ± 3.2 (25.9-31.6)	34.77 ± 1.4 (31.4-36.4)
b	6.4 ± 0.7 (5.6-7.2)	7.1 ± 0.4 (6.7-7.7)	5.12 ± 1.2 (4.0-6.5)
b′	–	4.5 ± 0.5 (4.0-5.1)	–
c	18.3 ± 2.7 (14.6-22.6)	19.0 ± 2.2 (15.5-21.5)	15.56 ± 1.3 (13.7-17.3)
c′	2.2 ± 0.3 (1.8-2.5)	2.3 ± 0.2 (2.0-2.6)	3.8 ± 0.4 (3.1-4.2)
Stylet (μm)	16.9 ± 1.0 (15.5-18.0)	17.2 ± 0.6 (16.0-18.0)	11.7 ± 0.5 (11.0-12.0)
Tail (μm)	–	27.1 ± 2.0 (24-30)	59.7 ± 2.7 (55-62)
V (%)	83.075 ± 1.9 (80.0-85.9)	75.7 ± 1.8 (72.5-78.1)	79.66 ± 2.5 (76.5-84.2)
PUS (μm)	–	–	82.9 ± 6.1 (75-89)
PUS/VA (%)	–	–	72.77 ± 6.4 (67.9-87.9)
PUS/VBW	–	–	3.25 ± 0.3 (2.4-3.5)

Values are mean ± SE (range). L: stylet, tail and post-uterine sac (PUS) are expressed in μm; VA: vulva-to-anus distance; VBW: body width at the vulva; –: not recorded.

mean ± standard error; the error bars represent variability among field replicates. Statistical letters in Figure 4 refer to the overall treatment main effect pooled across cultivars and not to separate within-cultivar tests. The corresponding P_i, P_f and RF values are presented in Supplementary Table S4. Year-specific ANOVA revealed a significant overall fluopyram treatment effect on *P. neglectus* population change in both 2022 ($P = 0.04998$) and 2023 ($P = 0.03792$). By contrast, the overall treatment effect on *D. destructor* was not statistically significant in either 2022 ($P = 0.23893$) or 2023 ($P = 0.05779$). No significant cultivar effects or treatment × cultivar interactions were detected for either nematode species in either growing season ($P > 0.05$).

The RF pattern for *D. destructor* was less consistent. In fluopyram-treated plots, RF values were above 1 in all cultivars in 2022 but below 1 in all cultivars in 2023. Thus, the direction of population change differed between growing seasons. Year- and cultivar-specific RF values are shown in Figure 4C, D and the corresponding P_i, P_f and RF values are presented in Supplementary Table S4.

Discussion

This study showed that potato production areas in Erzurum Province harbour a diverse plant-parasitic nematode fauna and that several economically important species should be considered in regional production systems. The detection of plant-parasitic nematodes in 186 of 213 samples indicates that nematode infestation is widespread in the surveyed potato fields.

The identification of 17 plant-parasitic nematode species belonging to ten genera and seven families demonstrates that potato fields in the region provide suitable host and ecological conditions for several nematode genera. Worldwide, important nematode genera associated with potato include *Pratylenchus*, *Ditylenchus*, *Meloidogyne* and *Globodera* (Brodie *et al*., 1993; Jones *et al*., 2013; Lima *et al*., 2018; Orlando *et al*., 2020). Previous studies conducted in Türkiye have also reported the occurrence of different plant-parasitic nematode genera in potato fields, with variable frequencies and population densities (İmren, 2018; Demirbaş Pehlivan *et al*., 2020; Evlice, 2021). For example, *Pratylenchus* spp. were among the dominant nematodes in potato fields in Bolu Province, whereas *Meloidogyne* spp. and *Globodera* spp. have been reported from İzmir and other production regions (İmren, 2018; Demirbaş Pehlivan *et al*., 2020; Evlice, 2021). The absence of cyst nematodes in the present study indicates that *Globodera* species were not detected in the sampled fields and sampling period, but continued regional monitoring remains necessary.

Nematode morphology, morphometrics and species-specific PCR assays were used in the identification of *P. neglectus*, *P. thornei* and *D. destructor* in the current study. Morphology remains essential in nematode identification, whereas molecular assays provide an additional line of evidence in genera such as *Pratylenchus* and *Ditylenchus*, which include closely related species with over-

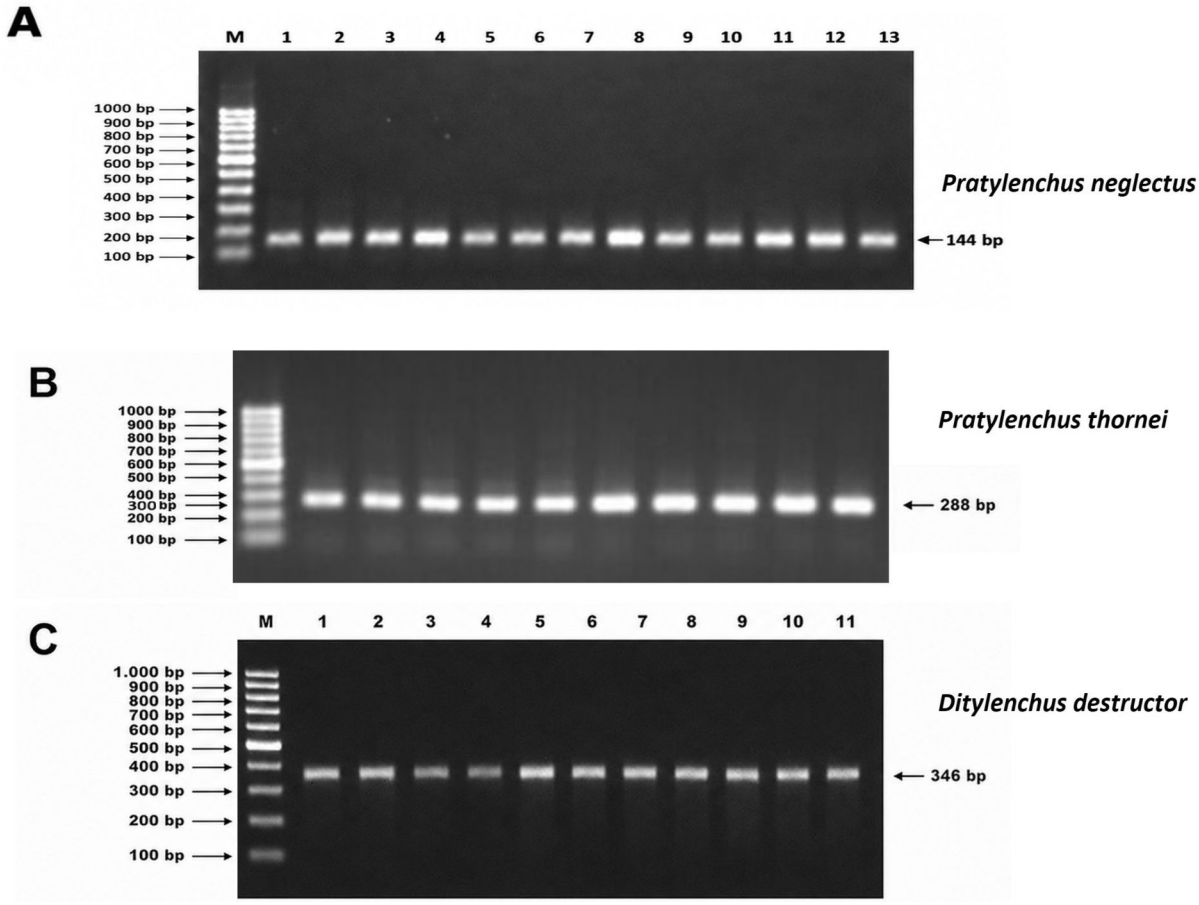

Fig. 2. Species-specific PCR amplification products of economically important plant-parasitic nematode species detected in potato production areas of Erzurum Province. A: *Pratylenchus neglectus* amplified with PNEG-F1/D3B5 primers, showing a 144 bp product; M: 100 bp DNA Ladder; lanes 1: Aşkale; 2-5: Aziziye; 6-9: Palandöken; 10-13: Yakutiye. B: *Pratylenchus thornei* amplified with PTHO/D3B primers: showing a 288 bp product; M: 100 bp DNA ladder; lanes 1-10: Pasinler. C: *Ditylenchus destructor* amplified with D1/D2 primers, showing a 346 bp product; M: 100 bp DNA Ladder; lane 1: Aşkale; lanes 2-4: Aziziye; lanes 5-7: Palandöken; lanes 8-11: Yakutiye.

lapping morphological characters (Waeyenberge *et al*., 2000; Oliveira *et al*., 2017; Song *et al*., 2023; Orlando *et al*., 2024).

The widespread detection of *P. neglectus* suggests that this species may be an important species in potato production in Erzurum. *Pratylenchus* species are migratory endoparasites that feed in root tissues, causing necrotic lesions, reduced root function and impaired plant growth (Castillo & Vovlas, 2007; Orlando *et al*., 2020). *Pratylenchus neglectus* can reproduce on potato and may cause yield losses under certain conditions (Olthof, 1990). In field microplot experiments, Olthof (1990) reported reductions in potato tuber number and weight at an initial density of 11.5 *P. neglectus* individuals (100 g soil)$^{-1}$. The highest population density recorded in the present survey (87.5 individuals (100 g soil)$^{-1}$ in Yakutiye) exceeded this experimental value, indicating potential agronomic relevance. However, differences in experimental conditions and sampling procedures should be considered when interpreting this comparison. Its broad host range and ability to persist in different cropping systems can complicate management.

Pratylenchus thornei showed a more limited distribution than *P. neglectus*, but the frequency and population density values recorded in Palandöken district suggest that it should not be ignored at the regional scale. Therefore,

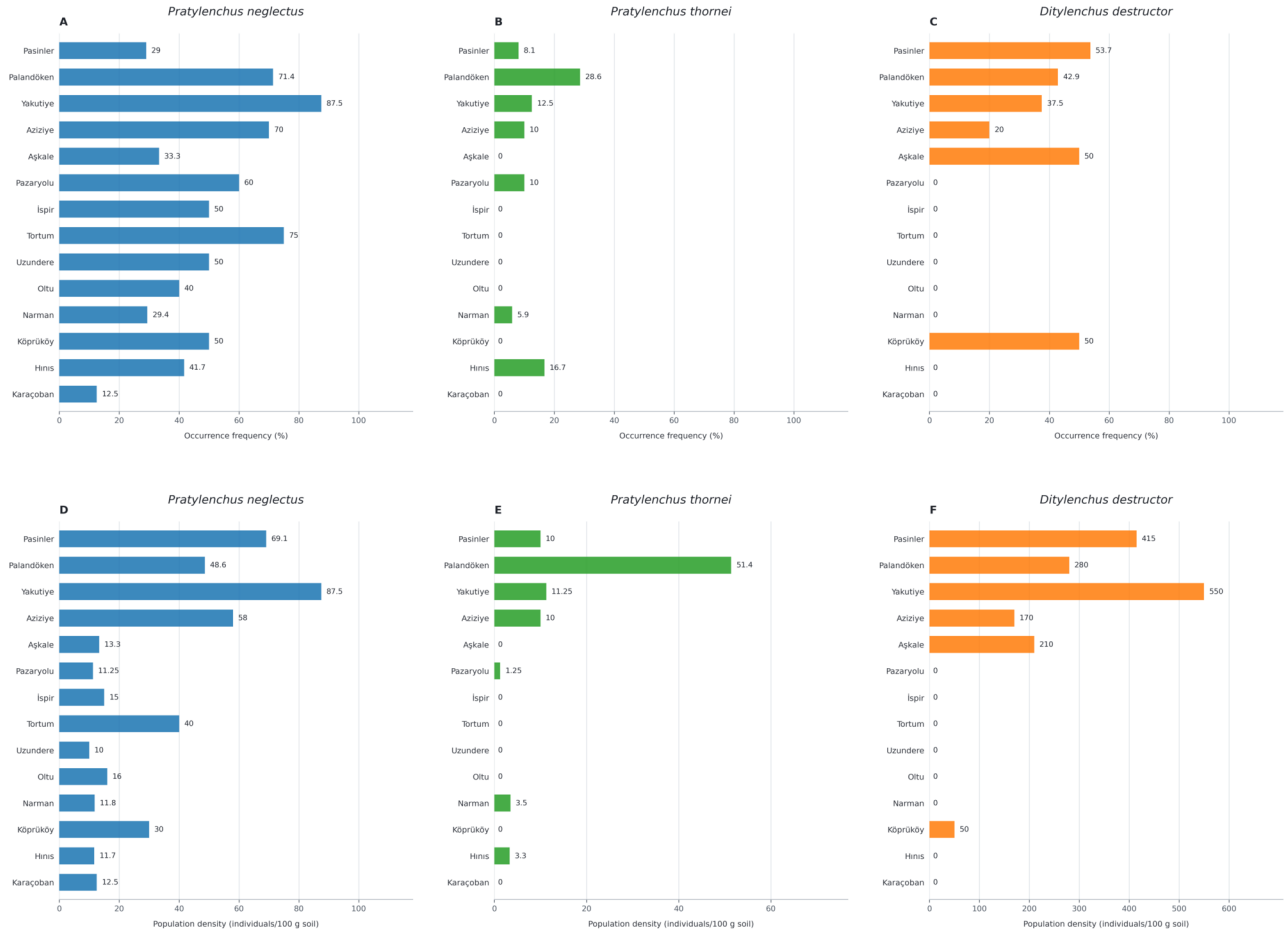

Fig. 3. Occurrence frequency (%) and population density (individuals per 100 g soil) of economically important plant-parasitic nematode species across 14 potato-growing districts of Erzurum Province, Türkiye. A-C: occurrence frequencies of *Pratylenchus neglectus*, *P. thornei* and *Ditylenchus destructor*, respectively. D-F: corresponding population densities of the same species. Zero values indicate districts where the respective species was not detected.

the results for *P. thornei* should be interpreted in the context of survey and diagnostic data only. Considering that wheat, sunflower and sugar beet are commonly grown in rotation with potato in the study region, the occurrence of *P. thornei* highlights the importance of considering the host suitability of rotation crops in regional nematode management. Previous studies have demonstrated differences in the host suitability of wheat cultivars for *P. thornei* (Duman *et al*., 2021). By contrast, relatively few *P. thornei* individuals were recovered from sunflower and sugar beet roots under experimental conditions (Di Vito *et al*., 2002). Similarly, Owen *et al*. (2014) reported relatively low RFs of *P. thornei* in most sunflower cultivars evaluated, highlighting the importance of cultivar selection in crop rotation programmes. These findings suggest that the selection of rotation crops and cultivars should consider their host suitability for this nematode.

Ditylenchus destructor is especially important for potato tuber quality. The symptoms observed in the present study were consistent with typical damage associated with this species, including internal discolouration, spongy tissue, cracking, necrotic areas and rot (Yüksel, 1978; Mwaura *et al*., 2015; EPPO, 2017; CABI, 2021; Song *et al*., 2023). The highest population density of *D. destructor* recorded in the present survey was 550 individuals (100 g soil)$^{-1}$ in Yakutiye district. Previous experimental research demonstrated that increasing initial populations of *D. destructor* were associated with greater external and

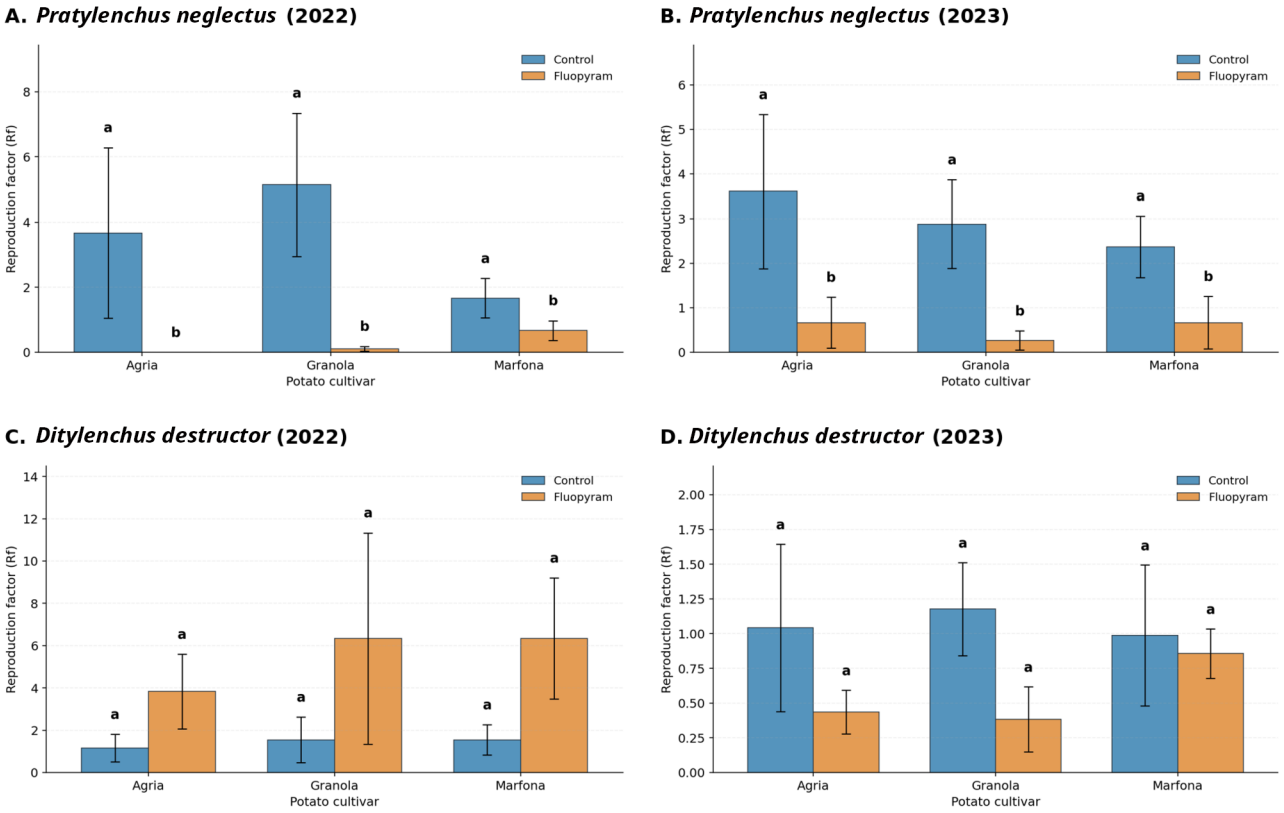

Fig. 4. Reproduction factor (RF) values of *Pratylenchus neglectus* and *Ditylenchus destructor* in 'Agria', 'Granola' and 'Marfona' potato cultivars under control and fluopyram treatments. A: *P. neglectus* (2022); B: *P. neglectus* (2023); C: *D. destructor* (2022); D: *D. destructor* (2023). Error bars indicate standard errors (SE). Different letters indicate a significant overall treatment main effect pooled across cultivars within a given year and nematode species ($P < 0.05$).

internal potato tuber rot (Mwaura *et al*., 2015). Although the relatively high density observed in the present survey suggests a potential risk to tuber quality, a direct relationship between nematode density and tuber damage could not be established from the available field observations.

The previous record of potato rot nematode in Erzurum Province by Yüksel (1978) provides an important historical basis for the occurrence of this species in the region. Because *D. destructor* can be disseminated through infested tubers, healthy seed tubers and storage hygiene are critical components of management (EPPO, 2017; Cheng *et al*., 2019). Comparison of the survey results with previously published damage-associated population densities highlights the potential economic importance of the nematode species detected in Erzurum Province. Olthof (1990) reported reductions in potato tuber number and weight at an initial density of 11.5 Pratylenchus neglectus individuals (100 g soil)$^{-1}$. In the present survey, *P. neglectus* population densities ranged from 10 to 87.5 individuals (100 g soil)$^{-1}$ across 14 districts, with the reported experimental damage-associated density exceeded in 12 districts. Similarly, Li *et al*. (2022), citing Butorina *et al*. (2006), reported serious potato damage associated with *D. destructor* densities of 2-5 individuals (100 g soil)$^{-1}$. In our survey, *D. destructor* densities ranged from 50 to 550 individuals (100 g soil)$^{-1}$ in six districts, considerably exceeding previously reported levels. These comparisons indicate that the observed population densities may represent a substantial risk to potato production in the region. Nevertheless, the published values reflect damage-associated population levels rather than universally established economic thresholds. For *P. thornei*, no reliable potato-specific numerical damage threshold was available for comparison.

In the RF-based assessment, fluopyram-treated plots consistently had *P. neglectus* RF values below 1, whereas

control plots had values above 1. This pattern indicates population decline under treatment and population increase in non-treated plots under the conditions of the trial. Fluopyram acts in plant-parasitic nematodes through inhibition of succinate dehydrogenase and has been reported to reduce nematode mobility, root invasion and infection capacity in some species (Faske & Hurd, 2015; Schleker *et al*., 2022). The present findings are restricted to the dose, application timing, cultivars and field conditions evaluated here.

Although numerical differences in RF values were observed among 'Agria', 'Granola' and 'Marfona', ANOVA revealed no statistically significant cultivar effects or treatment × cultivar interactions for either nematode species in either growing season ($P > 0.05$). Further controlled studies across different locations and growing conditions are needed to evaluate potential cultivar-specific responses to nematode infestation and fluopyram treatment.

By contrast, the response of *D. destructor* to fluopyram varied between growing seasons. RF values in fluopyram-treated plots were above 1 for all cultivars in 2022, indicating that nematode population increase was not prevented under the conditions of that season. In 2023, however, RF values were below 1 for all cultivars, indicating a numerical decline in nematode populations; the overall treatment effect was not statistically significant in that year. This year-dependent response may reflect effects of environmental conditions, initial population density, tuber infestation status, nematode biology or other field-specific factors. Previous studies have shown that damage and reproduction of *D. destructor* can be density-dependent and influenced by host tissues and environmental conditions (Švilponis *et al*., 2011; Mwaura *et al*., 2015; Cheng *et al*., 2019).

The close association of *D. destructor* with potato tubers indicates that management based only on soil-applied chemical treatment may not be sufficient under all conditions. Management of this species should integrate healthy seed tubers, exclusion of infested tubers from the production chain, appropriate crop rotation, field sanitation, improved storage conditions and chemical measures when needed (EPPO, 2017; Cheng *et al*., 2019; Song *et al*., 2023).

Overall, fluopyram showed a more consistent suppression of *P. neglectus* than of *D. destructor* under the conditions evaluated. This emphasises the importance of species-level diagnosis and target-specific management strategies. Because the field component was conducted at one naturally infested site, the treatment patterns should be validated across additional locations and population densities. Future studies incorporating root-associated nematode populations and quantitative assessments of tuber yield and disease severity would provide a more comprehensive evaluation of fluopyram efficacy under field conditions. As nematode population densities were determined from soil samples only, *P. neglectus* individuals present within root tissues were not included in the population estimates, potentially resulting in an underestimation of total nematode abundance. Nevertheless, the survey and two-year field assessment provide regional baseline information for high-altitude potato production areas in Erzurum Province and support regular nematode monitoring and integrated management. Regional monitoring programmes should prioritise *P. neglectus*, *P. thornei and D. destructor* in potato production areas of Erzurum Province.

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Author contributions

A.A. contributed to conceptualisation, field survey, sample collection, laboratory analyses, data curation, statistical evaluation, interpretation of results, visualisation and writing of the original draft. İ.H.E. contributed to supervision, methodology, molecular diagnosis, validation of species identification, interpretation of results and critical review of the manuscript. Ö.Ç. contributed to supervision, methodology, project administration, resources, interpretation of results and critical review of the manuscript. All authors read and approved the final manuscript.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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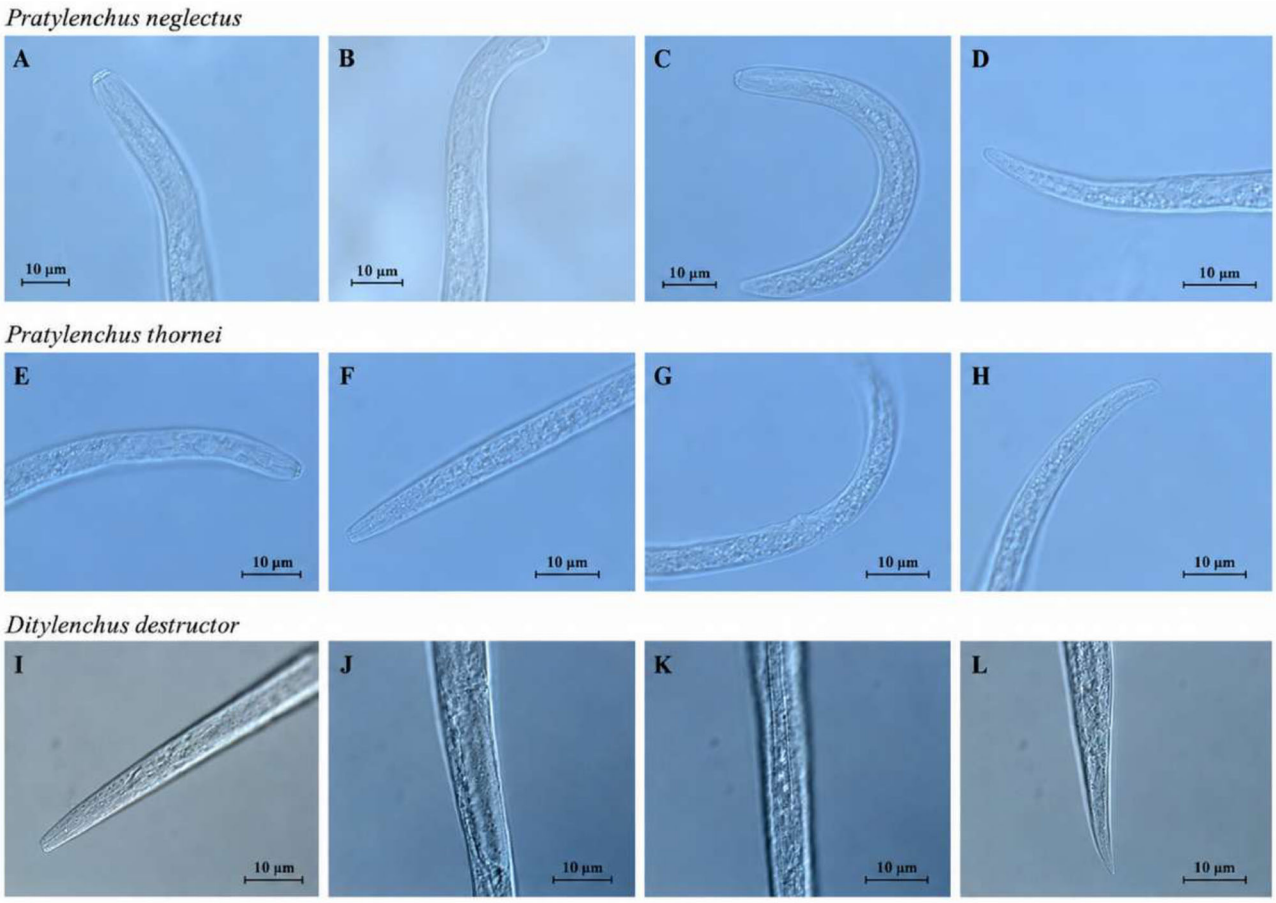
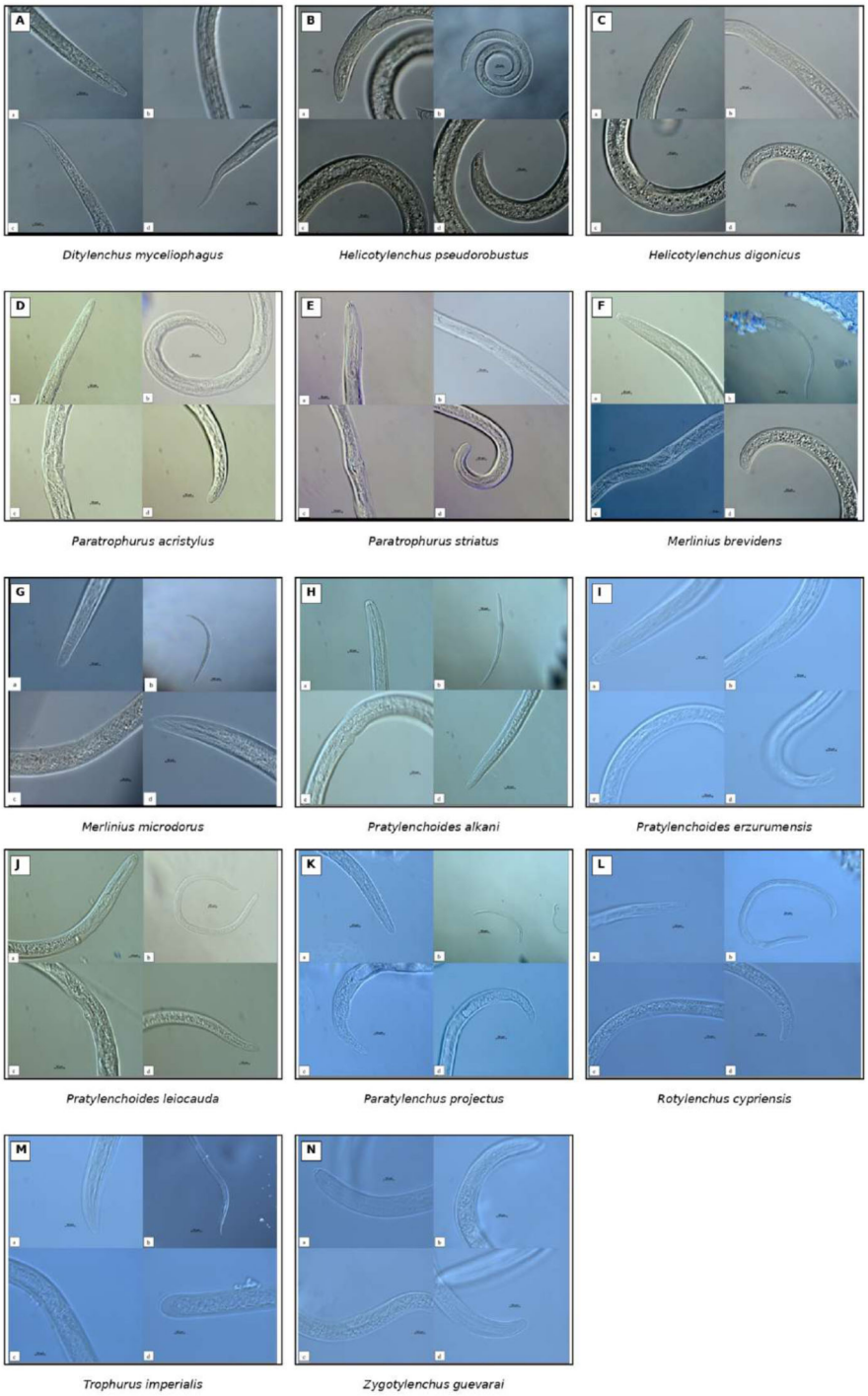
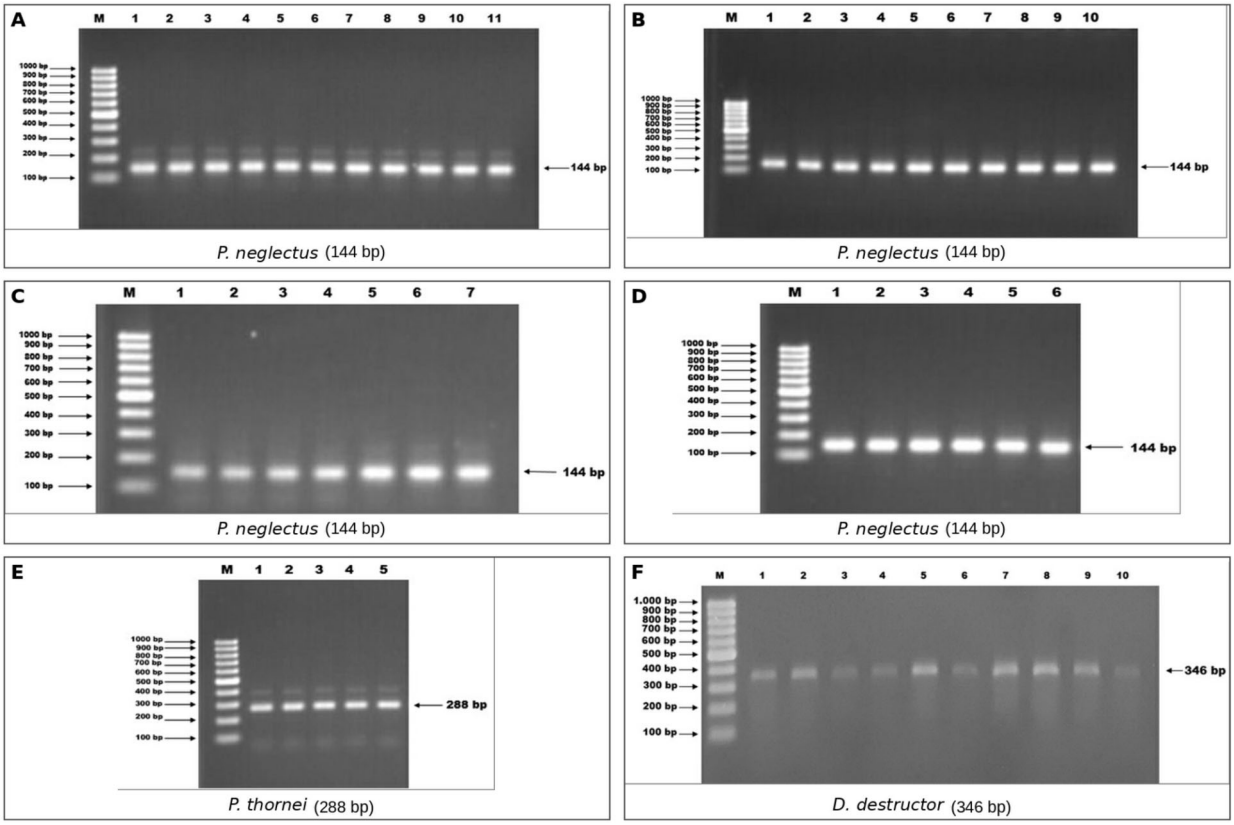


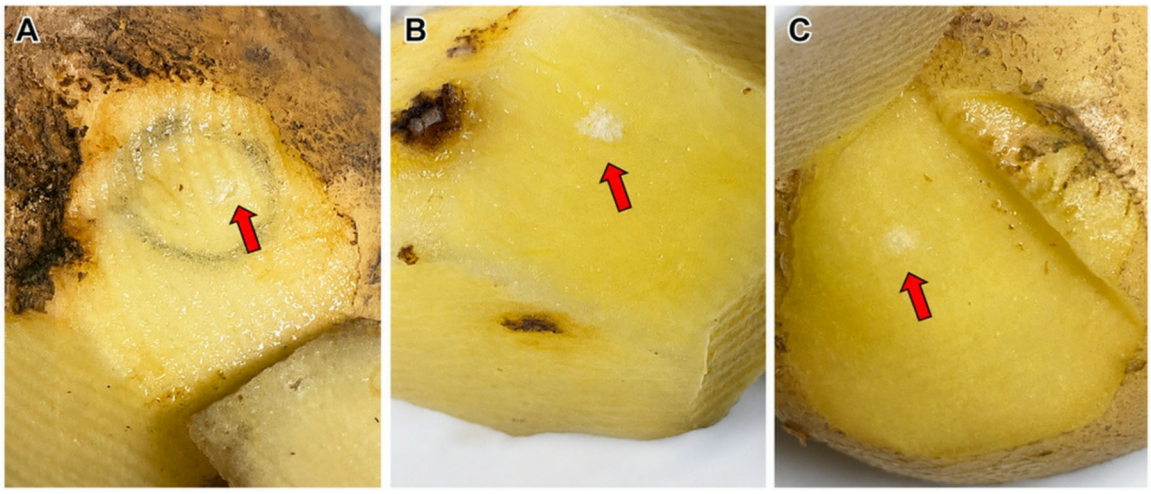
Supplementary Fig. S1. Diagnostic morphological characters of economically important plant-parasitic nematode species detected in potato production areas of Erzurum Province, Türkiye. A-D: *Pratylenchus neglectus*; A: anterior region, lip region and stylet; B: pharyngeal-intestinal junction; C: vulval region; D: tail. E-H: *Pratylenchus thornei*; E anterior region, lip region and stylet; F: pharyngeal-intestinal junction; G: vulval region; H: tail. I-L: *Ditylenchus destructor*; I: anterior region, lip region and stylet; J, lateral lines; K: vulva and post-uterine sac; L: anus and tail. Scale bars = 10 μm.



Supplementary Fig. S2. Diagnostic morphological characters of additional plant-parasitic nematode species detected in potato production areas of Erzurum Province, Türkiye. A: *Ditylenchus myceliophagus*; B: *Helicotylenchus pseudorobustus*; C: *Helicotylenchus digonicus*; D: *Paratrophurus acristylus*; E: *Paratrophurus striatus*; F: *Merlinius brevidens*; G: *Merlinius microdorus*; H: *Pratylenchoides alkani*; I: *Pratylenchoides erzurumensis*; J: *Pratylenchoides leiocauda*; K: *Paratylenchus projectus*; L: *Rotylenchus cypriensis*; M: *Trophurus imperialis*; N: *Zygotylenchus guevarai*. Scale bars = 10 μm.



Supplementary Fig. S3. Additional PCR gel images from survey districts not fully represented in the main Fig. 2. A-D: *Pratylenchus neglectus* (expected product 144 bp): A: lanes 1-2 İspir: 3-6 Pazaryolu: 7-9 Tortum: 10-11 Uzundere; B: lanes 1-9 Pasinler: 10 Köprüköy; C: lanes 1-4 Narman: 5-7 Oltu; D: lanes 1-5 Hınıs: 6 Karaçoban. E: *P. thornei* (expected product 288 bp): lane 1 Aziziye: 2-3 Palandöken: 4-5 Yakutiye. F: *Ditylenchus destructor* (expected product 346 bp): lanes 1-9 Pasinler: 10 Köprüköy; M: 100 bp DNA size marker.



Supplementary Fig. S4. Representative potato tuber symptoms observed in samples from the field experiment. Discolouration, necrotic lesions and pale mealy areas. Red arrows indicate visually symptomatic tissues; the photographs do not independently demonstrate nematode causality.

Supplementary Table S1. Distribution of soil samples collected from potato production areas of Erzurum Province, Türkiye, and number of samples positive for plant-parasitic nematodes.

District	Total number of samples	Number of positive samples
Aşkale	3	1
Aziziye	8	8
Hınıs	9	7
İspir	3	2
Karaçoban	5	4
Narman	11	10
Oltu	7	7
Palandöken	8	7
Pasinler	118	110
Pazaryolu	11	8
Tortum	5	3
Uzundere	2	2
Yakutiye	20	16
Köprüköy	3	1
Total	213	186

Supplementary Table S2. Selected soil properties of the field trial site.

Parameter	Unit	Value
Sand	%	38
Clay	%	34
Silt	%	28
Texture class	–	Clay loam
pH (25°C)	1:2.5	7.5
EC	mS cm-1	0.48
Lime	%	2.9
Organic matter	%	2.97
Nitrogen (N)	%	0.15
Phosphorus (P)	ppm	42.68
Potassium (K)	ppm	813
Calcium (*Ca*)	ppm	3237
Magnesium (Mg)	ppm	423
Sodium (Na)	ppm	217
Exchangeable Na percentage	%	4.15
Iron (Fe)	ppm	9.4
Manganese (Mn)	ppm	12.6
Zinc (Zn)	ppm	22.31
Copper (Cu)	ppm	1.78
Boron (B)	ppm	1.77

Supplementary Table S3. Species-specific SCAR primers used for molecular identification.

Target species	Primer	Sequence (5′ →3′)	Expected amplicon size (bp)	Reference
Pratylenchus neglectus	PNEG-F1	CGC AAT GAA AGT GAA CAA TGT C	*ca* 144	Yan *et al*. (2008)
	D3B5	AGT TCA CCA TCT TTC GGG TC		
Pratylenchus thornei	PTHO	GAA AGT GAA GGT ATC CCT CG	*ca* 288	Al-Banna *et al*. (2004)
	D3B	TCG GAA GGA ACC AGC TAC TA		
Ditylenchus destructor	D2	TGG ATC ACT CGG CGG CTC GTA GA	*ca* 346	Liu *et al*. (2007)
	D1	ACT GCT CTG CGT TTG GCT TCA		

Supplementary Table S4. Initial and final nematode population densities and reproduction factors for *Pratylenchus neglectus* and *Ditylenchus destructor* in the 'Agria', 'Granola' and 'Marfona' potato cultivars during 2022 and 2023.

Year	Cultivar	Species	Control P_i	Control P_f	Control RF	Flu. P_i	Flu. P_f	Flu. RF
2022	'Agria'	*P. neglectus*	36.0 ± 13.3	132.0 ± 46.7	3.67	12.0 ± 4.9	0.0 ± 0.0	0.00
2022	'Agria'	*D. destructor*	52.0 ± 13.9	60.0 ± 31.0	1.15	24.0 ± 14.7	92.0 ± 28.7	3.83
2023	'Agria'	*P. neglectus*	56.0 ± 24.8	202.0 ± 56.5	3.61	36.0 ± 19.4	24.0 ± 14.7	0.67
2023	'Agria'	*D. destructor*	288.0 ± 137.0	300.0 ± 60.3	1.04	220.0 ± 72.1	96.0 ± 51.2	0.44
2022	'Granola'	*P. neglectus*	28.0 ± 23.3	144.0 ± 65.9	5.14	38.0 ± 16.3	4.0 ± 4.0	0.11
2022	'Granola'	*D. destructor*	44.0 ± 25.6	68.0 ± 18.6	1.55	24.0 ± 7.5	152.0 ± 81.4	6.33
2023	'Granola'	*P. neglectus*	40.0 ± 14.1	115.0 ± 27.9	2.88	60.0 ± 20.0	16.0 ± 11.7	0.27
2023	'Granola'	*D. destructor*	204.0 ± 57.4	240.0 ± 28.9	1.18	188.0 ± 83.1	72.0 ± 24.2	0.38
2022	'Marfona'	*P. neglectus*	36.0 ± 13.3	60.0 ± 17.9	1.67	12.0 ± 4.9	8.0 ± 4.9	0.67
2022	'Marfona'	*D. destructor*	44.0 ± 25.6	68.0 ± 18.6	1.55	24.0 ± 7.5	152.0 ± 81.4	6.33
2023	'Marfona'	*P. neglectus*	76.0 ± 7.5	180.0 ± 42.3	2.37	24.0 ± 9.8	16.0 ± 11.7	0.67
2023	'Marfona'	*D. destructor*	316.0 ± 97.8	312.0 ± 84.3	0.99	112.0 ± 23.3	96.0 ± 24.2	0.86

P_i: initial population density; P_f: final population density (individuals (100 g soil)$^{-1}$); RF: mean P_f/mean P_i; Flu.: fluopyram. P_i and P_f values are mean ± SE, whereas RF values are ratios of group means.