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Article

Association of Plant-Parasitic Nematodes and Soil Physicochemical Properties in Tomatoes in Turfloop, Limpopo Province, South Africa

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Abstract: Turfloop constitutes an area in Mankweng, situated in the Limpopo Province of South Africa, where several villages are home to smallholder farmers who specialize in vegetable farming. Among the most crucial crops cultivated in this region is tomato, a fruit that has gained significant commercial importance due to its high demand and versatility in various culinary applications. To determine the relationship of plant-parasitic nematodes and soil physicochemical properties, soil samples were collected from tomato fields. Overall, our results showed that seven nematode genera were in the tomato fields. There was a significant positive correlation between the number of *Meloidogyne* and potassium ($r = 0.903$) and a negative correlation with Na ($r = -0.684$). In contrast, there was no association between the number of *Meloidogyne* spp. and the pH and texture of the fields. The number of *Criconema* in the field was negatively correlated with pH ($r = -0.732$). Soil texture percentages, including clay ($r = 0.744$), sand ($r = -0.744$), and silt ($r = 0.706$), were only correlated with the number of *Criconema*. The number of dagger nematodes, *Xiphinema*, was only correlated negatively with NH_4^+ ($r = -0.589$) and positively with boron (B) ($r = 0.779$). None of the soil variables were correlated with the number of *Pratylenchus*. The principal component analysis (PCA) placed soil samples of tomatoes together, in which the number of *Meloidogyne* was not correlated to any soil sample site. In conclusion, plant-parasitic nematodes that were associated with tomatoes are of high economic importance as they can reduce the yield. *Criconema* was found to be sensitive to the soil's physicochemical properties. In addition, *Helicotylenchus* was found in all soil samples. Our results suggest that the plant-parasitic nematodes in tomatoes have high diversity with the potential to reduce crop production.

Keywords: crop; harmful nematodes; Mankweng; soil properties; yield

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1. Introduction

Soil nematodes are minute and diverse creatures that thrive in all types of soils. These microscopic animals are so abundant that they are often considered the most numerous multicellular organisms on the planet. Their diversity ranges from free-living to plant-parasitic, with an estimated 100,000 different species worldwide. The impact of soil nematodes on soil health and nutrient cycling is immense, making them a crucial component of any healthy soil ecosystem [1].

Plant-parasitic nematodes (PPNs) are soil-borne organisms that subsist on plant tissues. Despite their small size, *Meloidogyne* and *Pratylenchus* can have a significant economic impact by causing a reduction in yield or visual damage, rendering some economic plant products unsuitable for sale. As a result, PPNs represent a significant threat to the agricultural industry, and their control is of utmost importance for sustainable agriculture [2]. The impact of the plant-parasitic nematodes has been recently studied in tomato production in Ethiopia [3], Kenya [4], and South Africa [5]. Jones et al. [6] identified *Meloidogyne* spp. as the most crucial plant-parasitic nematodes due to their ability to significantly impact crop yields. These nematodes, also known as root-knot nematodes, infect plant roots, causing the formation of knots that impede water and nutrient uptake. In South Africa, root-knot nematodes, particularly *M. incognita* and *M. javanica*, are a significant threat to tomato crops [5]. These nematodes can cause stunted growth, reduced fruit production, and even plant death, leading to significant economic losses for farmers.

Tomatoes are a widely cultivated crop in South Africa, grown by commercial and smallholder farmers. Production occurs across all provinces, with Limpopo being the main production area, with about 3590 hectares cultivated to the crop as reported by the Department of Agriculture, Forestry and Fisheries [7]. Turfloop is an area in the Limpopo Province between the towns of Haenertsburg and Tzaneen and has soil and climate well suited for vegetable production. However, little information on how the soil's physical and chemical properties support proliferation of plant-parasitic nematodes is available. Therefore, the aims of the study were (1) to assess the composition of soil plant-parasitic nematodes and (2) to evaluate the correlation between plant-parasitic nematodes and physicochemical properties of tomato fields in Turfloop.

2. Materials and Methods

2.1. Soil Sampling

Soil samples were collected from three different sites of tomato production in Syferkuil (GPS coordinates: 23°51′15.0″ S 29°42′49.0″ E), Turfloop region, Limpopo Province, South Africa (Figure 1). A total of 60 samples were collected, with 20 samples from each location, separately using a simple random technique from 10 to 30 cm below the soil surface. The samples were collected after removing the aboveground plant debris from well-grown and healthy plants. The sampling method ensured we recovered ectoparasitic and endoparasitic plant nematodes present in the root zone and roots. The samples were stored at 4 °C in cooler boxes and then taken to the Nematology laboratory of the Aquaculture Research Unit at the University of Limpopo for processing and identification of the nematodes.

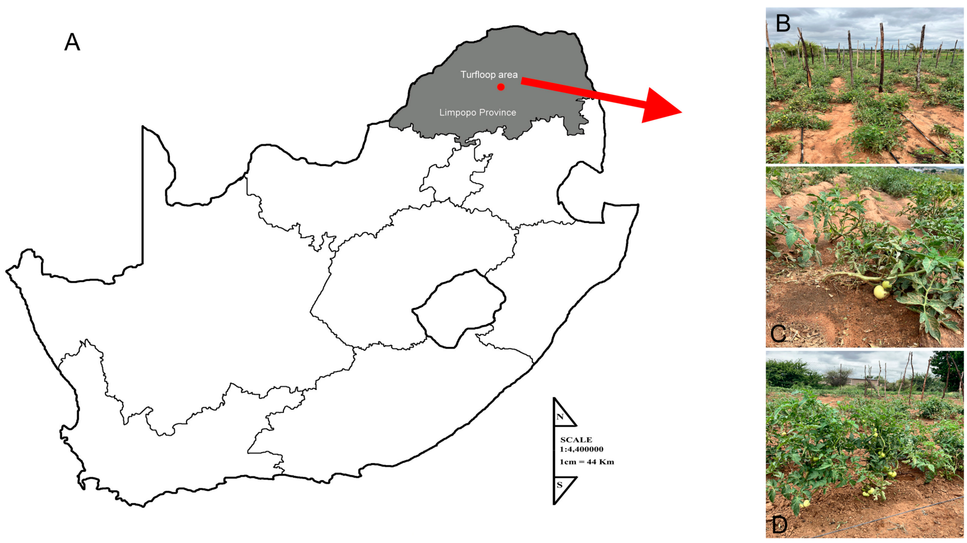

Figure 1. Location of the sampling from tomato fields in Turfloop area, Limpopo Province, South Africa. (**A**): South Africa map, indicating Limpopo Province. (**B**): Site 1, (**C**): site 2, and (**D**): site 3.

2.2. Nematode Identification

Nematodes were extracted from 200 g soil from each location on the same day of collection using a modified tray technique [8]. The nematodes were counted with a stereomicroscope (Zeiss; Discovery V8; Baden-Württemberg, Germany), and their genera identification was finalized using a light microscope (Zeiss, Lab.A1; AX10; Baden-Württemberg, Germany). Nematodes were then fixed with a hot 4% formaldehyde solution and transferred to anhydrous glycerin [9] for species identification. The nematode genera were identified according to the classification provided by Siddiqi [10], and Geraert [11,12]. The light microscope (LM) pictures were taken using a VWR microscope (BL384; Milan, Italy).

2.3. Nematode Community Analysis

Nematode community analysis was carried out through online Nematode Indicator Joint Analysis (NINJA), which is an automated calculation system for nematode-based biological monitoring [13]. The number of nematodes counted for each site was submitted to NINJA. Then, nematode community analysis, including feeding type proportion, and ecological indices, including the sigma maturity index, plant-parasitic index, total biomass, and herbivore footprint, were calculated. Additionally, the percentage of each feeding type for nematodes counted, including sedentary parasites, migratory endoparasites, semi-endoparasites, and ectoparasites as a percentage of total herbivores, were estimated. The sigma maturity index (MI) or plant-parasitic index (PPI) were calculated through NINJA online software [13,14] using the equation below:

$$\text{MI or PPI} = \sum (v_i \times f_i)/n$$

where v_i = colonizer-persister (c-p) value assigned to family, f_i = frequency of family i in sample, and n = total number of individuals in a sample.

Nematode biomass was calculated using the equation below:

$$\mathrm{W} = (\mathrm{L}^3/\mathrm{a}^2)/(1.6 \times 10^6)$$

where W is the fresh weight (μg) per individual, L is the nematode length (μm), and a is the ratio of body length/greatest body diameter (μm).

The herbivore footprint can be calculated as the equation below:

$$\mathrm{F} = \Sigma\ (\mathrm{N_t}\ (0.1\ (\mathrm{W_t}/\mathrm{m_t}) + 0.273\ (\mathrm{W_t}^{0.75})))$$

where $\mathrm{W_t} = (\mathrm{L}^3/\mathrm{a}^2)/(1.6 \times 10^6)$, $\mathrm{N_t}$ = individual numbers of the plant-parasitic nematodes, and $\mathrm{m_t}$ is the plant-parasitic group (P-p) of nematodes.

2.4. Soil Properties Analysis

The Aquaculture Research Unit laboratory conducted an analysis of various chemical properties of soil, including its nutrient levels. The Hach spectrophotometric device from the United States was used to evaluate these properties using the company's prescribed protocol. The pH of the soil was measured using the Thermo Scientific Orion 3 Star pH Benchtop from the United States. The APHA [15] method was employed in analyzing potassium (K), copper (Cu), zinc (Zn), manganese (Mn), boron (B), iron (Fe), sodium (Na), calcium (Ca), and magnesium (Mg) in the samples, using test number EPA 200.7. The determination of ammonium (NH_4^+) was conducted using test number 1.14537.0001 [16]. Results for ammonia and copper were obtained using the USEPA PhosVer 3 [16] method. Spectrophotometry was employed to analyze all soil properties. The soil texture was determined following the procedure outlined by van Capelle et al. [17].

2.5. Relationship of Nematode and Soil Variables

The correlation between the number of plant-parasitic and soil physicochemical properties was studied using Pearson correlation implemented in XLSTAT [18]. In order to examine the connection between several soil factors (including pH, K, Cu, Zn, Mn, B, Fe, Na, Ca, and Mg; the soil texture; and nematodes), a principal component analysis (PCA) was performed, following the methodology of Renčo et al. [19]. The abundance of nematode genera was utilized to arrange the sites through a PCA conducted with XLSTAT [18]. Supplementary variables, representing soil properties, were used to identify the correlation between the abundances of plant-parasitic nematodes and soil variables. Each variable was assigned a score based on the principal components, and the first two components (PC1 and PC2) were utilized to create a two-dimensional plot based on the eigenvalues given by the XLSTAT software.

3. Results

3.1. Analysis of the Nematode Communities

Seven plant-parasitic nematodes belonging to seven genera were identified in the soil samples collected from the three sites in the tomato field surveyed (Table 1; Figure S1). From the overall genera collected, *Helicotylenchus*, *Criconema*, and *Pratylenchus* were observed in all soil samples. In contrast, *Meloidogyne* and *Tylenchorhynchus* were only observed in site 2 and site 1 samples, respectively.

Table 1. Mean abundance of nematode species (per 200 g soil) associated with tomatoes in Turfloop, Limpopo Province, South Africa.

Nematode Genus	Site 1	Site 2	Site 3	P-p Class *	Nematode Lifestyle	Mass, µg
Criconema	8.75	51.3	17.3	3	Herbivores—ectoparasites	0.659
Helicotylenchus	238.8	230	152.5	3	Herbivores—semi-endoparasites	0.294
Meloidogyne	0	22.5	0	3	Herbivores—sedentary parasites	86.985
Pratylenchus	17.5	21.3	27.3	3	Herbivores—migratory endoparasites	0.144
Rotylenchus	2.5	17.5	0	3	Herbivores—semi-endoparasites	0.872
Tylenchorhynchus	2.5	0	0	3	Herbivores—ectoparasites	0.234
Xiphinema	2.5	0	55.5	5	Herbivores—ectoparasites	5.515

* P-p = plant-parasitic class; numbers for the sites are average of nematode density; Mass is the average weight of nematode number per site counted in 200 g soil.

Seven plant-parasitic species (PPNs), namely, *Criconema mutabile*, *Rotylenchus brevicaudatus*, *Tylenchorhynchus* sp., *Meloidogyne incognita*, *Pratylenchus* sp., *Helicotylenchus pseudorobustus*, and *Xiphinema* sp., were identified from the soil samples (Table 1). The plant-parasitic nematodes associated with tomatoes in Turfloop showed that the majority of the nematodes belong to semi endoparasites, namely, *H. pseudorobustus* (Table 1; Figure 2).

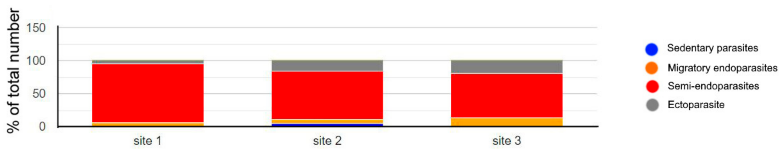

Figure 2. Types of plant-parasitic nematodes associated with a tomato field in Turfloop, Limpopo Province, South Africa.

3.2. Indices of the Nematode Communities

Community analysis revealed no significant differences ($p < 0.001$) in the sigma maturity index, plant-parasitic index, or herbivore footprints among nematode numbers in tested soil samples (Table 2). Changes in the sigma maturity (SMI) and plant-parasitic index (PPI), which shows the abundance of plant-parasitic nematodes representing the vigor status of the host plant, both ranged from 3.0 to 3.2, respectively (Table 2). In contrast, the herbivore footprint, which is energy entering the soil food web via C channels, ranged from 35.2 to 285.1. Total nematode biomass, which is fresh weight (µg) per individual, ranged from 0.1 to 2.1 across all soil samples surveyed in the Turfloop region. The plant-parasitic index was the highest (3.2), as *Criconema*, *Helicotylenchus*, *Pratylenchus*, and *Xiphinema* were found in soil samples (Tables 1 and 2; Figure 3).

Table 2. Nematode community indices, biomass, and plant-parasitic index associated with tomatoes in Turfloop, Limpopo Province, South Africa. Data are presented as averages of the individual per 200 g soil (mean ± S.D).

Index Name	Site 1	Site 2	Site 3	*p* Value
Sigma maturity index	3.0 ± 0.1	3.0 ± 0.0	3.2 ± 0.4	0.413
Plant-parasitic Index	3.0 ± 0.1	3.0 ± 0.0	3.2 ± 0.4	0.413
Total biomass, mg	0.1 ± 0.0	2.1 ± 3.9	0.4 ± 0.6	0.448
Herbivore footprint	35.2 ± 11.4	285.1 ± 481.9	84.5 ± 130.1	0.461
Total number, ind	272.5 ± 65.4	342.5 ± 83.9	252.5 ± 207.4	0.626
Herbivores, % of total	100	100	100	-
Sedentary parasites, % of herbivores	0.0	5.1	0.0	-
Migratory endoparasites, % of herbivores	5.8	6.3	13.3	-
Semi-endoparasites, % of herbivores	89.7	72.4	66.6	-
Ectoparasites, % of herbivores	4.5	16.2	20.1	-
P-p 3, % of herbivores *	99.2	100	89.8	-
P-p 5, % of herbivores	0.8	0.0	10.2	-

* P-p = Plant-parasitic feeding group.

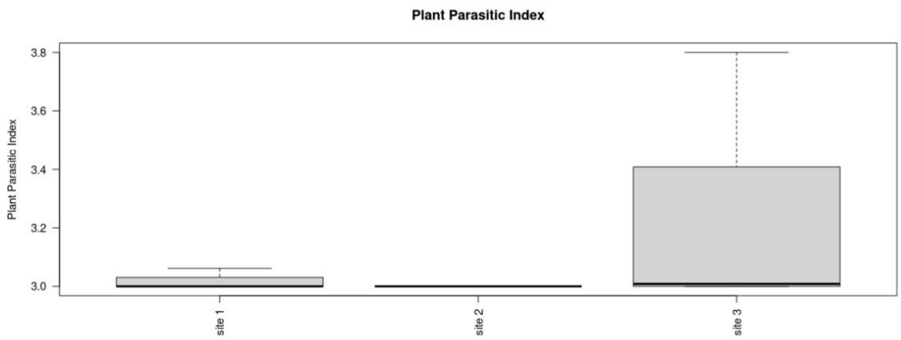

Figure 3. Plant-parasitic index of various species associated with tomatoes in Turfloop, Limpopo Province, South Africa.

3.3. Correlation of Selected Soil Parameters with Nematodes

The results indicated a significant correlation ($p < 0.05$) between clay ($r = 0.744$), sand ($r = -0.744$), silt ($r = 0.706$), and number of *Criconema*. The number of *Rotylenchus* was negatively correlated ($r = -0.800$) with copper (Cu). The number of *Meloidogyne* was negatively ($r = -0.684$) correlated with Na and positively correlated with K ($r = 0.903$). The number of *Xiphinema* was negatively correlated ($r = -0.589$) with ammonium (NH_4^+), whereas it positively correlated ($r = 0.779$) with boron (B). The number of *Helicotylenchus* was positively ($r = 0.534$) correlated with K. Individual numbers of two genera, namely, *Pratylenchus* and *Tylenchorhynchus*, were not correlated strongly with any soil physicochemical properties. The result showed that soil textures had no effect on the nematode community in the soil, except for the numbers of *Criconema* and *Rotylenchus*. pH of the soil showed a negative correlation only with the number of *Criconema* ($r = -0.732$), while other plant-parasitic nematodes did not correlate to the pH of the soils (Figure 4).

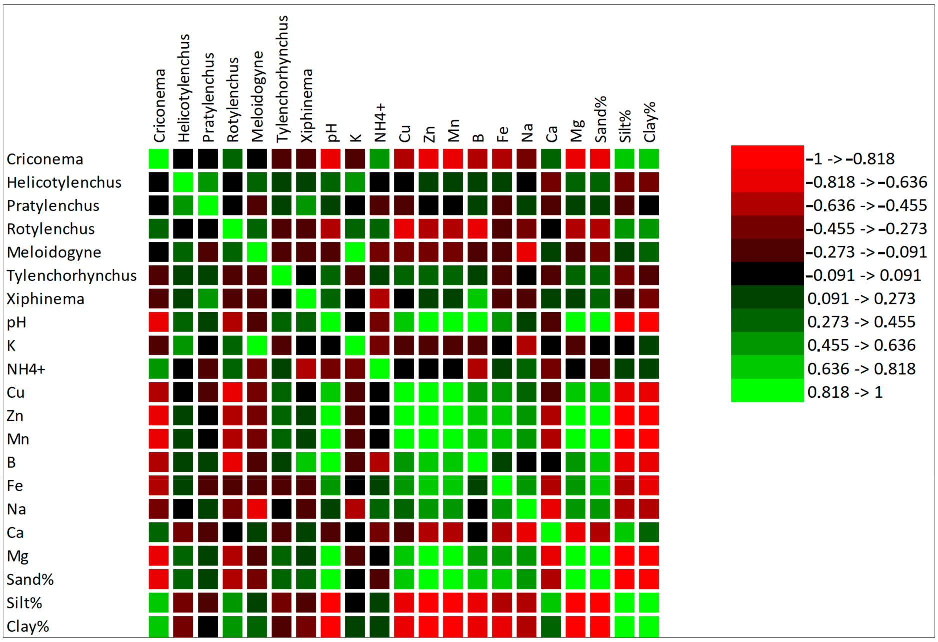

Figure 4. Correlation of soil variables with plant-parasitic nematodes of tomatoes in Turfloop, Limpopo Province, South Africa. [-> indicate the range].

3.4. Correlation of Nematodes and Soil Variables

The results of the analysis of the soil samples collected from each site were subjected to PCA to study the correlation between the individual numbers of nematodes and soil variables. An accumulated variability of 48.4% was observed in the analysis of nematodes and sites, where 26.6% for PC1 and 21.8% for PC2 were detected. The contribution of nematode genera and sites of the study to the PCA indicated that *Helicotylenchus*, *Meloidogyne*, *Rotylenchus*, and *Criconema* were dominant in site 2. In contrast, *Tylenchorhynchus*, *Pratylenchus*, and *Xiphinema* were dominant in the site 1 and site 3 with tomato fields.

The principal component analysis (PCA) (Figure 5) showed that *Criconema* has a negative correlation with sand, whereas a positive correlation with clay and silt was observed. *Pratylenchus* and *Meloidogyne*, as the most destructive nematode in the present study, showed no correlation with soil texture.

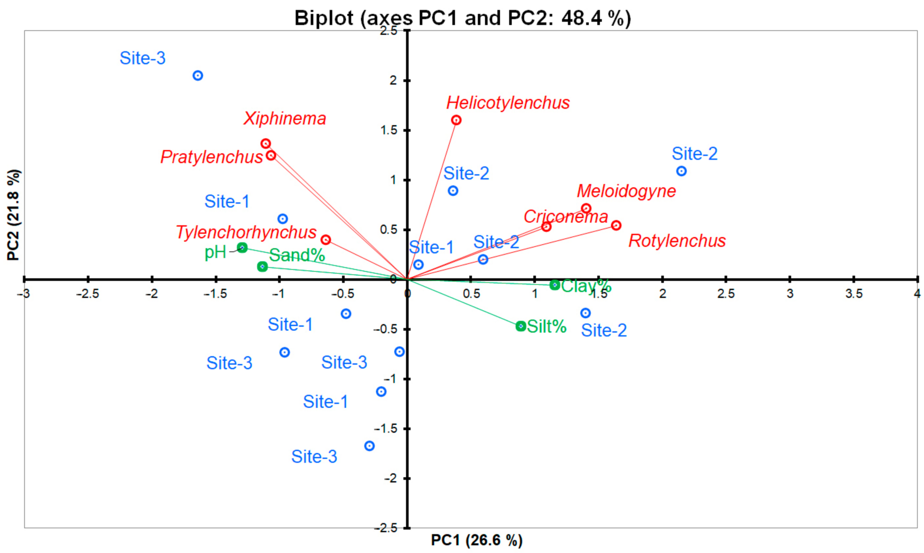

Figure 5. PCA plot of the relationship of the pH and soil texture with plant-parasitic nematodes in the tomato field of Turfloop, Limpopo Province, South Africa.

The PCA plot of the minerals of the soil showed that potassium had a strong affinity with *Meloidogyne*. In contrast, *Criconema* had a negative correlation with Zn, and Mn (Figure 6). *Rotylenchus* had a positive correlation with copper (Cu).

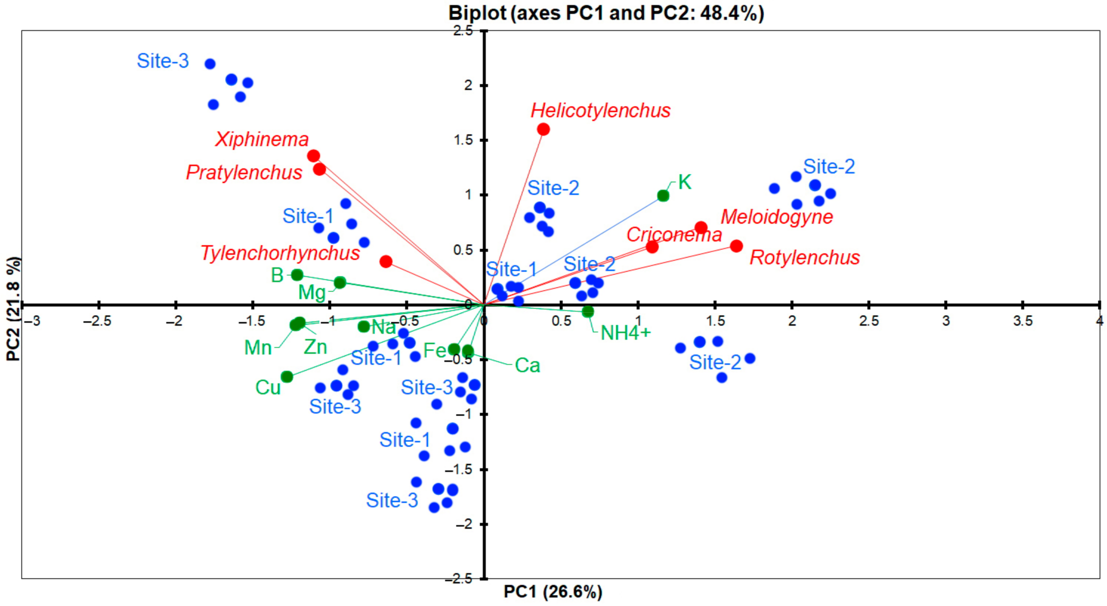

Figure 6. PCA plot of the relationship of the selected soil minerals with plant-parasitic nematodes in the tomato field of Turfloop, Limpopo Province, South Africa.

4. Discussion

Human activities in agricultural systems can have significant impacts on the nematode populations in soil. As such, the physicochemical properties of the soil play a crucial role in regulating the dynamics of these microscopic organisms, which are essential for maintaining the health of the ecosystem. According to the research conducted by Fiscus and Neher [20], nematodes in agricultural systems are highly sensitive to changes in the soil's physical and chemical attributes, which can influence their survival, reproduction, and overall abundance. Plant-parasitic nematodes depend on the host plants to develop their life stages. A healthy and strong plants cause a decrease in plant-parasitic nematode number and their diversity in the soil. Therefore, it is important to carefully manage the soil properties to ensure a healthy and productive agricultural system.

Several studies have delved deep into the influence of the chemical properties of soils affecting plant vigor and consequently affecting the distribution and population density of nematodes. These studies have shown that chemical composition significantly regulates nematode population dynamics by affecting plant health and productivity [5,21].

The SMI and PPI showed changes in plant-parasitic nematodes in the rhizosphere of tomato. However, the result showed that there are no significant differences among the sites studied in relation to the number of plant-parasitic nematodes (Table 2; $p \leq 0.413$). However, ectoparasite and migratory endoparasite (*Criconema* and *Xiphinema*) and ectoparasite (*Pratylenchus*) were higher in site 3 than other sites. That is why the PPI and SMI are higher in site 3. The soil food web is a complex system comprising various trophic levels with different organisms interacting with each other. A high value of the SMI (more than 3) in the soil food web index is an indication of a complex soil food web. In the present study, the SMI values for all sites were 3 or more, indicating that there is a good connectivity and energy flow between the different trophic levels, which includes larger plant-parasitic nematodes, such as *Xiphinema*. Interestingly, this index is less sensitive to enrichment in agricultural soils, meaning that it can help identify healthy soil food webs even in soils that have been heavily impacted by human activities [13]. On the other hand, the PPI indicated the presence of certain nematodes, such as medium and large (semi-) endoparasites like

Meloidogyne or ectoparasitic virus-transmitting nematodes like *Xiphinema*. This means that plant-parasitic nematode assemblages dominate in the soil. Higher values of these nematodes can potentially lead to plant damage and lower crop yields, making it important to monitor their population levels in soil [13].

The herbivore footprint refers to the impact of herbivore nematodes on the soil ecosystem. It is determined by examining the nematode indicators of carbon and energy that enter the soil food web through various channels. These indicators offer insights into the overall health and functioning of the soil ecosystem, as well as the impact of herbivores on the nutrient cycling processes that are necessary for plant growth and ecosystem sustainability. By understanding the herbivore footprint, we can better manage and conserve our soil resources and ensure the long-term health and productivity of our ecosystems. The result of the present study showed that the herbivore footprint is not significant for the sites studied. Therefore, its effect on using soil sources, such as carbon, is not comparable to its effect on soil health and carbon cycling [22]; however, more studies using more samples are recommended.

The results of our study indicate that the pH levels of the soil had no significant correlation with the nematode community. However, our analysis did reveal that the presence of *Criconema* was negatively correlated with higher pH levels, as demonstrated by a high negative correlation with pH in the PCA analysis. Furthermore, previous research by Neher [23] suggests that soil pH may indeed play a critical role in shaping the nematode community in agricultural land. These findings may have important implications for farmers and researchers looking to better understand and manage soil health and biodiversity. Soil pH was also highly correlated with plant-parasitic nematode diversity in France, especially *Meloidogyne* [2]. The acidity or alkalinity of soil, commonly referred to as soil pH, plays a crucial role in determining the availability of nutrients that plants need for growth and development. Soil pH also significantly impacts the composition and activity of microorganisms in the soil, which can either benefit or harm plant growth. Therefore, understanding the role of soil pH in plant–soil interactions is essential for successful agriculture and environmental management. Additionally, Barros et al. [24] showed that pH had no correlation with *Meloidogyne* associated with soybeans in Brazil. The same result was obtained in the present study. In Turfloop, farmers used cow manure, which may change the microorganisms of the soil, and therefore, pH was also affected. The only nematode that was correlated with pH was *Criconema*. This nematode at a high population density may affect crop production. McKenry [25] reported that grape yields in California decrease by 10 to 15% when *Mesocriconema xenoplax* nematode populations exceed 500 individuals per kilogram of soil.

Soil nutrients play a vital role in determining the overall health and growth of plants. This is because they have a secondary impact on the nematode community of the soil, which is closely linked to plant development. As the density of nematodes in the soil increases or decreases, it can have profound implications for the well-being of plants, making it essential to maintain a proper balance of nutrients in the soil.

Potassium (K) is a vital nutrient for plants that has been found to have a positive correlation with *Meloidogyne*, a nematode pest that is associated with tomatoes in Turfloop. The use of potassium phosphite can increase the hatching of *M. exigua* and help in controlling *Heterodera avenae* and *M. marylandi* in wheat and oats [26]. Potassium is naturally present in high concentrations in the cytosol and vacuole as a free ion (K^+) and is known to play a crucial role in enzymatic activation and membrane crossover. Proper plant nutrition with the correct amount of potassium can increase resistance to the penetration and development of pathogens, thus reducing the likelihood of diseases. The increase in plant resistance is mainly due to the thickening of the epidermal cell wall, which boosts the structural rigidity of tissues and provides a physical barrier against pests and other pathogens. Potassium also regulates stomata functioning, which is essential for the exchange of gases between the plant and the environment and promotes rapid recovery of injured tissue. Additionally, the use of potassium fertilizer leads to susceptible plants with a stronger root system and therefore reduces the females of *Meloidogyne* in the root system [27]. It should be noted that potassium was not correlated with other plant-parasitic nematodes of the present study. By increasing the amount of potassium to a specific level (100–250 mg/kg soil; personal communication with commercial farmer), it is possible to reduce the infestation caused by *Meloidogyne* and *Pratylenchus* without causing any harm to the plant.

Copper, symbolized by Cu, is a vital micronutrient required for the healthy growth and development of plants. It plays a crucial role in numerous enzymatic activities, including the synthesis of lignin, an essential component of the plant cell wall. Copper is also necessary for the production of chlorophyll, which gives plants their green color and helps in photosynthesis. Furthermore, copper is essential for the production of healthy seeds, which are crucial for plant propagation and crop yield. A deficiency of copper can lead to various problems in plants, including increased susceptibility to diseases [28]. The result of the present study showed that only *Rotylenchus* had a negative correlation with copper, whereas the rest of the nematodes were not correlated with copper.

Zinc (Zn) is a vital micronutrient for plant growth as it serves as a necessary element for various biological processes such as enzyme functions, metabolic activities, and ion transportation. Additionally, Zn plays a key role in the physicochemical interactions between soil and plants. However, the availability of Zn in soil is often limited, which can negatively impact plant nutrition and growth. This inadequacy can result in a significant decrease in crop yield and the nutrient content of grains. Therefore, ensuring adequate levels of Zn in the soil is crucial for maintaining optimal plant health and maximizing crop production [29]. Application of Zn in pepper showed that the nematode community decreased [30]. The same result was obtained in the present study that *Criconema* was negatively correlated with Zn. In contrast, other plant-parasitic nematodes were not significantly correlated with Zn. Tomato plants were shown to be moderate absorbers of zinc; therefore, a higher zinc level might be needed to adjust to the needs of plants for their proper growth. Recent studies [31] have underscored the importance of providing plants with an appropriate amount of zinc to ensure their healthy growth and proper functioning. In addition, zinc absorbance in plants is correlated with phosphorus, and an excess amount of phosphorus leads to a decreased absorption of zinc [32]. Therefore, constant monitoring of phosphorous and zinc should be implemented in plant production strategies to balance the abovementioned nutrients to ensure healthy plants and less nematode damage in *Meloidogyne* and *Pratylenchus*.

Ammonium (NH_4^+) was shown to have a positive (*Rotylenchus*) or negative (*Rotylenchulus*) correlation with plant-parasitic nematodes [5]. The same result was obtained in the present study with a positive correlation between NH_4^+ and *Rotylenchus*. Other plant-parasitic nematodes were not correlated significantly with NH_4^+. With the increase in NH_4^+ in soil, the available food resources for organisms are compromised. This ultimately results in a toxic environment for nematodes, which can cause significant harm to their population and overall health [33]. When ammonium (NH_4^+), which is a major inorganic form of nitrogen, is applied in excessive amounts, it can lead to a toxic condition in plants known as NH_4^+ toxicity. This condition manifests in various ways, including reduced uptake of potassium (K^+), the yellowing of leaves due to chlorosis, and stunted growth of plants. Therefore, it is essential to ensure proper application of ammonium to prevent toxicity and promote healthy plant growth. In addition, NH_4^+ has the potential to reduce *Meloidogyne* infectivity [27]. Therefore, providing an adequate amount of NH_4^+ is crucial to preventing nematode damage and promoting healthier tomatoes.

According to the findings of the present study, magnesium (Mg) is negatively correlated with the number of *Criconema*. However, other types of plant-parasitic nematodes had no correlation with magnesium. It was observed that the increased levels of Mg and the consequent rise in pH levels significantly interfere with the soil ecosystem, leading to a loss of ecological balance [34]. It is noteworthy that while Mg has been reported to reduce the proliferation of other plant metabolites that protect plants against nematode attacks, it also decreases their prevalence, which could lead to a decrease in the risk of nematode infestations [35]. Magnesium is a vital element for the growth and development of plants. Its presence is crucial in many plant processes, including the synthesis of chlorophyll, the activation of enzymes, the synthesis of proteins, and the transportation of photoassimilates. Without magnesium, plants would struggle to produce the energy they need to survive and grow. Additionally, magnesium plays a critical role in the movement of sugars and other nutrients within the plant. All in all, magnesium is a key component in the complex machinery that keeps plants healthy and thriving [36]. Additionally, magnesium is critical for fruit quality of tomatoes, which impact product marketing. Therefore, using an adequate amount of magnesium can make the tomato healthy and stronger, leading to less damage by *Meloidogyne* as the main cause of yield loss in tomatoes.

The result showed that pH together with Mg, Cu, and Zn were the factors that strongly correlate with all trophic groups of nematodes [34].

Soil textures have been confirmed to have an effect on nematode movement and development [37]. The study showed that sandy soil affects positively carrot growth. In contrast, sandy soil has a lesser effect on the development of *M. hapla* associated with carrots [37]. The same result, that plant-parasitic nematodes movement or development were not affected by sand particles of the soil in tomatoes, except for *Criconema*, was obtained in the present study. *Criconema* moves very slowly in the soil, and, therefore, a negative correlation with sand resulted in the low population of this nematode in the soil.

The research conducted by Sasser [38] indicated that the infestations of *M. incognita* and *M. hapla* are more frequent in sandy loam soils as compared to clay soils. This suggests that the soil type plays a crucial role in the prevalence of these plant-parasitic nematodes. Hence, it is imperative to consider the soil type while devising strategies to combat infestations caused by *M. incognita* and *M. hapla*. The result of the present study showed that there is no correlation between *Meloidogyne* and soil textures. Another survey of tomatoes in South Africa showed that soil textures, including clay, silt, and sand, had no effect on *Meloidogyne* [5]. Moreover, *Rotylenchulus* showed a negative correlation with boron (B). Boron deficiency is related to phenol accumulation in plant tissue [27]. As phenol compounds are one of the plant defense system's mechanisms against nematodes, they might negatively impact *Rotylenchulus* populations. Boron, a trace mineral, plays a crucial role in the growth and development of plants. It is essential for the proper functioning of various physiological processes in plants, including cell wall formation, root development, and reproductive growth. Without boron, plants may experience stunted growth and poor fruit and seed production, and other abnormalities. Therefore, it is important to ensure that plants receive adequate amounts of boron to promote healthy growth and development. Boron (B) had a detrimental effect on the *M. incognita* in grape orchards [39]. Therefore, increasing B in such levels without phytotoxicity is a potentially effective strategy for managing root-knot nematodes in tomato fields.

To ensure a balanced level of soil properties that enhance tomato yield and reduce plant-parasitic nematodes, mineral levels in the soil must be effectively monitored. This results in stronger plants that are less susceptible to infestations by plant-parasitic nematodes. Therefore, by monitoring mineral levels in soil, farmers can ensure that their tomato plants are healthy, robust, and resistant to pests, leading to a bountiful harvest.

5. Conclusions

Tomato is one of the most important vegetables in South Africa, and it has a significant contribution to the economy. The present study showed a high diversity of plant-parasitic nematodes associated with tomatoes, including *Meloidogyne* and *Pratylenchus*. It is worth mentioning that the presence of soil minerals has a significant impact on the root development system of tomatoes, which consequently affects the plant-parasitic nematode density. In order to effectively combat destructive plant-parasitic nematodes like *Meloidogyne* and *Pratylenchus*, it is imperative that future research directions prioritize mineral management strategies. By implementing focused research on this area, we can potentially mitigate the damage caused by these harmful nematodes and protect the health and vitality of tomatoes. Small holding farmers in South Africa can benefit from monitoring their fertilizer use. This helps to improve the health and yield of their tomato crops, while also controlling plant-parasitic nematodes. To achieve this, it is important to monitor fertilizer levels in soil, which supports small-scale farmers in South Africa and helps them produce stronger and healthier tomatoes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae10040328/s1, Figure S1: Plant-parasitic nematodes associated with tomato in Turfloop, Limpopo Province, South Africa. A: *Criconema*, B: *Tylenchorhynchus*. C: *Pratylenchus*. D: *Xiphinema*, E: *Helicotylenchus*, F: *Rotylenchus*, G, H: *Meloidogyne*.

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