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Effect of Silver Nanoparticles and Vermicompost on the Control of *Aphelenchoides fragariae* and *Meloidogyne hapla* in Jerusalem Artichoke (*Helianthus tuberosus* L.)

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Abstract: Root-knot nematodes *Meloidogyne* spp. are sedentary endoparasites that infest a wide range of plant species; they are also widely distributed, making them one of the most economically significant pests. Similarly, damage caused by *Aphelenchoides fragariae* can lead to substantial reductions in both crop yield and quality. This research focused on the rhizosphere of *Helianthus tuberosus* L. (variety Albik), grown in a Polish plantation. The experiment was conducted at the National Institute of Horticultural Research in Skierniewice, using concrete rings filled with medium sandy soil amended with 10% peat. The treatments included the following: control (no amendments), silver solution (Ag+) (120 mg/L soil), and vermicompost (Ve) (20 L of *Eisenia fetida* vermicompost). Each treatment was replicated four times. Compared with control, (Ve) significantly decreased the numbers of *Aphelenchoides fragariae* and *Meloidogyne hapla*, by about 48% and 31%. The application of (Ag+) led to the most significant reduction in population density in both nematode species, with *A. fragariae* decreasing by over 67% and *M. hapla* by approximately 75%.

Keywords: rhizosphere microbiota; Eisenia fetida; reproduction rate; soil bioactivity

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1. Introduction

Due to the increasing need for alternatives to fossil fuels, renewable energy sources are receiving greater attention. As a result, interest in plant biomass has surged. The high biomass yield and rapid growth of *H. tuberosus* L. make it a promising substrate for renewable energy production and have earned it increasing recognition in recent studies [1–7]. In addition to its energy potential, *H. tuberosus* L. has a variety of other significant applications. Its tubers, shoots, and flowers are rich in bioactive compounds, including fructooligosaccharides and inulin, which are utilized in the production of functional foods and dietary supplements [8–11]. These compounds are known for their beneficial effects on glucose metabolism, particularly in managing blood sugar levels in diabetic patients.

Furthermore, *H. tuberosus* L. has applications in the pharmaceutical and cosmetic industries due to its phytochemicals, which possess antioxidant and anti-inflammatory properties [12,13]. The plant is also valuable in agricultural systems, in which it is used as animal feed, and it has potential for phytoremediation due to its ability to absorb and detoxify pollutants from the soil [14,15].

Vermicomposting is a natural decomposition process in which organic waste is converted into humus by the activity of earthworms and microorganisms. Earthworms play a vital role in breaking down, aerating, and mixing the waste, a process which promotes bio-oxidation and decomposition. This process results in the formation of stabilized humus, which improves soil fertility and is widely utilized as an organic fertilizer in agriculture. The castings produced by earthworms are rich in essential nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium, making them highly beneficial for plant growth [16].

Plant-parasitic nematodes cause significant damage to agricultural crops, resulting in substantial economic losses [17]. Consequently, the development of environmentally friendly and highly effective nematicides is critical. Organic amendments, such as vermicompost, have been shown to effectively control a variety of plant-parasitic nematodes, including root-knot nematodes, cyst nematodes, root lesion nematodes, and dagger nematodes, while also enhancing soil health [18–20]. Vermicompost not only promotes the growth of beneficial microorganisms but also helps in controlling pathogens and pests [21]. By stimulating beneficial microbiota and predatory nematodes, vermicompost enhances the soil food web, thereby improving the soil's ability to nourish plants and protect them against pathogens [22].

Silver nanoparticles, with sizes ranging between 1 and 100 nm, belong to the class of nanomaterials. Due to their small size, they exhibit superior capacity and an elevated surface area-to-volume ratio compared to bulk silver. At the nanoscale, these materials possess distinct electrical, optical, and catalytic properties, which has led to significant progress in the development of products for targeted drug delivery, diagnostics, detection, and imaging [23,24]. The exceptional antibacterial properties of silver nanoparticles have attracted considerable attention from both researchers and industries. These nanoparticles have shown antimicrobial effects against a broad spectrum of infectious and pathogenic microorganisms, including bacteria that are resistant to multiple drugs [25,26]. Silver nanoparticles exert antibacterial activity on various different bacterial types, including Gram-negative and Gram-positive bacteria [27].

The aim of this study is to evaluate the effects of silver nanoparticles and vermicompost on the control of the nematodes *Aphelenchoides fragariae* and *Meloidogyne hapla* in *Helianthus tuberosus* L. It is hypothesized that the application of silver nanoparticles and vermicompost will reduce the population density and reproduction rate of *A. fragariae* and *M. hapla* in the rhizosphere of this plant, offering an effective biocontrol strategy for these nematode species.

2. Materials and Methods

2.1. Experimental Design

The experiment was conducted in 2021–2022 at the National Institute of Horticultural Research in Skierniewice, Poland (51°96′15″ N, 20°13′69″ E). Twelve concrete circles, each measuring 150 cm in diameter and 60 cm in depth, were filled with medium sandy soil that had been left fallow for two years. Additionally, 20 L of nematode-free peat soil were mixed in. The experiment was conducted in four replications and had three treatments:

1. Control—no amendments;
2. (Ag+)—silver nanoparticle solution (dose 120 mg per 1 L soil);
3. (Ve)—20 L of vermicompost (with 150–200 specimens of *E. fetida:* 30% adult and 70% larvae).

Prior to the start of the experiment, the initial populations of selected plant-parasitic nematode species (PPN) were assessed. Preliminary analyses revealed that among migratory endoparasites and foliar nematodes, there were 38 individuals of *Pratylenchus fallax* Seinhorst, 1968, and 28 individuals of *A. fragariae* Ritzema Bos, 1891. Among semi-endoparasites, there were 41 individuals of *Helicotylenchus digonicus* Perry, 1969, and 48 individuals of *Rotylenchus robustus* De Man 1876. Among migratory ectoparasites, there were 32 individuals of *Bitylenchus dubius* Butschli, 1873; 21 individuals of *Merlinius brevidens* Allen, 1955; 12 individuals of *Scutylenchus tartuensis* Krall, 1959; and 16 individuals of *Paratylenchus nanus.* These species were recovered from 100 cm of soil.

Following this, ten *H. tuberosus* L. tubers of the Albik variety were planted in each plot on 10 March 2021.

Three weeks later, within each circle, *A. fragariae* (80 specimens per 1 L of soil) and *M. hapla* (120 specimens per 1 L of soil) in water solution were inoculated close to the root system as initial population (Pi). Two days prior to the experiment, using the Baermann method, *A. fragariae* were isolated from infected leaves and stems of strawberry seedlings from a plantation in Zduny, near Łowicz (Poland) (Table 1). Similarly, *M. hapla* was extracted from soil containing carrot roots infected by *M. hapla* from a field in Skierniewice (Table 2). The species were classified based on the Species Recognition Guide for the genus *Meloidogyne*, Nematode diagnostics [28].

Table 1. Morphometrics of the *Aphelenchoides fragariae* population used in the experiment. Range of values (X_1–X_{10}) of individual traits, mean ± SD, *n* = 10. Measurements were conducted in µm.

Location: Zduny, Poland (52°1484331′ N, 19°8112456′ E) **Host Plant: *Fragaria* × *ananassa***		
Character	(X_1–X_{10})	Mean ± SD
Body length L	598.4–835.0	752.0 ± 90.2
Stylet length	10.2–11.5	10.7 ± 0.4
Tail length	34.6–52.8	44.2± 6.3
PUS%	33.3–73.5	57.7 ± 0.1
a	48.2–58.6	53.1 ± 3.0
b′	4.4–6.3	6.2 ± 0.6
c	12.6–19.3	17.2 ± 1.9
c′	4.3–5.9	4.9 ± 0.4
V/AT	2.9–5.1	4.2 ± 0.7
V%	61.0–72.7	68.2 ± 3.4

L = body length; in millimeters; a = ratio of body length to largest body width; PUS (%) = ratio of postvulval sac to the vulva anus distance (V/A × 100%); b′ = ratio of body length to pharynx length from head to pharyngeal–intestinal junction; c = ratio of body length to tail length; c′ = ratio of tail length to body width at anus level; V/AT = ratio of vulva–anus distance to tail length; V% = distance from anterior end to vulva, expressed in percentage of body length × 100%.

Table 2. Morphometrics of the *Meloidogyne hapla* population used in the experiment. Measurements were conducted in µm.

Location: Skierniewice, Poland (51°5717′5″ N, 20°9301″ E) **Host Plant: *Daucus carota* L.**		
Character	(X_1–X_{10})	Mean ± SD
Stylet length	17–23	19.5 ± 2.06
J2 body length	305–517	446.4 ± 75.09
J2 tail length	30–69	50.5 ±12.36
J2 hyaline length	6–20	13.8 ±4.9
Stylet knob shape	oval	

The final population (Pf) for both the *A. fragariae* and the *M. hapla* species, along with the multiplication factor (R), was calculated on 15 October 2022. Descriptive statistics and ANOVA were performed using STATISTICA 13.3 (StatSoft, Hamburg Germany).

2.2. Vermicompost Preparation

E. fetida were used to produce vermicompost over a one-month period using a mixture of organic waste. Moisture levels were regularly checked, and water was added when needed. Composting took place in a sealed bin equipped with a drainage system to remove excess water. The final chemical composition was characterized by a neutral pH (7.17) and an electrical conductivity of 2.41 mS·cm^{-1}. The nutrient profile included nitrate (200 mg·kg^{-1}), ammonium (68.7 mg·kg^{-1}), phosphorus (617 mg·kg^{-1}), potassium (1795 mg·kg^{-1}), calcium (1410 mg·kg^{-1}), magnesium (369 mg·kg^{-1}), and chlorine (189 mg·kg^{-1}). The organic carbon content was 5.08%, while total nitrogen was 0.23%, resulting in a carbon-to-nitrogen (C/N) ratio of 21:1.

2.3. Silver Nanoparticle Application

Silver nanoparticles (37 ppm) were purchased from Alter Medica (Zywiec, Poland) and applied to the soil at a dose of 120 mg per 1 L of soil.

2.4. Soil Analysis

Mineral components were determined via a universal method [29], The pH in soil samples was determined with the potentiometric method and EC (electrical conductivity) and total salinity by using the conductivity method. Mineral components such as N-NO_3-, N-NH+ were analyzed by the potentiometric method; P, K, Ca, Mg, and Ag were determined by the spectrophotometric method using the sequential emission spectrometer (ICP) model Optima 2000 DV, Perkin-Elmer, Boston, MA, USA. Selected elements were determined at their characteristic wavelengths [30]. The N content (total nitrogen) was analyzed using the Kjeldahl method using the Vapodest Kjeldahl apparatus, Gerhardt GmbH & Co., KG, Königswinter, Bonn, Germany. Total organic carbon content (Corg.) was determined by Dumas' method with a CS-530 apparatus (Eltra, GmbH, Neuss, Germany) [31].

2.5. Physiological Parameters of Plants

In October of 2021 and 2022, measurements were taken for stem height, stem count, stem thickness, and yield across three treatment variants: control, (Ag+), and (Ve). To assess stem height, 10 plants were randomly selected from each group and measured. Shoot diameter was recorded at a height of 10 cm above the soil surface for each treatment separately. Additionally, the tuber yield (kg/m^2) was measured and recorded.

The physiological assessment included measuring the leaf gas exchange rates, the maximum quantum efficiency of PSII photochemistry (Fv/Fm), and the relative chlorophyll content (chlorophyll content index, CCI). A CCM-200 portable chlorophyll content meter (Opti-Sciences, Hudson, NH, USA) was used to measure chlorophyll levels in 40 leaves from each treatment. These measurements were conducted on September 10, with the plants near the final stages of tuber development, using fully developed and healthy leaves.

Leaf gas exchange (net photosynthesis and transpiration rate) was determined using an LCpro+ portable photosynthesis system (ADC BioScientific, Hoddesdon, UK) for 32 leaves from each treatment. Temperature, CO_2 concentration, and irradiance in the leaf chamber during analysis were set to approximate ambient conditions.

Fv/Fm was measured using a pulse-modulated, hand-held fluorimeter (OS1-Fl, Opti-Sciences, USA) on 20 darkness-adapted leaves from each experimental treatment.

2.6. Nematode Extraction

The nematode population density was analyzed by a method described by Zapałowska and Skwiercz [32] for five trophic groups of nematodes: plant-parasitic (PPN), bacterivorous (B), fungivorous (F), omnivorous (O), and predatory (PN) nematodes. From each of the soil samples a subsample of 100 cm^3 was taken and blended; nematodes were isolated from the soil by centrifugation and killed by 6% formalin. Permanent slides were made in glycerin by the Seinhorst method [33]. PPN were identified as to genus according to the Brzeski key [34], whereas populations of the B, F, O, and PN groups of nematodes were identified by use of the Andrassy key [35].

2.7. Microorganisms in Soil and Dehydrogenase Activity

Four samples from each treatment were subjected to microbiological analysis. Each sample was sieved to remove stones and large particles. Then, 10 g subsamples were added to 100 mL 0.85% NaCl water solution and shaken for 20 min. The soil dilution plating method on agar media was used to evaluate the numbers of the following microbial groups: bacteria, including *Actinomycetes*, were enumerated on soil extract medium [36] after 7 days incubation at 28 °C; fluorescent *Pseudomonas* was determined on the S1 medium under UV light [37] after 2 days incubation at 28 °C; and phosphate-solubilizing bacteria were counted on Pikovskaya medium [38] after 7 days incubation at 28 °C. The presence of phosphate solubilization by the bacteria was indicated by formation of clear zones around the colonies. Fungi were counted on Rose Bengal medium [39] after 7 days incubation at 25 °C. The number of microorganisms was expressed in terms of colony forming units (cfu) g^{-1} relative to soil dry weight.

The activity of the enzyme dehydrogenase (DHA) in the soil was measured according to the Cassidy procedure described by Brzezińska and Włodarczyk [40]. Briefly, 3 g of sieved soil was placed in a 15 mL dark tube to restrict the light, and, successively, the following were added: 1.8 mL of sterile deionized water, 600 µL of 1% glucose suspension, and 600 µL of 3% water solution of 2,3,5-triphenyltetrazolium chloride (TTC). The mixture was incubated for 24 h at 30 °C in the darkness, and TTC was reduced to water-insoluble 1,3,5-triphenylformazane (TPF) in a pink-colored suspension. The enzymatic reaction was stopped by the addition of ethanol. Then, the samples were agitated for one hour in the dark and centrifuged (12,000 rpm/min.) for 8 min at 4 °C. The supernatant was used for spectrophotometric measurements of TPF concentration at λ = 485 nm, with the use of spectrophotometer (UVLINE 9600, Aqualabo, Champigny-sur-Marne, France). The obtained values were related to the standard curve (using the determined TPF concentrations). The dehydrogenase activity was expressed as the amount of TPF produced by 1 g of soil during a 24 h period (µmol TPF/g s·m·24 h) [41].

3. Results

3.1. Soil Properties

Soil parameters were impacted by the applications of both amendments: vermicompost (Ve) and silver solution (Ag+) (Table 3). The results demonstrate that the (Ve) treatment significantly increased potassium (K) ($p < 0.0001$), phosphorus (P) ($p = 0.007$), and ammonium nitrogen (N-NH_4) ($p < 0.0001$) levels in the soil. The highest (113.667 ($mg \cdot kg^{-1}$)) potassium concentration was observed in (Ve), whereas (Ag+) and control had significantly lower values (59.778 $mg \cdot kg^{-1}$ and 41.333 $mg \cdot kg^{-1}$, respectively). Phosphorus (P) availability was significantly affected with (Ve) treatment, with the sample exhibiting the highest (240.889 $mg \cdot kg^{-1}$) concentration. Additionally, both the (Ag+) and the (Ve) treatments led to a significant rise in soil salinity (NaCl) ($p < 0.001$), with determinations of 0.278 $g \cdot L^{-1}$ and 0.253 $g \cdot L^{-1}$, respectively.

Table 3. Effects of silver nanoparticles (Ag+) and vermicompost (Ve) on soil properties (2022).

Parameter	Treatment (Mean ± SD)		
	Control	Ag+	Ve
pH	6.71 ± 0.18 a	6.77 ± 0.08 a	6.82 ± 0.14 a
Salinity [NaClg·L^{-1}]	0.198 ± 0.03 ba	0.278 ± 0.02 a	0.253 ± 0.04 a
N-NO_3 [mg·kg^{-1}]	26.66 ± 13.21 a	25.22 ± 9.95 a	30.33 ± 9.39 a
P [mg·kg^{-1}]	202.66 ± 38.17 b	236.44 ± 9.73 a	240.889 ± 19.52 a
K [mg·kg^{-1}]	41.33 ± 18.9 b	59.77 ± 37.15 b	113.66 ± 25.98 a
Mg [mg·kg^{-1}]	161 ± 12.01 a	167.3± 11.82 a	170.1 ± 14.33 a
Ca [mg·kg^{-1}]	2417.2 ± 144.58 a	2362.4 ± 78.42 a	2315 ± 76.11 a
N-NH_4 [mg·kg^{-1}]	453.33 ± 91.92 b	544.33 ± 68.2 b	2126.66 ± 76.32 a
Ag [mg·kg^{-1}]	0 ± 0.00 b	0.229 ± 0.08 a	0 ± 0.00 b
C_{org} [%]	3.84 ± 0.43 a	3.77 ± 0.25 a	3.93 ± 0.24 a

Note: Different letters in the rows indicate significant differences ($p < 0.05$), ($n = 4$).

3.2. Biometric Parameters of Plants

Table 4 presents physiological parameters, including the photosynthesis rate, transpiration, fluorescence, and chlorophyll concentration index, along with stem count, stem thickness, stem yield, tuber yield, and plant height.

Table 4. Effects of silver nanoparticles (Ag+) and vermicompost (Ve) on the physiological and biometrical parameters of the plants.

Parameter	Treatment (Mean ± SD)		
	Control	Ag+	Ve
Net photosynthetic rate [µmol [CO_2·$m^{-2}s^{-1}$]	12.36 ± 0.51 a	13.52 ± 0.48 b	13.69 ± 0.53 b
Transpiration rate [mmlo [H_2O·$m^{-2}s^{-1}$]	1.58 ± 0.28 a	2.77 ± 0.36 b	3.14 ± 0.41 c
PSII [Fv/Fm]	0.83 ± 0.09 a	0.82 ± 0.08 a	0.82 ± 0.10 a
Chlorophyll concentration index (CCI)	19.84 ± 0.64 a	19.85 ± 0.66 a	20.58 ± 0.71 b
Stem count [number]	39	39	40
Stem thickness [cm]	3.06 ± 0.72 a	3.67± 0.62 a	3.85 ± 0.61 a
Stem dry yield [kg·m^{-2}]	2.22 ± 0.26 a	2.57 ± 0.28 a	2.49 ± 0.27 a
Tuber yield [kg/m^{-2}]	6.38 ± 0.31 a	8.54 ± 0.35 b	9.26 ± 0.36 c
Plant height [cm]	238.00 ± 47.13 a	259.00 ± 23.80 a	247.00 ± 22.17 a

Note: Different letters in the rows indicate significant differences ($p < 0.05$); ($n = 120$) for plants' physiological parameters; ($n = 4$) for plants' biometrical parameters.

The results highlight notable differences in photosynthetic activity and water usage among treatments, with (Ve) showing the highest values for both photosynthesis and transpiration. Regarding the net photosynthesis intensity, variants (Ag+) and (Ve) demonstrated in the highest values (13.52 and 13.69 µmol CO_2·$m^{-2}s^{-1}$), while the control (12.36 µmol CO_2·$m^{-2}s^{-1}$) was associated with the lowest net photosynthetic rate levels. Transpiration rate reached its post-application peak in variant (Ve), while variant (Ag+) also displayed relatively high rate measurements compared to the control. An analysis of the obtained results reveals that the maximal photochemical efficiency of PSII (Fv/Fm) was similar across all analyzed variants, with no significant differences observed among them. The chlorophyll concentration index showed no significant differences between the control

and (Ag+) treatments. However, the (Ve) treatment had a significantly higher CCI (20.58) than the other groups ($p < 0.05$). The number of stems remains relatively stable across different conditions or experimental groups. The standard deviation remains similar across all groups (around 0.61–0.72 cm), indicating that variability in stem thickness is consistent. The significant increase ($p = 0.01$) in tuber yield, following the trend control < (Ag+) < (Ve), suggests that the (Ve) treatment had the most positive effect on yield. There were no statistically significant differences in plant height relative to treatment.

3.3. Nematode Population

The final analysis (Pf) identified nematode species across the three treatment groups. Nematode populations were significantly lower in treated soils compared to the control, particularly under (Ag+) conditions (Figure 1). In the control treatment, the population of plant-parasitic nematodes (PPN) increased by 27% over a 1-year period, remaining the highest, compared to the (Ag+) and (Ve) treatments. Both the (Ag+) and the (Ve) treatments displayed a similar decreasing trend in (PPN) abundance from Pi to Pf, with reductions of 15.5% and 33.9%, respectively. However, the reduction in the (Ve) treatment appeared more pronounced than in (Ag+), suggesting a stronger suppressive effect of this treatment relative to (PPN) populations.

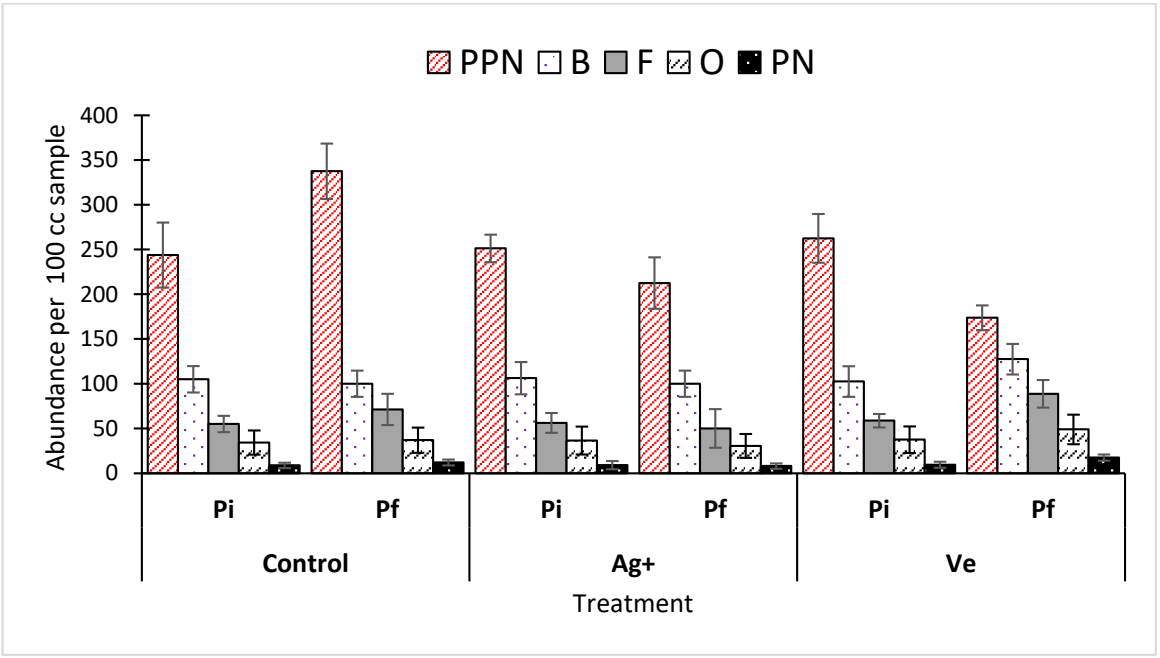


Figure 1. The nematode density per 100 cc sample at the level of five trophic groups, namely, plant-parasitic nematodes (PPN); bacterivores (B); fungivores (F); omnivores (O); and predators (PN), during the treatment period (Pi- on the initial day of the experiment, Pf- on the last day of the experiment), ($n = 4$).

In the soil, bacterivore populations included *Cephalobus acuminatus*, *Plectus longicaudatus*, *Diplogasteritus* spp., *Acrobeles* spp., *Acrobeloides nanus*, and *Cylindrolaimus communis*. Fungivore nematodes were represented by *Aphelenchoides composticola*, *A. saprophilus*, the *Aphelenchus avenae* group, *Ditylenchus medicaginis*, *Coslenchus costatus*, *Tylenchus elegans*, and *Tylencholaimellus crassus*. Omnivore nematodes observed were *Mesodorylaimus* spp., *Eudorylaimus* spp., and *Discolaimus* spp. Predatory nematodes included *Mylonchulus brevicaudatus* and *Clarkus papillatus*. The plant-parasitic nematodes identified were of the *M. hapla*, *A. fragariae*, *Pratylenchus fallax*, and *Hoplolaimidae* species.

The total bacteriovore nematode (B) populations varied across treatments, with the highest count observed in the Ve Pf treatment (125 individuals), followed by Pi Pf (105 individuals), control (95 individuals), and (Ag+) Pf (100 individuals).

Cephalobus acuminatus was most abundant in Ve Pf (30 individuals), while its lowest count was in the control (15 individuals). *Plectus longicaudatus* showed similar trends, with Ve Pf having the highest population (30 individuals) and the control treatment showing the lowest (20 individuals). *Diplogasteritus* spp. exhibited a notable increase in Ve Pf (20 individuals), while its population was lowest in Pi Pf (10 individuals) and control (8 individuals). *Acrobeloides nanus* was relatively stable across treatments, ranging from 20 individuals (control) to 30 individuals (Ve Pf). *Cylindrolaimus communis* showed a different pattern, peaking in control (27 individuals), while being least abundant in Ve Pf (15 individuals).

The total fungivore nematode (F) populations varied among treatments, with the highest count observed in Ve Pf (85 individuals), followed by control (75 individuals), Pi Pf (55 individuals), and the lowest in (Ag+) Pf (45 individuals).

Aphelenchoides composticola was most abundant in Ve Pf (30 individuals) and least in (Ag+) Pf (10 individuals). The *Aphelenchus avenae* group showed the highest population in control and Ve Pf (25 individuals), while its lowest count was in (Ag+) Pf (12 individuals). *Ditylenchus medicaginis* had its peak population in control (20 individuals) and Ve Pf (20 individuals), while it was lowest in Pi Pf (10 individuals). *Coslenchus costatus* was most abundant in Pi Pf (18 individuals) but showed lower numbers in other treatments, with the lowest being observed in (Ag+) Pf (8 individuals).

The total omnivore nematode (O) populations varied among the treatments, with the highest count in Ve Pf (50 individuals), followed by control (45 individuals), and Pi Pf (40 individuals); the lowest was observed in (Ag+) Pf (30 individuals).

Mesodorylaimus spp. was most abundant in Ve Pf (20 individuals) and least in (Ag+) Pf (10 individuals). *Eudorylaimus* spp. peaked in Ve Pf (15 individuals) and had the lowest count in (Ag+) Pf (8 individuals). *Discolaimus* spp. showed a stable population in Pi Pf and control (18 each), while it was least abundant in (Ag+) Pf (12 individuals).

The total predatory (PN) nematode populations varied among treatments, with the highest count in Ve Pf (20 individuals), followed by control (15 individuals), and Pi Pf (12 individuals), while the lowest was observed in (Ag+) Pf (10 individuals).

Mylonchulus brevicaudatus was most abundant in Ve Pf (10 individuals) and least in (Ag+) Pf (5 individuals). *Clarkus papillatus* followed a similar trend, with the highest population in Ve Pf (10 individuals) and the lowest in (Ag+) Pf (5 individuals).

The total plant-parasitic nematode (PPN) populations varied significantly, with the highest count observed in control (335 individuals), followed by Pi Pf (245 individuals), and (Ag+) Pf (200 individuals); the lowest was observed in Ve Pf (170 individuals).

M. hapla was most abundant in control (133 individuals) and least in (Ag+) Pf (33 individuals). *A. fragariae* followed a similar trend, peaking in control (116) and being lowest in (Ag+) Pf (38 individuals). *Pratylenchus fallax* showed a different pattern, with its highest population in Ag Pf (45 individuals) and lowest in Ve Pf (24 individuals). Hoplolaimidae (*Rotylenchus* and *Helicotylenchus*) showed its highest population in control (25 individuals) and its lowest in Ve Pf (6 individuals). Belonolaimidae (*Merlinius*, *Scutylenchus* and *Bitylenchus* spp.) was most abundant in (Ag+) Pf (50 individuals) and control (41 individuals), but significantly lower in Pi Pf (8 individuals) and Ve Pf (6 individuals).

PPN populations increased by 36% over the course of the experiment in the control treatment. However, the Ve combination resulted in the most significant decrease in population densities across all tested PPN species. In the (Ag+) treatment, Hoplolaimidae, Belonolaimidae, and the migratory species *Pratylenchus fallax* showed resistance to silver.

The results presented in Table 5 highlight the effects of silver nanoparticles (Ag+) and vermicompost (Ve) on the final population densities of *A. fragariae* and *M. hapla*, two significant plant-parasitic nematodes. Nematode populations were quantified from 100 cm^3 of soil, with samples being taken at the beginning (Pi) and end (Pf) of the experiment. The population densities were each determined as the mean of the four replications in each of the three combinations. The findings indicate that both the (Ag+) and the (Ve) treatments were effective ($p < 0.0001$) in reducing the *A. fragariae* and *M. hapla* populations.

Table 5. Effects of silver nanoparticles (Ag+) and vermicompost (Ve) on the final population density (Pf) of *Aphelenchoides fragariae* and *Meloidogyne hapla*.

Pf	Treatment (Mean ± SD)		
	Control	**Ag+**	**Ve**
Aphelenchoides fragariae	116.25 ± 11.08 a	38.00 ± 8.48 b	58.58 ± 12.79 b
Meloidogyne hapla	133.75 ± 21.36 a	33.5 ± 8.06 c	76.75 ± 10.75 b

Note: Different letters in the rows indicate significant differences ($p < 0.05$), ($n = 4$).

The application of silver nanoparticles (Ag+) resulted in the most significant reductions in the population density for both nematode species. For *A. fragariae*, the population decreased by over 67%. Similarly, the population of *M. hapla* was reduced by approximately 75%. These results indicate that silver nanoparticles possess a strong nematicidal effect, likely due to their antimicrobial properties, which could impact nematode survival, reproduction, or development. Previous studies have shown that silver nanoparticles can disrupt nematode cuticles, interfere with cellular processes, and negatively impact the viability of nematodes [42,43].

The application of vermicompost (Ve) also reduced the nematode populations, but to a lesser extent compared to (Ag+). As for *A. fragariae*, the population was reduced by about 48%, and in *M. hapla,* it decreased by about 31%. Although these reductions are significant, they are less pronounced than those observed in the (Ag+) treatment. Vermicompost is known to improve soil health by enhancing microbial activity and enriching the soil with beneficial organisms that may suppress plant-parasitic nematodes. The presence of nematicidal compounds or beneficial microorganisms in the vermicompost could explain the observed reduction in nematode populations. However, the lesser effect compared to (Ag+) suggests that the nematicidal action of vermicompost is likely more gradual and dependent on interactions in the soil microbiota.

The results demonstrate that while both (Ag+) and (Ve) treatments reduce the populations of *A. fragariae* and *M. hapla*, the silver nanoparticles had a more immediate and pronounced effect. The greater efficacy of Ag+ suggests that it may be more suitable for scenarios requiring rapid control of nematode populations, while vermicompost may offer a more sustainable, long-term approach, particularly in promoting overall soil health and microbiological diversity.

The correlation matrix provided (Figure 2) presents the relationships between various soil parameters, including pH, salinity, nutrients (N-NO_3, P, K, Mg, Ca, N-NH_4), Ag, and organic carbon (Corg), and the presence of *A. fragariae* and *M. hapla*. The statistically significant differences indicate that, in the analyzed soil, (Ve) had the most substantial influence on ammonium nitrogen accumulation (Table 3). The negative correlation with N-NH_4 ($r = -0.285$) suggests that ammonium availability does not support *A. fragariae* growth (Figure 2). Strong negative correlations with pH ($r = -0.628$) and salinity ($r = -0.714$) suggest that *A. fragariae* thrives in conditions which are more acidic and less saline. Additionally, the negative correlation with (Ag+) ($r = -0.411$) implies that the silver treatment led to a reduction in ammonium levels. Notably, a strong positive correlation ($r = 0.876$) be-

tween *A. fragariae* and *M. hapla* suggests that these two species co-occur, likely due to shared environmental preferences. Magnesium has a minimal impact on nematode presence, as indicated by its weak negative correlations with *A. fragariae* (r = −0.138) and *M. hapla* (r = −0.135). Higher calcium concentrations appear to favor nematode presence, while increased silver levels are associated with a decline in nematode populations. Calcium exhibits a moderate positive correlation with *A. fragariae* (r = 0.337) and *M. hapla* (r = 0.434), suggesting that elevated Ca levels may promote their presence. In contrast, silver shows a strong negative correlation with *A. fragariae* (r = −0.614) and *M. hapla* (r = −0.690), indicating that higher Ag concentrations may suppress nematode populations. Organic carbon (Corg) exhibits a weak positive correlation with *A. fragariae* (r = 0.371) but shows little to no relationship with *M. hapla* (r = 0.08). This suggests that increased organic matter may slightly promote *A. fragariae* while having a negligible effect on *M. hapla*.

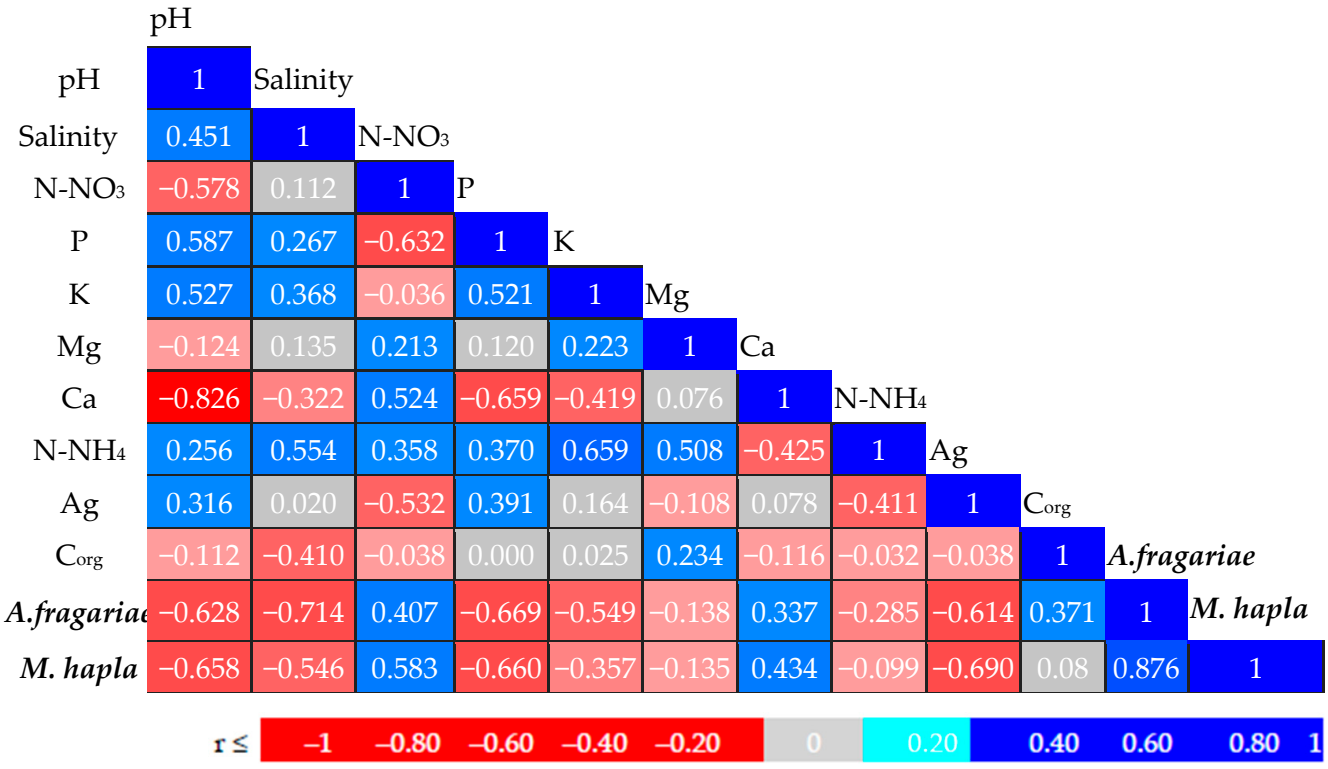
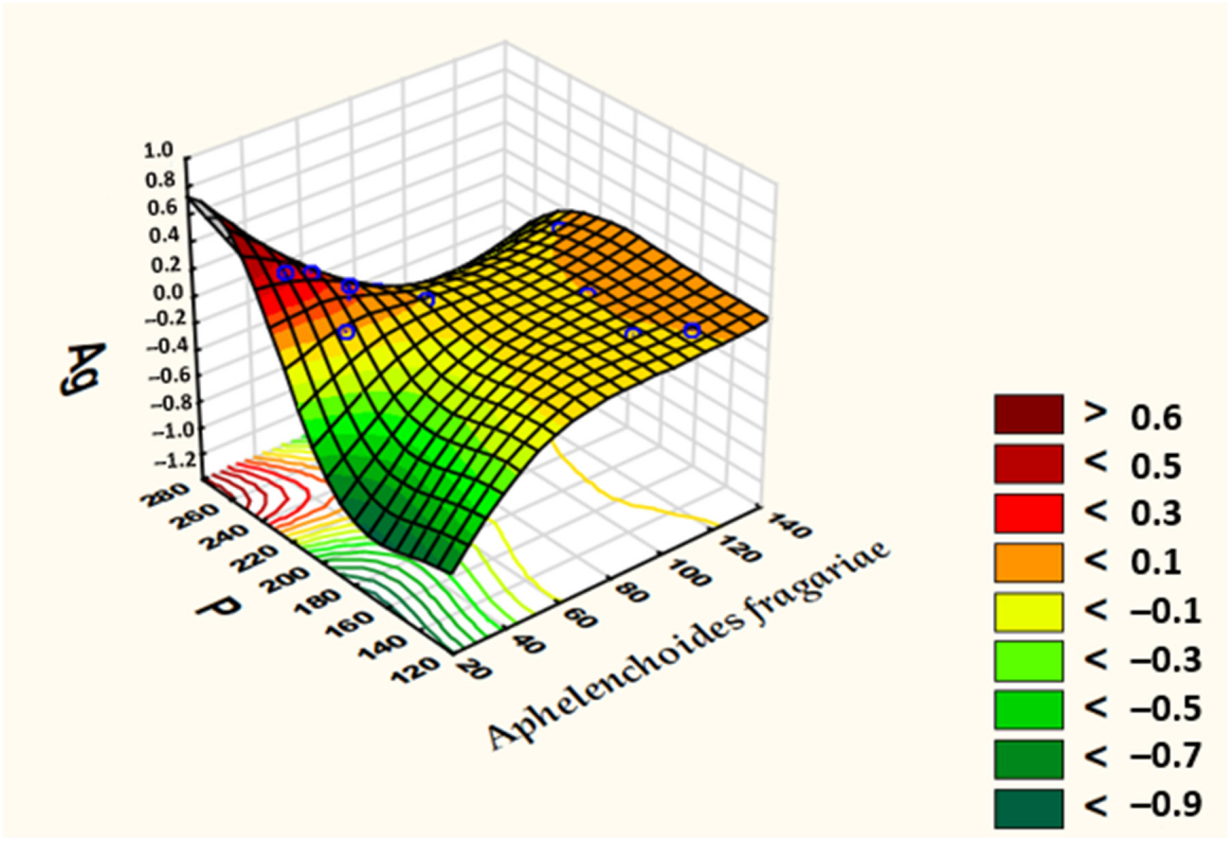


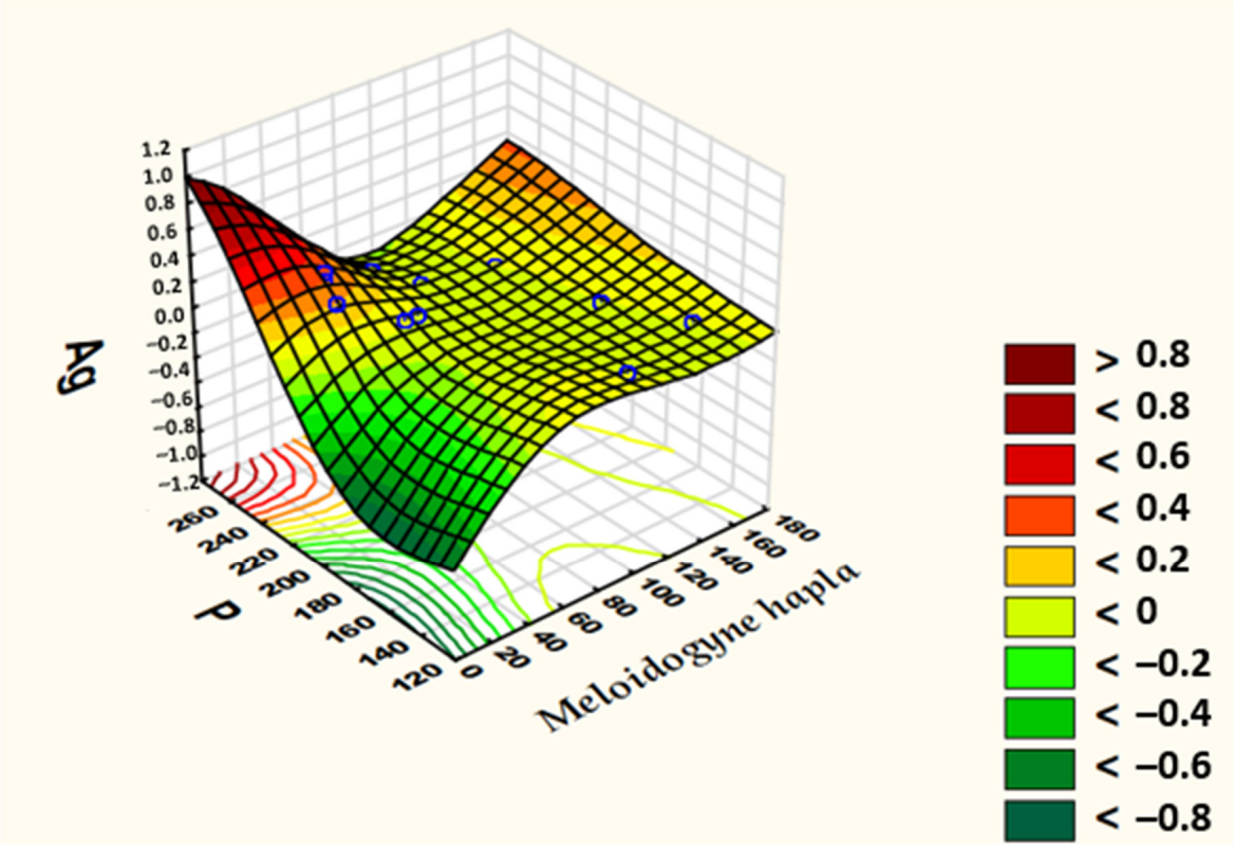
Figure 2. Correlation coefficients (r) between the selected parameters of the tested composition.

Strong negative correlations with potassium (K) (r = –0.549) and phosphorus (P) (r = –0.669) (Figures 2 and 3A) suggest that increased levels of these nutrients suppress *A. fragariae* populations. A similar trend is observed for *M. hapla*, which also exhibits negative correlations with both K and P. Specifically, *M. hapla* shows a moderate negative correlation with phosphorus (r = −0.660) and a weaker negative correlation with potassium (r = −0.357), indicating that elevated P levels may have a greater suppressive effect on this species, compared to that seen with K.

Furthermore, *M. hapla* demonstrates a strong negative correlation with pH (r = −0.658) and salinity (r = −0.546), suggesting a preference for environments which are more acidic and less saline. In contrast, the species is positively correlated with nitrate ($N\text{-}NO_3$) (r = 0.583), indicating that higher nitrate concentrations may promote its presence.



(**A**)



(**B**)

Figure 3. Correlation coefficients between the selected parameters of the analyzed traits: *A. fragariae* /P/Ag (**A**), *M. hapla*/ /P/Ag (**B**). The correlation coefficients are considered significant at $p < 0.05$.

3.4. Evaluations of the Microorganisms and Dehydrogenase Activity

Application of the vermicompost to the soil had a minor effect on the studied microbial groups, as determined at the end of the experiment (Table 6). The overall numbers of bacteria and fungi did not differ significantly, compared to control. A similar effect was observed in the enzyme dehydrogenase activity, which was comparable to control. However, within the bacterial community, the numbers of *Actinomycetes* and phosphate-solubilized bacteria have shown a tendency to increase. Contrastingly, fluorescent *Pseudomonas* bacteria were significantly reduced in the soil, where vermicompost was added (0.21×10^5 cfu g^{-1} in vermicompost added soil and 2.10×10^5 cfu g^{-1} in control). In the soil treated with silver nanoparticles (Ag+) the microbial activity was significantly reduced compared to the other options, as shown by the lower activity of the enzyme dehydrogenase (25.36 and 33.73 µmol TPF g^{-1} for (Ag+) and control, respectively). (Ag+) decreased the numbers of bacteria and fungi; however, this effect was not significant when compared to the control soil.

Table 6. Effects of silver nanoparticles (Ag+) and vermicompost (Ve) on the numbers of microorganisms.

Microorganisms	Treatment (Mean ± SD)		
	Control	Ag+	Ve
Bacteria cfu $\times 10^7$	5.23 ± 0.74 a	4.17 ± 0.83 a	4.51 ± 2.13 a
Actinomycetes cfu $\times 10^7$	2.43 ± 1.23 a	1.442 ± 0.42 a	3.1075 ± 1.74 a
Fluorescent Pseudomonas cfu $\times 10^5$	2.102 ± 2.02 b	0.8725 ± 0.47 ab	0.2075 ± 0.04 a
Phosphate-solubilized bacteria cfu $\times 10^5$	5.525 ± 4.33 a	4.575 ± 2.43 a	7.65 ± 2.73 a
Fungi cfu $\times 10^4$	2.36 ± 2.36 a	1.205 ± 1.51 a	2.025 ± 3.54 a
Dehydrogenase activity µmol TPF/g	33.727 ± 3.53 b	25.362 ± 1.51 a	36.412 ± 1.45 b

Note: Different letters in the rows indicate significant differences ($p < 0.05$), ($n = 4$).

4. Discussion

Root-knot nematodes are among the most destructive plant-parasitic nematodes, causing significant economic losses. According to Rossini [4], many phytophagous organisms and microorganisms have been recorded on *H. tuberosus* L., but very few of them are capable of causing significant damage to the crop. As reported by Long [13], *H. tuberosus* L. is host to the tobacco mosaic virus and several nematode species, including *Caconema radicicola*, *Ditylenchus dipsaci* (stem nematode), *Aphelenchoides ritzemabosi* (leaf nematode), *Heterodera marioni*, *Heterodera schachtii*, and *Meloidogyne* sp. (root-knot nematode). *A. fragariae* had previously been found to colonize the leaves of *H. tuberosus* [29]. As noted by Khan et al. [44], *A. fragariae* has the potential to be a harmful pest of *H. tuberosus.*

A. fragariae can cause several symptoms in *H. tuberosus*. Infected plants may exhibit chlorosis (yellowing) of the leaves, stunted growth, and reduced tuber production. Symptoms caused by *A. fragariae* on *H. tuberosus* L. include the formation of cavities in the palisade mesophyll, which are indicative of tissue damage (Figure 4). Plant tissue is directly damaged by nematode feeding, leading to necrosis and anatomical alterations of the roots, such as root galls formed by root-knot nematodes. Reduced water uptake, photosynthesis, and plant growth can result from deformations and impaired root growth [45]. The nematode infests the roots and vascular tissues, leading to impaired water and nutrient transport. This disruption in physiological functions can result in reduced plant vigor, wilting under drought stress, and deformation of the root system. The damage caused by *A. fragariae* can significantly decrease both the yield and the quality of the crop.

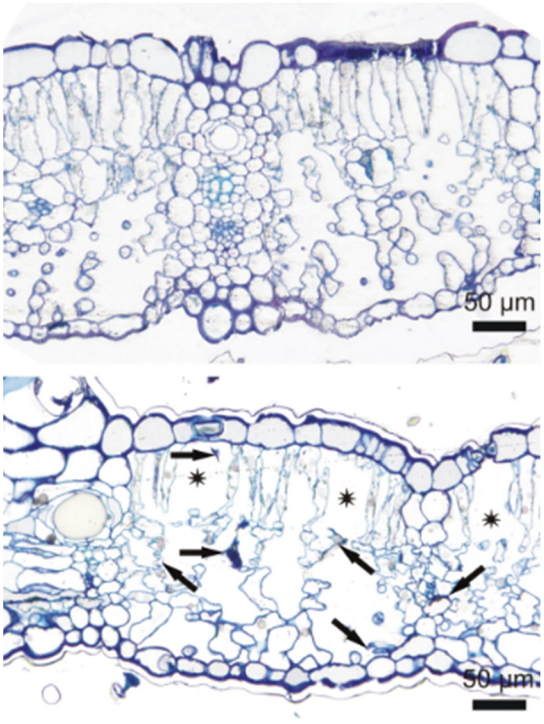


Figure 4. Symptoms caused by *Aphelenchoides fragariae* on *Helianthus tuberosus* L. Electron microscope photographs of *A. fragariae* in cells of *Helianthus tuberosus* L. Bar = 50 µm. Asterisks indicate cavities formed in the palisade mesophyll, and arrows point to remnants of cells destroyed during nematode feeding. Creator: Mirosław Sobczak, Warsaw University of Life Sciences.

Vermicompost has been proven to be a very valuable soil organic amendment, improving soil fertility, as well as biochemical and biological parameters [46,47]. It can promote plant growth by enhancing nutrient uptake and the resistance to biotic and abiotic stress [48], in addition to other factors, by improving soil microbial diversity and functional activity [18]. Vermicompost is rich in microorganisms, especially bacteria, actinomycetes, and fungi, since the vermicomposting process, i.e., the passage of the substrate through the earthworm intestines, changes the structure and function of the microbial community [49]. Numerous reports show that the application of vermicompost is beneficial for the soil microbiome: it increases the abundance of N-fixers, actinomycetes, spore-forming bacteria, phosphate-solubilizing bacteria, and mycorrhizal fungi, as well as enhances soil enzyme activity [46,48].

Organic amendment has been suggested as a promising alternative practice which can be used to improve soil quality and plant health, including the suppression of plant-parasitic nematodes [50–52]. The root-knot nematodes *Meloidogyne* spp. are sedentary endoparasites associated with many plant species and are widespread; they are considered to be very economically important pests. Xiao et al. [53] found that vermicompost effectively suppresses *Meloidogyne* spp. by influencing soil properties and enhancing plant defense mechanisms.

In our study, the application of vermicompost (Ve) led to reductions in nematode populations, decreasing *A. fragariae* by approximately 48% and *M. hapla* by around 31%. Additionally, the impact of vermicompost on soil microorganisms, assessed at the end of the experiment, was minimal concerning the overall populations of bacteria and fungi. The low effect of vermicompost on soil microorganism abundance was supported by the value determined for enzyme dehydrogenase activity, which was similar to control. Dehydrogenase activity (DHA) indicates the presence of physiologically active microorganisms. It is present only in living microbial cells, as a part of their respiratory system, and is a

functional indicator of soil microbial activity [54]. Maková et al. [55] reported that the addition of different doses of vermicompost to the soil in a greenhouse experiment did not affect DHA significantly, although, the values were higher than in untreated control soil. The authors suggested that the low levels of difference were probably due to the humified nature of the organic matter added with the vermicompost, which was resistant to microbial decomposition. In our case, thet low dose of added vermicompost could be a reason for the lack of increase in microbial activity. However, application of vermicompost might change the composition of the microbial community in the soil. This is suggested by its tendency to increase the numbers of phosphate-solubilized bacteria and actinomycetes in vermicompost-enriched soil, and this would be in line with other reports [48,56]. Both of these bacterial groups are beneficial for plant growth, given the associated release of nutrients essential for plants from insoluble complexes [57] and the production of enzymes and antibiotics [58].

The other soil treatment, as studied in the described experiment, was the application of silver nanoparticles (Ag+). While both (Ag+) and (Ve) treatments reduced the populations of *A. fragariae* and *M. hapla*, the silver nanoparticles had a more immediate and pronounced effect. The greater efficacy of (Ag+) suggests that it may be more suitable for scenarios requiring rapid control of nematode populations, while vermicompost may offer a more sustainable, long-term approach, particularly in promoting overall soil health and microbiological diversity. The (Ag+) application reduced microbial activity in the soil as evidenced by the significantly lower DHA relative to control. The numbers of bacteria, actinomycetes, and fungi were also reduced, even though the differences were not statistically significant. The antimicrobial effect of (Ag+) is well documented [59], and these treatments are considered to be an alternative approach for the control of plant diseases. Mittal et al. [60] extracted biogenic silver ions (Ag+) from the culture filtrates of plant growth-promoting (PGP) bacteria *Serratia marcescens* and *Burkholderia cepacia* and evaluated their effectiveness against various fungal strains, including *Aspergillus niger, A. fumigatus, Fusarium oxysporum, Pythium* sp., and *Rosellinia* sp. The associated reduction in growth for these phytopathogenic fungi on an agar medium was more than 80%. Mossa et al. [61] also successfully used silver nanoparticles of plant extracts for reducing the growth of pathogenic *Fusarium* in vitro. They suggest the potential use of biogenic (Ag+) to reduce the burdens of chemical-based pesticides.

To date, (Ag+) treatments have been effectively used to control postharvest diseases of fresh fruits such as kiwifruits, mangoes, strawberries, and apples [62,63]. In their recent review, Kim et al. [64] discussed the perspectives relating to the use of silver nanoparticles in the prevention of plant diseases. They also briefly addressed factors influencing antimicrobial efficacy and toxicity-related–environmental concerns linked to (Ag+). The environmental impacts of silver nanoparticles should be carefully considered, as soil application causes long-term inhibitory effects on microbial abundance and activity in general. In the cases of postharvest or sanitary use, such preparation might be useful; however, repetitive soil applications can have an adverse effect on the soil microbiome and reduce soil functions.

The findings support the well-established preference for *E. fetida* in ecotoxicology and highlight the potential roles of protective and immune mechanisms uniquely optimized for each species within its ecological niche [65,66]. Research by Baccaro et al. [67] confirmed that dissolution is the primary factor driving the uptake of metal nanoparticles in earthworms. Their study found no statistically significant difference between the concentrations of ionic and particulate silver in earthworms. However, in the case of gold, ionic Au was detected at concentrations twenty times higher than its particulate counterpart. In a subsequent study, Baccaro et al. [68] demonstrated that only 5% of the total metal accumulation in earthworms

was in the bimetallic particulate form. Interestingly, the Ag shell thickened, suggesting that a biotransformation process occurred on the nanoparticle's surface. This further supports the conclusion that dissolution is the dominant mechanism governing metal NP uptake in earthworms. The risks posed by nanotechnology in agriculture extend beyond soil health and carry broader implications for human well-being. As demonstrated by Kokhanyuk et al. [69], silver nanoparticles exhibit striking similarities in their interactions with both human and earthworm immune cells. This highlights the urgent need to deepen our understanding of the ecotoxicological consequences of nanoparticle exposure.

5. Conclusions

In conclusion, both vermicompost and silver nanoparticles demonstrate significant potential as sustainable pest-management strategies. Nematodes, such as *A. fragariae* and *M. hapla*, were effectively reduced by approximately 48% and 31%, respectively, through the application of vermicompost. The research showed that vermicompost not only reduces pest populations but also improves soil health and promotes plant growth. Silver nanoparticles, however, exhibited an even greater nematicidal activity, reducing these pests by over 67% and 75%. Although silver nanoparticles are highly effective in controlling nematodes, their potential environmental impact must be carefully evaluated. Future research should focus on the long-term effects of both treatments and explore the benefits of combining them for integrated pest management. Understanding their interactions with soil microbiota and crop health will be essential for developing effective, environmentally responsible pest-control strategies.

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References

1. Matías, J.; Encinar, J.M.; González, J.; González, J.F. Optimisation of ethanol fermentation of *Jerusalem artichoke* tuber juice using simple technology for a decentralised and sustainable ethanol production. *Energy Sustain. Dev.* **2015**, *25*, 34–39. [CrossRef]
2. Piskier, T. A method of estimation of the caloric value of the biomass. Part I. Biomass energy potential. *J. Mech. Energy Eng.* **2017**, *1*, 189–194. Available online: https://bibliotekanauki.pl/articles/95285 (accessed on 28 November 2024).
3. Epie, K.E.; Santanen, A.; Mäkelä, P.S.A.; Stoddard, F.L. Fertilizer and intercropped legumes as nitrogen source for *Jerusalem artichoke* (*Helianthus tuberosus* L.) tops for bioenergy. *Agric. Food Sci.* **2018**, *27*, 199–205. [CrossRef]
4. Rossini, F.; Provenzano, M.E.; Kuzmanović, L.; Ruggeri, R. *Jerusalem artichoke* (*Helianthus tuberosus* L.): A versatile and sustainable crop for renewable energy production in Europe. *Agronomy* **2019**, *9*, 528. [CrossRef]

5. Jankowski, K.J.; Dubis, B.; Kozak, M. Sewage sludge and the energy balance of *Jerusalem artichoke* production. A six-year field experiment in Poland. *Energy* **2021**, *276*, 121545. [CrossRef]
6. Bogucka, B.; Jankowski, K.J. The effect of harvest strategy on the energy potential of *Jerusalem artichoke*. *Ind. Crops Prod.* **2022**, *177*, 114473. [CrossRef]
7. Jankowski, K.J.; Dubis, B. *Jerusalem artichoke*: Nitrogen Fertilization Strategy and Energy Balance in the Production Technology of Aerial Biomass. *Energies* **2024**, *17*, 5202. [CrossRef]
8. Cieślik, E.; Gębusia, A.; Florkiewicz, A.; Mickowska, B. The content of protein and of amino acids in *Jerusalem artichoke* tubers (*Helianthus tuberosus* L.) of red variety Rote Zonenkugel. *Acta Sci. Pol. Technol. Aliment.* **2011**, *10*, 433–441. Available online: https://pubmed.ncbi.nlm.nih.gov/22230925/ (accessed on 28 November 2024).
9. Sawicka, B.; Skiba, D.; Pszczółkowski, P.; Aslan, I.; Sharifi-Rad, J.; Krochmal-Marczak, B. *Jerusalem artichoke* (*Helianthus tuberosus* L.) as a medicinal plant and its natural products. *Cell Mol. Biol.* **2020**, *66*, 160–177. Available online: https://pubmed.ncbi.nlm.nih.gov/32583794/ (accessed on 28 November 2024). [CrossRef]
10. Manokhina, A.A.; Dorokhov, A.S.; Kobozeva, T.P.; Fomina, T.N.; Starovoitov, V.I. *Jerusalem artichoke* as a Strategic Crop for Solving Food Problems. *Agronomy* **2022**, *12*, 465. [CrossRef]
11. Cornescu, G.M.; Panaite, T.D.; Soica, C.; Cismileanu, A.; Matache, C.C. *Jerusalem artichoke* (*Helianthus tuberosus* L.) as a Promising Dietary Feed Ingredient for Monogastric Farm Animals. *Appl. Sci.* **2023**, *13*, 12748. [CrossRef]
12. Breton, C.; Kiru, S.D.; Bervillé, A.; Anushkevich, N.Y. Breeding of *Jerusalem artichoke* with the desired traits for different directions of use: Retrospective, approaches, and prospects. *Agric. Biol.* **2017**, *52*, 940–951. [CrossRef]
13. Long, X.H.; Shao, H.B.; Liu, L.; Liu, L.P.; Liu, Z.P. *Jerusalem artichoke*: A sustainable biomass feedstock for biorefinery. *Renew. Sustain. Energy Rev.* **2016**, *54*, 1382–1388. [CrossRef]
14. Manokhina, A.A.; Dorokhov, A.S.; Kobozeva, T.P.; Fomina, T.N.; Starovoitova, O.A. Varietal Characteristics of *Jerusalem artichoke* as a High Nutritional Value Crop for Herbivorous Animal Husbandry. *Appl. Sci.* **2022**, *12*, 4507. [CrossRef]
15. Antonkiewicz, J.; Kołodziej, B.; Bielińska, E.J.; Witkowicz, R.; Tabor, S. Using *Jerusalem artichoke* to Extract Heavy Metals from Municipal Sewage Sludge Amended Soil. *Pol. J. Environ. Stud.* **2018**, *27*, 513–527. [CrossRef]
16. Kumar, S.; Kumar, R.; Sood, P. Role of Microbial Enriched Vermicompost in Plant-Parasitic Nematode Management. In *Nematodes-Recent Advances, Management and New Perspectives*; Chapter 3; IntechOpen: London, UK, 2022; Available online: https://www.intechopen.com/chapters/77343 (accessed on 28 November 2024). [CrossRef]
17. Gimenez, E.; Salinas, M.; Manzano-Agugliaro, F. Worldwide Research on Plant Defense against Biotic Stresses as Improvement for Sustainable Agriculture. *Sustainability* **2018**, *10*, 391. [CrossRef]
18. Rehman, S.U.; De Castro, F.; Aprile, A.; Benedetti, M.; Fanizzi, F.P. Vermicompost: Enhancing Plant Growth and Combating Abiotic and Biotic Stress. *Agronomy* **2023**, *13*, 1134. [CrossRef]
19. Yatoo, A.M.; Ali, M.N.; Baba, Z.A.; Hassan, B. Sustainable management of diseases and pests in crops by vermicompost and vermicompost tea. A review. *Agron. Sustain. Dev.* **2021**, *41*, 7. [CrossRef]
20. Chatterjee, R.; Debnath, A.; Mishra, S. Vermicompost and Soil Health. In *Soil Health*; Giri, B., Varma, A., Eds.; Soil Biology; Springer: Cham, Switzerland, 2020; Volume 59, pp. 69–88. [CrossRef]
21. Gudeta, K.; Bhagat, A.; Julka, J.M.; Sinha, R.; Verma, R.; Kumar, A.; Kumari, S.; Ameen, F.; Bhat, S.A.; Amarowicz, R.; et al. Vermicompost and Its Derivatives against Phytopathogenic Fungi in the Soil: A Review. *Horticulturae* **2022**, *8*, 311. [CrossRef]
22. Ntalli, N.; Adamski, Z.; Doula, M.; Monokrousos, N. Nematicidal Amendments and Soil Remediation. *Plants* **2020**, *9*, 429. [CrossRef]
23. Silva, L.P.; Silveira, A.P.; Bonatto, C.C.; Reis, I.G.; Milreu, P.V. Silver Nanoparticles as Antimicrobial Agents: Past, Present, and Future. In *Nanostructures for Antimicrobial Therapy*; Nanostructures in Therapeutic Medicine Series; Elsevier: Amsterdam, The Netherlands, 2017; pp. 577–596. [CrossRef]
24. Yaqoob, A.A.; Ahmad, H.; Parveen, T.; Ahmad, A.; Oves, M.; Ismail, I.M.I.; Qari, H.A.; Umar, K.; Mohamad Ibrahim, M.N. Recent Advances in Metal Decorated Nanomaterials and Their Various Biological Applications: A Review. *Front. Chem.* **2020**, *8*, 341. [CrossRef] [PubMed]
25. Siddiqi, K.S.; Husen, A.; Rao, R.A.K. A review on biosynthesis of silver nanoparticles and their biocidal properties. *J. Nanobiotechnol.* **2018**, *16*, 14. [CrossRef] [PubMed]
26. Marambio-Jones, C.; Hoek, E.M.V. A review of the antibacterial effects of silver nanomaterials and potential implications for human health and the environment. *J. Nanoparticle Res.* **2010**, *12*, 1531–1551. [CrossRef]
27. Bruna, T.; Maldonado-Bravo, F.; Jara, P.; Caro, N. Silver Nanoparticles and Their Antibacterial Applications. *Int. J. Mol. Sci.* **2021**, *22*, 7202. [CrossRef]
28. Dobosz, R.; Gawlak, M.; Karnkowski, W. *Instrukcja Rozpoznawania Gatunków z Rodzaju Meloidogyne*; Instytut Ochrony Roślin. Państwowy Instytut Badawczy: Poznan, Poland, 2008; ISBN 9788389867360. Available online: https://www.ior.poznan.pl/1004,2014?nobreakup#plik_2125 (accessed on 28 November 2024).

29. Nowosielski, O. *Rules for Fertilizer Recommendations in Gardening*; PWRiL: Warsaw, Poland, 1988; Volume 310, Available online: https://www.scirp.org/reference/referencespapers?referenceid=2468331 (accessed on 28 November 2024).
30. Boss, C.H.; Fredeen, K.J. *Concepts, Instrumentation, and Techniques in Inductively Coupled Plasma Optical Emission Spectrometry*, 3rd ed.; Perkin-Elmer: Shelton, CT, USA, 2004; Available online: https://www.scirp.org/reference/referencespapers?referenceid=2215107 (accessed on 28 November 2024).
31. Available online: https://www.dijkstra.net/media/catalog/category/Dijkstra_Vereenigde_Gerhardt_Dumatherm.pdf (accessed on 28 November 2024).
32. Zapałowska, A.; Skwiercz, A.T. Populations of parasitic nematodes colonizing *Jerusalem artichoke* (*Helianthus tuberosus* L.). *Acta Soc. Bot. Pol* **2018**, *87*, 3578. [CrossRef]
33. Seinhorst, J.W. A rapid method for the transfer of nematodes from fixative to anhydrous glycerin. *Nematology* **1959**, *4*, 67–69. [CrossRef]
34. Brzeski, M.W. *Nematodes of Tylenchina in Poland and Temperate Europe*; Museum and Institute of Zoology, Polish Academy of Sciences: Warsaw, Poland, 1998.
35. Andrássy, I. Free-living nematodes of Hungary. In *Nematoda Errantia*; Vol. II; Pedozoologica Hungarica, Volume 4; Hungarian Natural History Museum, Systematic Zoology Research Group of the Hungarian Academy of Sciences: Budapest, Hungary, 2007.
36. Sinclair, J.B.; Dhingra, O.D. *Basic Plant Pathology Methods*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 1995. [CrossRef]
37. Gould, W.D.; Hagedorn, C.; Bardinelli, T.R.; Zablotowicz, R.M. New selective media for enumeration and recovery of fluorescent pseudomonads from various habitats. *Appl. Environ. Microbiol.* **1985**, *49*, 28–32. Available online: https://pmc.ncbi.nlm.nih.gov/articles/PMC238339/ (accessed on 28 November 2024).
38. Pikovskaya, R.I. Mobilization of phosphorus in soil in connection with the vital activity of some microbial species. *Microbiology* **1948**, *17*, 362–370.
39. Martin, P. Use of acid, rose Bengal and streptomycin in the plate method for estimating soil fungi. *Soil Sci.* **1950**, *69*, 215–232. [CrossRef]
40. Brzezińska, M.; Włodarczyk, T. Enzymy wewnątrzkomórkowych przemian redoks (oksydoreduktazy). *Acta Agrophysica Rozpr. I Monogr.* **2005**, *3*, 11–26. Available online: http://www.old.acta-agrophysica.org/artykuly/acta_agrophysica/ActaAgr_120_2005_0_3_11.pdf (accessed on 28 November 2024).
41. Casida, L.; Johnson, J.; Klein, D. Soil dehydrogenase activity. *Soil Sci.* **1964**, *98*, 371–376. [CrossRef]
42. Abdellatif, K.; Hamouda, R.; El-Ansary, M. Green Nanoparticles Engineering on Root-knot Nematode Infecting Eggplant plants and Their Effect on Plant DNA Modification. *Iran. J. Biotechnol.* **2016**, *14*, 250–259. [CrossRef] [PubMed]
43. Skwiercz, A.; Stefanovska, T.; Zhukov, O.; Zapałowska, A.; Masłoń, A. Effect of Silver Nanoparticles and Vermicompost on the Control of *Longidorus elongatus* (De Man, 1876) in Miscanthus × Giganteus and Its Growth and Development. *Sustainability* **2024**, *16*, 8093. [CrossRef]
44. Khan, Z.; Son, S.H.; Moon, H.S.; Kim, S.G.; Shin, H.D.; Jeon, Y.H.; Kim, Y.H. Description of a Foliar Nematode, *Aphelenchoides fragariae* (Nematoda: Aphelenchida) with Additional Characteristics from Korea. *J. Asia-Pac. Entomol.* **2007**, *10*, 313–315. [CrossRef]
45. Topalović, O.; Geisen, S. Nematodes as suppressors and facilitators of plant performance. *New Phytol* **2023**, *238*, 2305–2312. [CrossRef]
46. Lazcano, C.; Domínguez, J. The use of vermicompost in sustainable agriculture: Impact on plant growth and soil fertility. In *Soil Nutrients*; Miransari, M., Ed.; Nova Science Publishers: Hauppauge, NY, USA, 2011; Volume 10, pp. 1–23. ISBN 978-1-61324-785-3. Available online: https://jdguez.webs.uvigo.es/wp-content/uploads/2012/01/the-use-of-vermicompost.pdf (accessed on 28 November 2024).
47. Jayaswal, K.; Christian, J.; Singh, N.K.; Padhiyar, H.; Yadav, M.; Sanghvi, G. Effect of vermicompost on soil quality parameters for different land use patterns. In *ASMI-2023 IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2023; Volume 1280, p. 012054. [CrossRef]
48. Oyege, I.; Balaji Bhaskar, M.S. Effects of vermicompost on soil and plant health and promoting sustainable agriculture. *Soil Syst.* **2023**, *7*, 101. [CrossRef]
49. Domínguez, J.; Aira, M.; Crandall, K.A.; Pérez-Losada, M. Earthworms drastically change fungal and bacterial communities during vermicomposting of sewage sludge. *Sci. Rep.* **2021**, *11*, 15556. [CrossRef]
50. Collange, B.; Navarrete, M.; Peyre, G.; Mateille, T.; Tchamitchian, M. Root-knot nematode (Meloidogyne) management in vegetable crop production: The challenge of an agronomic system analysis. *Crop Prot.* **2011**, *30*, 1251–1262. [CrossRef]
51. Oka, Y. Mechanisms of nematode suppression by organic soil amendments—A review. *Appl. Soil Ecol.* **2010**, *44*, 101–115. [CrossRef]
52. Thoden, T.C.; Korthals, G.W.; Termorshuizen, A.J. Organic amendments and their influences on plant-parasitic and free-living nematodes: A promising method for nematode management? *Nematology* **2011**, *13*, 133–153. [CrossRef]

53. Xiao, Z.; Liu, M.; Jiang, L.; Chen, X.; Griffiths, B.; Li, H.; Hu, F. Vermicompost increases defense against root-knot nematode (*Meloidogyne incognita*) in tomato plants. *Appl. Soil Ecol.* **2016**, *105*, 177–186. [CrossRef]
54. Kaur, J.; Kaur, G. Dehydrogenase activity as a biological indicator of soil health. *Chem. Sci. Rev. Lett.* **2021**, *10*, 326–329. [CrossRef]
55. Maková, J.; Javoreková, S.; Elbl, J.; Medo, J.; Hricáková, N.; Kovacik, P. Impact of vermicompost on biological indicators of the quality of soil under maize in a greenhouse experiment. *J. Elem.* **2019**, *24*, 319–330. [CrossRef]
56. Szczech, M.M. Suppressiveness of vermicompost against *Fusarium wilt* of tomato. *J. Phytopathol.* **1999**, *147*, 155–161. [CrossRef]
57. Iftikhar, A.; Farooq, R.; Akhtar, M.; Khalid, H.; Hussain, N.; Ali, Q.; Malook, S.U.; Ali, D. Ecological and sustainable implications of phosphorous-solubilizing microorganisms in soil. *Discov. Appl. Sci.* **2024**, *6*, 33. [CrossRef]
58. Shouche, S.; Tiwari, D. Role of earthworms and actinomycetes in ecofriendly degradation of floral waste via vermicomposting and antimicrobial potential of actinomycetes. *Biol. Forum Int. J.* **2023**, *15*, 632–636. Available online: https://www.researchtrend.net/bfij/pdf/Role-of-Earthworms-and-Actinomycetes-in-Ecofriendly-Degradation-of-Floral-Waste-via-Vermicomposting-and-Antimicrobial-Potential-of-Actinomycetes-Deepika-Tiwari-98.pdf (accessed on 28 November 2024).
59. Crisan, C.M.; Mocan, T.; Manolea, M.; Lasca, L.I.; Tăbăran, F.A.; Mocan, L. Review on silver nanoparticles as a novel class of antibacterial solutions. *Appl. Sci.* **2021**, *11*, 1120. [CrossRef]
60. Mittal, D.; Kumar, A.; Balasubramaniam, B.; Thakur, R.; Siwal, S.S.; Saini, R.V.; Gupta, R.K.; Saini, A.K. Synthesis of biogenic silver nanoparticles using plant growth-promoting bacteria: Potential use as biocontrol agent against phytopathogens. *Biomater. Polym. Horiz.* **2022**, *1*, 22–31. [CrossRef]
61. Mossa, M.I.; El-Sharkawy, E.E.S.; El-Sharkawy, A.A. Antifungal activity of silver nanoparticles green biosynthesis from the extract of *Zygophyllum album* (L.f.) on *Fusarium wilt*. *J. Plant Prot. Res.* **2023**, *63*, 340–349. [CrossRef]
62. Li, L.; Pan, H.; Deng, L.; Qian, G.; Wang, Z.; Li, W.; Zhong, C. The antifungal activity and mechanism of silver nanoparticles against four pathogens causing kiwifruit post-harvest rot. *Front. Microbiol.* **2022**, *13*, 988633. [CrossRef]
63. Thammachote, N.; Sripong, K.; Uthairatanakij, A.; Laohakunjit, N.; Limmatvapirat, S.; Ma, G.; Zhang, L.; Kato, M.; Jitareerat, P. Influence of silver nanoparticles on postharvest disease, pericarp hardening, and quality of mangosteen. *Postharvest Biol. Technol.* **2024**, *204*, 112470. [CrossRef]
64. Kim, D.Y.; Patel, S.K.S.; Rasool, K.; Lone, N.; Bhatia, S.K.; Seth, C.S.; Ghodake, G.S. Bioinspired silver nanoparticle-based nanocomposites for effective control of plant pathogens: A review. *Sci. Total Environ.* **2024**, *908*, 168318. [CrossRef] [PubMed]
65. Bodo, K. Antimicrobial Peptides in *Eisenia andrei* Earthworms: Their Role in Immune Response, Regeneration Process and Interactions with Metal Nanoparticles. Ph.D. Thesis, University of Pecs, Pécs, Hungary, 2020.
66. Bodo, K.; Hayashi, Y.; Gerencser, G.; Laszlo, Z.; Keri, A.; Galbacs, G.; Telek, E.; Meszaros, M.; Deli, M.A.; Kokhanyuk, B.; et al. Species-Specific Sensitivity of Eisenia Earthworms Towards Noble Metal Nanoparticles: A Multiparametric In Vitro Study. *Environ. Sci: Nano* **2020**, *7*, 3509–3525. [CrossRef]
67. Baccaro, M. Quantification and Modelling of Accumulation Kinetics of Nanomaterials in Soil Organisms Under Environmentally Relevant Conditions. Chapter 3: Particle or Ion, what is the Influence of Dissolution on the Uptake of Metal Nanoparticles in Earthworm? Ph.D. Thesis, Wageningen University, Wageningen, The Netherlands, 2020; pp. 61–64. [CrossRef]
68. Baccaro, M.; Montano, M.D.; Cui, X.; Mackevica, M.; Lynch, L.; von den Kammer, F.; Lodge, R.W.; Khlobystov, A.N.; van den Brink, N.W. Influence of dissolution on the uptake of bimetallic nanoparticles Au@Ag-NPs in soil organisms *Eisenia fetida*. *Chemosphere* **2022**, *302*, 134909. [CrossRef]
69. Kokhanyuk, D.; Vantus, B.; Radnai, V.B.; Vamos, B.; Kajner, E.; Galbacs, G.; Telek, G.; Meszaros, E.; Deli, M.; Nemeth, M.A.; et al. Distinct Uptake Routes Participate in Silver Nanoparticle Engulfment by Earthworm and Human Immune Cells. *Nanomaterials* **2020**, *12*, 2818. [CrossRef]

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