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EFFECTS OF SILVER, GOLD, AND PLATINUM NANOPARTICLES ON SELECTED NEMATODE TROPHIC GROUPS

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ABSTRACT

As trophic organisms, nematodes play an essential role in the soil environment: they mineralize nutrients into plant-available forms, are a food source for other soil organisms, and feed on pathogenic organisms and plant pests, therefore regulating populations of soil microorganisms. The plant-parasitic nematodes are important pests of crops. Nanoparticles (NP) are increasingly used in agriculture and other production sectors. They are present in the soil, not necessarily in trace amounts, and can affect various soil organisms, including nematodes. In this article, the effects of silver (Ag), gold (Au), and platinum (Pt) nanoparticles on the mortality and reproduction activity of selected nematode species from two trophic groups: entomopathogenic nematodes (EPN) (*Heterorhabditis bacteriophora* and *Steinernema feltiae*) and plant parasitic nematodes (PPN) (*Xiphinema diversicaudatum*, *Ditylenchus dipsaci*, *Heterodera schachtii*) were studied under laboratory conditions. All nanoparticles decreased the nematode population to an extent depending on the nematode species, nanoparticle type, and exposure time. AgNP had the greatest nematicidal effect, except for AuNP, which reduced the population of *H. schachtii* the most. The greatest sensitivity to AgNP was observed in *X. diversicaudatum* (100% mortality), *D. dipsaci* (90% mortality), and 37 to 13% mortality in other species. Effect of AuNP and PtNP on entomopathogenic nematodes was comparable to the control, not treated with nanoparticles. AuNP and PtNP similarly influenced nematode mortality. However, the effect of nanoparticles on new generations of entomopathogenic nematodes developing in host larvae *Galleria mellonella* was inconclusive. All nanoparticles decreased the number of larvae of *S. feltiae* and increased the number of *H. bacteriophora* migrating outside the cadavers compared to the control.

Key words: entomopathogenic nematodes, plant parasitic nematodes

INTRODUCTION

Entomopathogenic nematodes (EPNs) of the Steinernematidae and Heterorhabditidae families are commonly distributed in nature. They are natural factors of environmental resistance to many soil-dwelling insect pests. EPNs are the most successful groups of microorganisms used for biological control of a wide range of pests. Biopreparations with EPNs are used in a variety of crops all over the world (Georgis et al. 2006; Ehlers 2011). *Steinernema feltiae* (Filipjev, 1934) and *Heterorhabditis bacteriophora* (Poinar, 1976) are the most commercially used EPN species (Abate et al. 2017).

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Steinernema feltiae is used for the control of various groups of insect pests, especially from the orders *Diptera* and *Thysanoptera* and *Heterorhabditis bacteriophora* for control of weevils and chafer larvae of the order *Coleoptera* (Kaya et al. 2006). Despite the unquestionable role of EPNs in biological pest management, in practice, the effectiveness of these beneficial nematodes depends on several biotic and abiotic factors that can influence their biological activity in the soil. Nematode activity and survival can be reduced by too low or too high moisture, low oxygen conditions, temperature, and pH of the soil (Kung et al. 1991; Koppenhöfer et al. 1995; Brown & Gaugler 1997; Shapiro-Ilan et al. 2002; Stuart et al. 2006). The success of biocontrol using EPNs can also be affected by fertilizers, chemical pesticides, or metal nanoparticles that can accumulate in the soil and have various effects on soil organisms (Shapiro-Ilan et al. 2012; Kim & Ryu 2013; Khanna et al. 2021). Nanoparticles (NP) are essential and natural components of the Earth (Lespes et al. 2020). However, human activity has disrupted their natural cycle through, among other, the introduction of anthropogenic nanoparticles (ANPs). Nanoparticles have unique physical and chemical properties, with dimensions below 100 nm. Nanotechnology has also found its way into agriculture with new tools for detecting and treating plant diseases, controlling viruses and other pathogens, or increasing the ability of plants to absorb nutrients (Mousavi & Rezaei 2011; Singh et al. 2015). Few studies are available on the effect of nanoparticles on EPN and other animals (Exbrayat et al. 2015). This issue requires detailed investigation, taking into account several factors regarding the physical-chemical properties of the nanoparticles themselves as well as the strength of their effect on different nematode species (Kucharska & Pezowicz 2009; Kucharska et al. 2011a, b; Taha & Abo-Shady 2016; Makirita et al. 2020).

Most studies on the control plant parasitic nematodes (PPN) by nanoparticles, was conducted on silver nanoparticles and *Meloidogyne incognita* in juvenile (J2) invasive stage (Cromwell et al. 2014; Taha 2016; El-Deen & El-Deeb 2018; Baronia et al. 2020). Less attention was paid to gold (AuNP) and platinum nanoparticles. Thakur and Shirkot (2017) and Ardakani (2013) found 100% mortality of J2 *M. incognita* in treatments of 800, 400 and 200 $mg \cdot dm^{-3}$ AgNP. Cromwell et al. (2014) inactivated 99% of *M. incognito* specimens after 6 hours of AgNP treatment, but in the case of *M. graminis*: 92% and 82% after 4 and 2 days exposure relatively. Thakur and Shirkot (2017) showed effective results using gold nanoparticles to control PPN. The nematocidal effect of PtNP on the *Caenorhabditis elegans* (Maupas, 1900) showed for the first time method to facilitate bio-active nanoparticles into living to establish the antioxidant effect in those organisms (Kim et al. 2010). Investigations of Prabhu and Poulose (2012) showed the mechanism of action of AgNP. AgNP attacks the cell walls of microbes, causing cell lysis. It leads to the formation of free radicals inside the cell. AgNP interacts with respiratory enzymes and then releases reactive oxygen, leading to cell destruction. AgNP binds to ribosomes and causes inhibition of protein synthesis, binds also to DNA bases, and disrupts its function.

The current work assessed the effects of AgNP, AuNP, and PtNP solutions on different trophic groups of nematodes naturally occurring in the environment. The following were assessed: 1) the viability, infectivity, and pathogenicity of EPN *Steinernema feltiae* and *Heterorhabditis bacteriophora*, the species most commonly used in practice to protect plants against pests, and 2) the effect on mortality of plant parasitic nematodes (PPN) (*Xiphinema diversicaudatum*, *Ditylenchus dipsaci*, *Heterodera schachtii*, *Hirschmanniella baltica*).

MATERIALS AND METHODS

Nematodes

The influence of silver (Ag), gold (Au), and platinum (Pt) nanoparticles on the biological activity of two groups of nematodes was studied. Entomopathogenic nematodes: *Heterorhabditis bacteriophora* (Poinar, 1976) (B-Green, Biobest Group NV, Belgium) and *Steinernema feltiae* (Filipjev, 1934) (Steinernema-System, Biobest Group NV, Belgium) constituted the first group. Plant parasitic nematodes: *Xiphinema diversicaudatum* (Micoletzky, 1927), *Ditylenchus dipsaci* (Kuhn, 1857),

Heterodera schachtii (Schmidt, 1871), and *H. baltica* belong to the second group, originating from the in-house culture at the National Institute of Horticultural Research in Skierniewice, Poland.

Biopreparations in the third stage of infective juveniles (IJ3) that were used for the experiment were purchased simultaneously with a guarantee of their highest quality. They were stored at 7°C (*Steinernema* spp.) and 10°C (*Heterorhabditis* spp.) before use (Kaya & Stock 1997). The nematodes were tested on the fifth-stage larvae, the greater wax moth (*Galleria mellonella* L.), a lepidopteran host highly susceptible to EPNs.

Colloids preparation

For the experiments, nanoparticle solutions suspended in deionized water were used at concentrations of Au 417 ppm (particle size: 24 ± 4 nm), Ag – 301 ppm (particle size: 30 ± 4 nm), and Pt – 381 ppm (particle size: 5 ± 3 nm). Colloidal solutions of nanoparticles were purchased from the Plant Breeding and Acclimatization Institute National Research Institute, Bonin Branch (Poland).

The tested gold and silver nanocolloids were characterized in previous publications by Wesołowska et al. (2019) and Jadczak et al. (2020) using spectral analysis in the UV-VIS range (300–900 nm), scanning electron microscope (SEM), and transmission electron microscope (TEM), respectively.

The aqueous suspensions were synthesized using the methods of Turkevich et al. (1951) and Liu et al. (2003) with modified synthesis conditions and two-stage microwave-convection heating. For this purpose, aqueous mixtures of 3.5 mM sodium citrate with 7.0 mM tetrachloroauric acid ($HAuCl_4$), 7.0 mM silver nitrate ($AgNO_3$) and 7.0 mM potassium tetrachloroplatinate II (K_2PtCl_4), respectively, were prepared. Their spectra were plotted with a UV-Vis Epoch microplate spectrophotometer (BioTek, Winooski, VT, USA), and the optical density of the fractions obtained was adjusted to a standard DEV value using the spectra absorbance maxima (λmax = 520 nm for gold c, λmax = 445 nm for silver, and λmax = 260 nm for platinum colloids). The similarities in the morphology, shape, and size of the synthesized and prepared AuNPs, AgNPs, and PtNPs were assessed by analyzing their images obtained using a transmission electron microscope (TEM) JEM-2100 (JOEL, Tokyo, Japan) and scanning electron microscope (SEM) FEI Quanta 200 FEG.

During the synthesis of nano colloids, no preservatives or additional substances preventing the aggregation of nanoparticles were used. The maximum content of other substances present in the tested solutions is < 0.04% sodium citrate (AuNP, AgNP, and PtNP), < 0.0001% nitrates NO_3 (AgNP), and < 0.0001% chlorides Cl_4 (PtNP). The pH of the obtained AuNP, AgNP, and PtNP nanocolloids was 6.71, 7.37, and 6.36, respectively.

The size and zeta potential of Au, Ag, and Pt colloid nanoparticles were measured using particle size, molecular weight, and zeta potential analyzer – Zetasizer Nano ZS Ver. 6.20 (Malvern Instruments, UK). Zeta potential (in mV), known as the electrokinetic potential, testifies to the stability and ability to agglomerate nanoparticles in the tested suspensions. It is the potential difference at the interfaces between solids and liquids. In colloids, the zeta potential is the difference in electrical potentials in the ionic layer around the charged ions of the colloids, which is a measure of the electrical charge of particles suspended in the liquid. The higher the zeta potential value for the tested particles, the more stable the colloid is. For the measurements of nanoparticles, values below −30 and above 30 mV indicate their stability (Table 1, Fig. 1).

Table 1. Characteristics of colloids used in the research

Colloid suspension	Zeta potential		Conductivity [mS·cm^{-1}]
	Mean [mV]	SD [mV]	
Au	−43,8	6,27	1,12
Ag	−57,5	13,60	1,10
Pt	−44,1	6,98	1,77

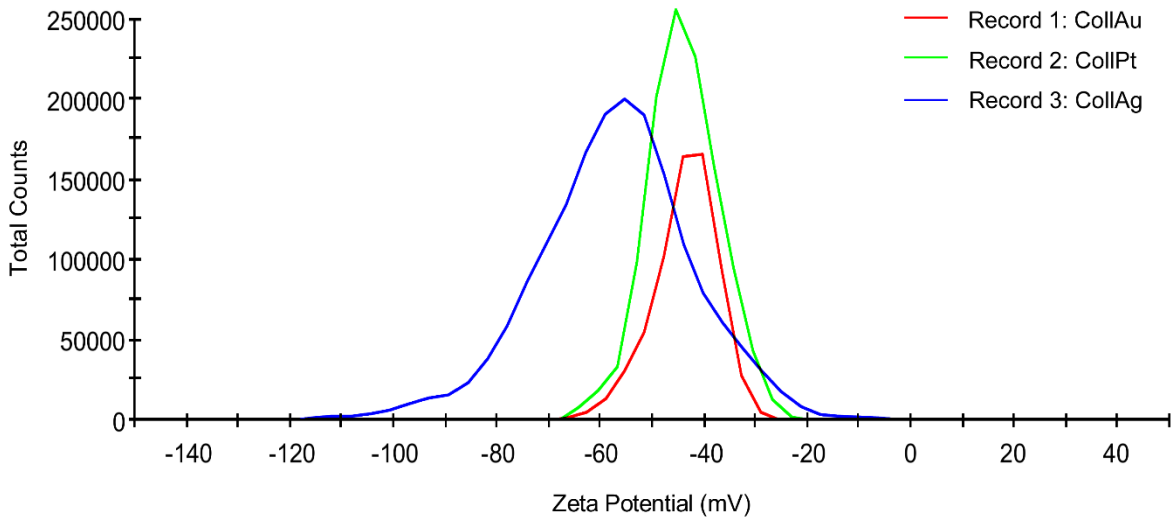


Figure 1. Zeta potential distribution (mV) od colloids used in the research

Effect of nanoparticles on the life cycle of nematodes

Evaluation of the viability of EPNs

1000 IJ EPN per 5 cm diameter Petri dish were added to aqueous solutions containing appropriate concentrations of nanosilver, nanogold, and nanoplatinum with three replicates for each nanocolloid variant. All repeats were incubated at 25 ± 2°C. The control group consisted of 1000 IJ3 EPNs kept in distilled water.

The viability of IJ3 nematodes in the nanocolloid solutions was tested every 24 hours until day 3 of the experiment. After 72 hours of nematode IJ3 exposure in colloid solutions, they were washed with distilled water on a sieve. Then, after 2 hours, the final nematode mortality was calculated for each replicate.

EPNs pathogenicity and reproduction

All live nematodes after 3-day exposure in colloid solutions of AuNP, AgNP, and PtNP were transferred in 1 ml distilled water to three Petri dishes (3 repetitions) of 9 cm diameter lined with filter paper containing each ten larval instars of *G. mellonella* in the appropriate order of repetition. Experiments were performed at 25 ± 2°C and 85–90% relative moisture. The insect mortality percentages were recorded every 24 hours for four days. The control consisted of *G. mellonella* larvae infected with nematodes that did not contact nanocolloids. The cadavers were washed and divided into two groups. Half of the cadavers were dissected in Ringer's solution. Dissection of host insects was done three days (*Steinernema*) and four days (*Heterorhabditis*) after infection to recover first-generation adults (males and females). The isolated nematodes (male and female or hermaphrodites) were identified on the basis of their morphological and morphometric criteria (Nguyen & Smart 1995; Hominick et al. 1997; Nguyen 2007) and then were counted. The second part of the dead insects was transferred to a sponge trap for reproduction and in vivo multiplication (Peters et al. 2017).

Assessment of the viability of PPN

The specimens of invasive larvae of PPN species were kept in aqueous solutions containing appropriate nanosilver, nanogold, and nanoplatinum with three replications for each nanocolloid for 48 hours. There were different initial population densities per replication: *X. diversicaudatum* (11 larvae) *D. dipsaci* (1500 specimens), *H. schachtii* (20 larvae), and *H. baltica* (1350 specimens).

Statistical analysis

The results of the nematode total number were analyzed with the Shapiro–Wilk distribution normality test and the homogeneity of variance was checked with Lavene's test. Dunnett's test (two-sided) was used for multiple comparisons with control ($p = 0.05$). The package XLSTAT version 2019.2.2 (Addinsoft 2019) was used to perform calculations.

RESULTS

Effect of nanoparticles on entomopathogenic nematodes (EPNs) viability

The mortality of infective juveniles (IJs) of entomopathogenic nematodes exposed to different types of nanoparticles depended on the type of nanoparticles, the time of exposure, and EPN species (Fig. 2A, B. The lowest mortality of *S. feltiae* larvae compared to the control was found after nematode contact with gold nanoparticles ($p > 0.05$). Only after 48 hours, single dead *S. feltiae* larvae were observed in the AuNP colloidal solution (Fig 1A). An increase in the mortality of *S. feltiae* relative to the control was recorded when the nematodes were in contact with AgNP ($p < 0.01$), in which about 22% of larvae died. AuNP and AgNP had a similar toxic effect on *H. bacteriophora* ($p < 0.01$) (Fig. 1B), but here, AgNP killed about 37% of larvae. Neither gold nor platinum nanoparticles significantly affected the viability of IJs *H. bacteriophora* ($p > 0.05$).

Effect of nanoparticles on plant parasitic nematodes (PPN) viability

All kinds of nanoparticles display nematicidal effect for the PPNs species: *D. dipsaci*, *X. diversicaudatum*, *H. baltica*, and *H. schachtii*, but nematodes sensitivity to nanoparticles depended on the species, type of nanoparticle, and time of exposition (Fig. 3A–D). The mortality was the lowest in control except for *X. diversicaudatum*, where it was almost total for each treatment (Fig. 3D). The first three above species were most sensitive to AgNP (about 18%, 100%, and 30% of larvae died within 48 hours, respectively (Fig. 3A, C, D), but 100% *H. schachtii* larvae dead when exposed to AuNP (Fig. 3B).

The mortality of *D. dipsaci* was low up to 24 h but increased to 13–18% for all nanoparticle treatments, although there were differences between them, whereas mortality in control was about 3% (Fig 3A). The mortality of *H. schachtii* increased gradually, reaching 100% in the treatment where larvae were exposed to AuNP. The exposure to AgNP and PtNP caused slightly lower mortality, about 80%. The mortality of larvae not exposed to nanoparticles was about 30% (Fig. 3B). *H. baltica* was the most resistant, and the highest larvae mortality (30%) was observed in the group treated with AgPN. The nanoparticles AuPN and PtPN killed 15–16% larvae. The mortality in control was about 13% (Fig. 3C). All larvae of *X. diversicaudatum* died after exposure to AgNP within 24 h. In the remaining group, the mortality increasing through 48 h, but finally, all larvae died (Fig. 3D).

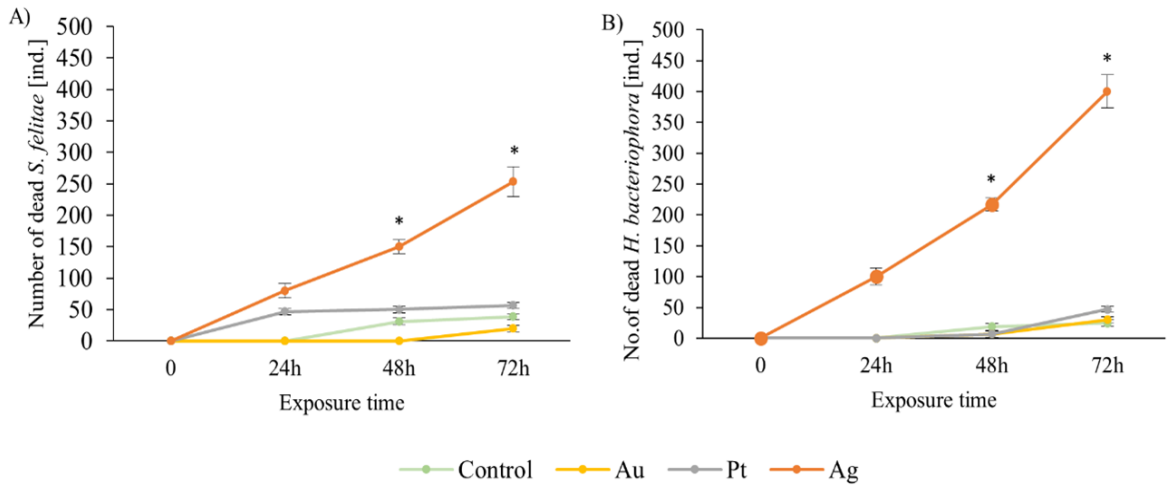


Figure 2. Effect of nanoparticles AuNP, PtNP, and AgNP on mortality of infective juveniles *S. feltiae* (A) and *H. bacteriophora* (B)
Error bars represent standard errors. Stars indicate means significantly different compared with the control not exposed to nanoparticles (Dunnett test, n = 3)

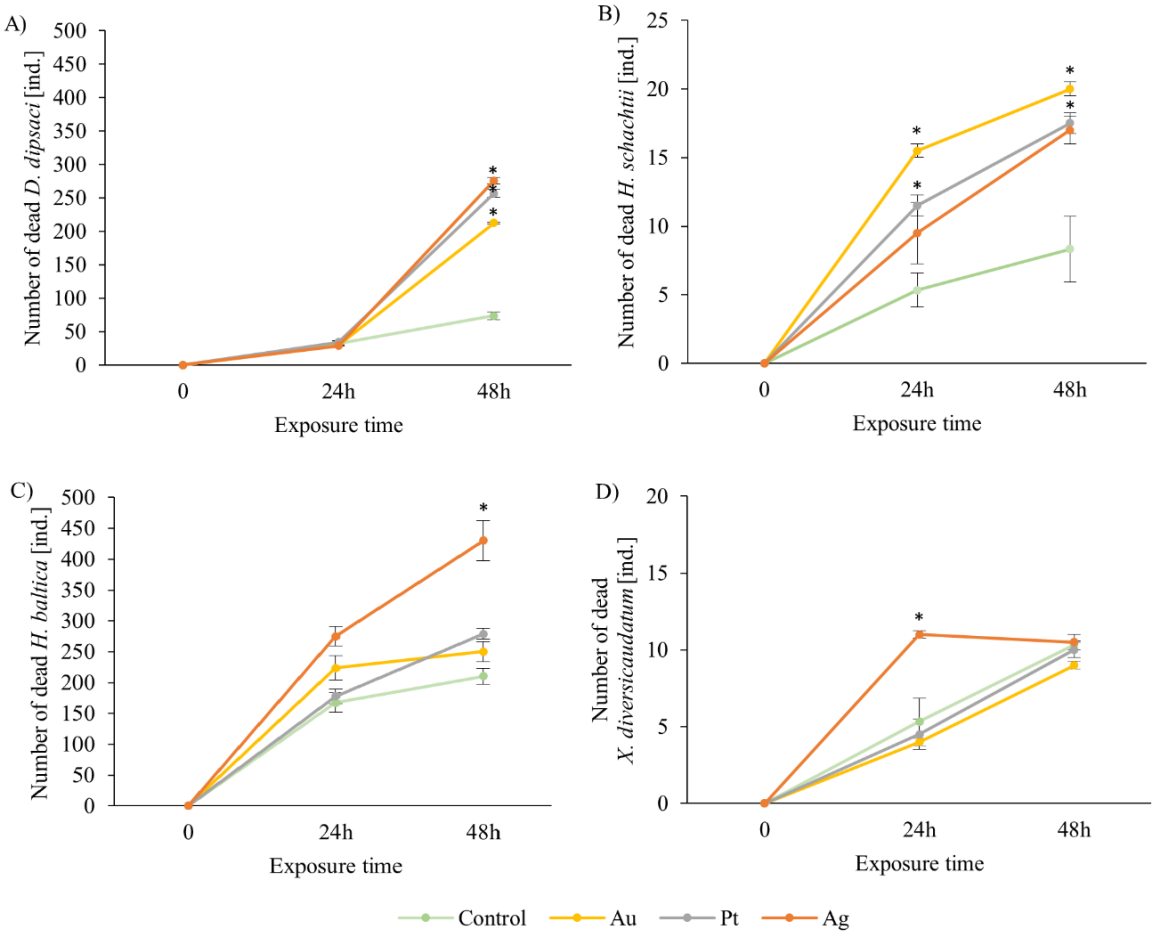


Figure 3. Effect of nanoparticles on mortality of *D. dipsaci* (A), *H. schachtii* (B), *H. baltica* (C), *X. diversicaudatum* (D)
Error bars represent standard errors. Stars indicate means significantly different to the control not exposed to nanoparticles (Dunnett test, n = 3)

Effect of nanoparticles on EPNs pathogenicity against *Galleria mellonella* and reproduction

Irrespective of the mortality of infective juveniles of *S. feltiae* kept in different nanoparticle solutions during the first stage of the experiment, no difference in the pathogenicity of these larvae concerning the host was recorded compared to the control. All *G. mellonella* caterpillars died within 48 hours of contact with the NPN nematodes. The reaction was different in *H. bacteriophora* larvae, which, after previous contact with silver and gold nanoparticles, infected the host only after 72 hours.

The results of dissecting *G. mellonella* larvae infected by EPNs demonstrate that nanoparticle solutions in which the infective larvae previously lived affected their biological activity and further developmental cycle within the host (Figs. 4 & 5). A particularly low frequency of *S. feltiae* adults in cadavers was recorded when these nematodes were exposed previously to silver and gold nanoparticles. These differences were statistically significant compared to the control (Fig. 4). In all experiment variants (nematodes in contact with nanoparticles and without contact – control trial), *S. feltiae* females dominated over males in the host.

In the case of *H. bacteriophora*, adverse strong effects on nematodes were found after contact with *H. bacteriophora* IJs with silver nanoparticles (Fig. 5). In this case, only single hermaphrodites were found in dissected, dead insects. Similarly, gold and platinum nanoparticles had a significant limiting effect on the further development of *H. bacteriophora*.

The production efficiency of EPNs migrating from the host-cadaver to water surroundings varied

depending on the nematode species tested and the type of nanoparticles used (Fig. 5). The average number of *H. bacteriophora* larvae emerging from the dead host was similar or even higher compared to the control, after initial contact of the nematodes with silver and platinum nanoparticles. A slightly lower migrating *H. bacteriophora* larvae density was recorded when IJs were initially contacted with gold nanoparticles. However, these differences were not statistically significant (Fig. 5). *Steinernema feltiae* was more sensitive to contact with the nanoparticles tested (AuNP, AgNP, PtNP) (Fig. 5). This was indicated by the markedly reduced fecundity of this species compared to the control. The average number of *S. feltiae* invasive larvae migrating from the dead host *G. mellonella* was almost half that of the control.

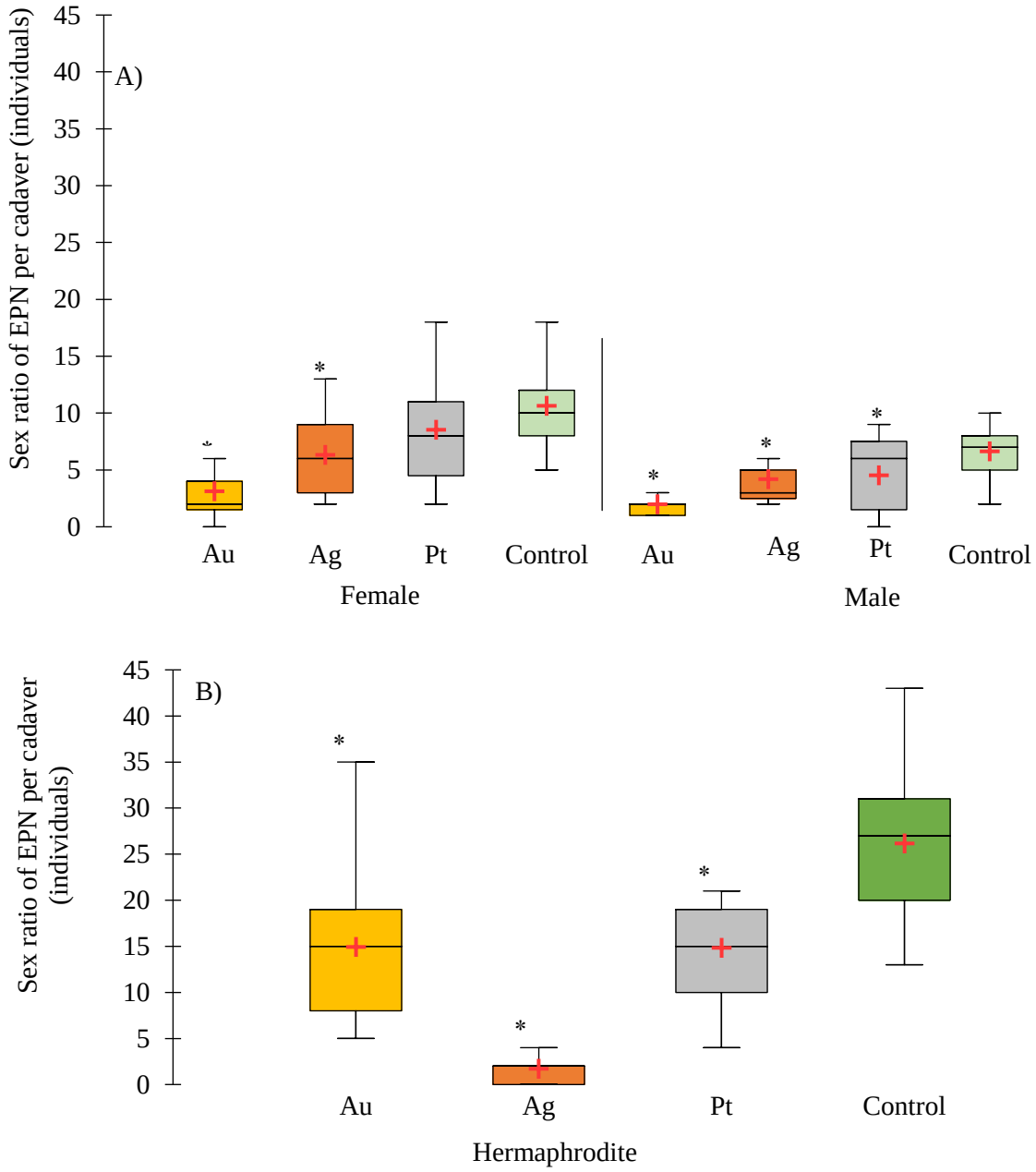


Figure 4. Effect of nanoparticles on sex ratio of *S. feltiae* (A) and *H. bacteriophora* (B)

Given are means per one cadaver. Error bars represent standard errors. Stars indicate means significantly different compared with the control not exposed to nanoparticles (Dunnett test, n=3)

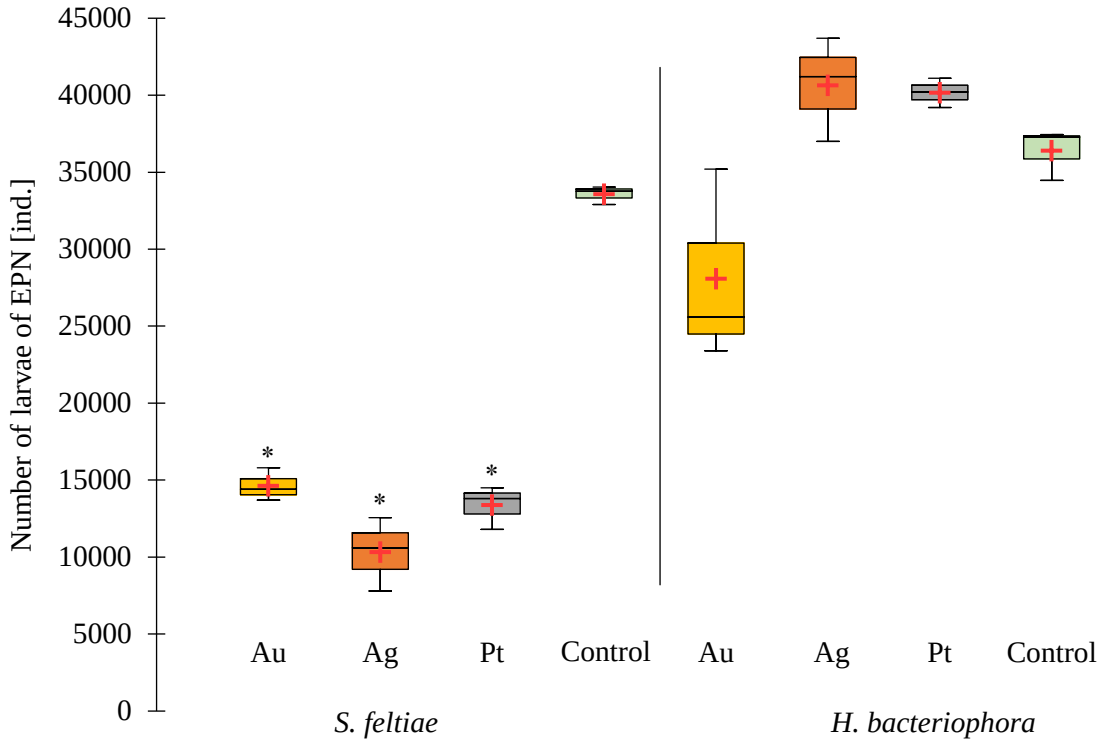


Figure 5. Effect of nanoparticles on fertility of *S. feltiae* and *H. bacteriophora* (i.e. average number of EPN larvae migrating from *G. mellonella* cadaver)

Error bars represent standard errors. Stars indicate means significantly different comparing with the control not exposed to nanoparticles (Dunnett test, n=3)

DISCUSSION

Metal nanoparticles can affect soil organisms to varying degrees. For example, it has been shown that silver ions (Ag+) can have strong toxic effects on many species of soil bacteria and fungi (Kim et al. 2007; Lara et al. 2011; Grün et al. 2019). However, the role of metal nanoparticles in the environment is unclear. On the one hand, they exert pressure on the soil environment; on the other, they restrict the growth of harmful organisms by acting as a potential nematicide, for example (Baronia et al. 2020). In addition, the strength of the effect of metal nanoparticles on the microbial community will depend on the type of nanoparticle, their concentration, exposure time, and the physical and chemical properties of the soil (Taha & Abo-Shady 2016; Grün et al. 2018, 2019).

Plant-parasitic nematodes are major agricultural pests causing crop losses worldwide. Although limited reports are available on the use of nanoparticles to control of plant-parasitic nematodes, the results obtained encourage the continuation of the research undertaken. Various studies have confirmed the high efficacy of AgNP against J2 stages of the root-knot nematode *M. incognita* (Ardakani 2013; Cromwell et al. 2014; Taha 2016; El-Deen & El-Deeb 2018). All the authors (except Ardakani 2013) declare no toxic symptoms of nanoparticles on surveyed plants. Only Ardakani (2013) noted a significant reduction of the roots and stem length. In our experiment on the PPN, treated by AgNP, AuNP, and PtNP, the highest sensitivity to nanoparticles was observed in the second stage larvae of *H. schachtii*, where a marked increase in mortality was observed after 24h and 48h when exposed to silver and platinum nanoparticles.

A similar trend was observed for the effect of AgNP on *X. diversicaudatum* after 24h exposure, where the mortality rate was more than double compared to the control. The least sensitive to nanoparticles was *H. baltica*, whose mortality increased only after 48h exposure to the AgNP solution. In other cases, this species had no significant response to PtNP nanoparticles.

In studies on the effect of nanoparticles on entomopathogenic nematodes, it was found that silver, gold, and copper nanoparticles can have a positive effect on nematode pathogenicity depending on the concentration used (Kucharska et al. 2011b; Kucharska et al. 2016) and the exposure time (Taha & Abo-Shady 2016). Of the different nanoparticles tested (AgNP, AuNP, and PtNP), silver nanoparticles proved the most toxic to *S. feltiae* and *H. bacteriophora* larvae. In contrast, there were no significant differences in mortality of nematode infective larvae after exposure to gold and platinum nanoparticles. Moreover, the mortality of entomopathogenic nematode IJs when exposed to AuNPs was comparable (for *H. bacteriophora*) or lower (for *S. feltiae*). Similar results for *S. feltiae* were obtained by Kucharska et al. (2011a) using lower doses of nanogold (0.5 ppm). Several studies suggest that prolonged exposure of EPN larvae to nanoparticle solutions can significantly increase their mortality (Kucharska & Pezowicz 2009; Taha & Abo-Shady 2016). The study by Kucharska et al. (2011b) showed that due to silver nanoparticles, the mortality of *S. feltiae* nematodes increased over time regardless of the nanosilver concentration used, i.e., 0.5 or 5 ppm. Under laboratory conditions, it has been shown that the biological activity of EPNs is influenced not only by the concentration of nanoparticles in the environment but also by the type of nanoparticle with which they are in direct contact. Despite similar concentrations (AuNP – 417 ppm, AgNP – 301 ppm, and Pt – 381 ppm), silver nanoparticles, compared to gold and platinum nanoparticles, had the strongest toxic effect on infective juveniles of the tested species of EPN, i.e., *S. feltiae* and *H. bacteriophora*. Similar results were obtained for the number of EPN adults found in the cadavers. However, the results were inconclusive during the migration of a new generation of EPN infective juveniles from dead insects. For *H. bacteriophora*, the number of IJs nematodes migrating outside the cadavers after contact with AgNP and PtNP was the highest compared to the control and other nanoparticles. Taha and Abo-Shady (2016) found in their study a slight effect of concentrations of nanosilver on EPN pathogenicity but a significant effect on EPN reproduction, especially at higher concentrations of silver nanoparticles.

Similarly, in experiments with silver, gold, and platinum nanoparticles, the nanoparticles tested affected the reproductive properties of nematodes significantly. This applies not only to the concentration of nanoparticle solutions, but also to the species of nematodes that came into contact with them. The reproductive properties of *S. feltiae* significantly decreased after contact with different types of nanoparticles, unlike in the case of *H. bacteriophora*, whose reproductive potential increased after contact with platinum and silver nanoparticles. Also, in Taha and Abo-Shada (2016), the reproductive properties of *H. indica* from Heterorhabditidae family were consistently higher than the control, regardless of the concentration of nanoparticles. Other studies show that some chemical compounds, e.g., neonicotinoids (Koppenhöfer et al. 2000; Manzoor 2012) similar to nanoparticles, can stimulate entomopathogenic nematodes with beneficial effects on their biological activity, e.g., EPNs pathogenicity and reproductivity (Kucharska et al. 2016; Taha & Abo-Shady 2016). The available studies show that AgNPs can have toxic effects on organisms by causing oxidative stress (Kim & Ryu 2013). None of the published studies have shown that they stimulate development, as in *H. bacteriophora* in our experiment.

Nanoparticles come in a wide range of sizes, shapes, and materials and can affect living organisms to varying degrees. For organisms, nanoparticles are foreign elements with specific physicochemical properties and sizes (Exbrayat et al. 2015). Due to their small size, nanoparticles can easily penetrate the cell membrane, bypassing the body's defense mechanisms. Various studies show that the size of nanoparticles affects the functioning of organisms;

often, the smaller the size of nanoparticles, the greater their toxicity (Exbrayat et al. 2015). In our study, this directly proportional relationship was not confirmed. The smallest-size platinum nanoparticles did not affect the mortality of third-stage infective juveniles of entomopathogenic nematodes as the larger silver nanoparticles.

CONCLUSION

Studies on the effect of nanoparticles on the biological activity of two trophic groups of nematodes – entomopathogenic and plant pathogenic showed that using nanoparticles in agriculture can increase the effectiveness of entomopathogenic nematodes in plant protection from pests. On the other hand, this protection can reduce the harmfulness of plant parasitic nematodes. The results encourage further research on the antagonistic or synergistic effect of nanoparticles on nematodes in the context of their use in biological pest control.

Declarations

The authors declare no competing interests.

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