



A synergistic combination of selenium nanoparticles, goldmine soil and water disrupt phytomorphological and biochemical parameters of *Abelmoscus esculentus*

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ABSTRACT

The combined influences of decommissioned goldmine soil (GS), goldmine water (GW), and selenium nanoparticles (SeNPs) on *Abelmoscus esculentus* physiology, morphology, and biochemistry were investigated in this study. The SeNPs were mediated with bark extract of *Cola nitida* and characterized with UV-Vis, FTIR, SEM-EDX and XRD techniques. SeNPs were crystalline and absorbed maximally at 290 nm characteristic of SeNPs. As, Cd, Cr, Al, U and Th were found in both GS and GW, with GW containing higher levels than recommended by the WHO. Different soil compositions were used to grow *A. esculentus* seeds with varying amounts of control soil, control water, goldmine soil, and goldmine water with and without SeNPs. *A. esculentus* exposed to different soil compositions besides control (control soil + control water) showed significant reductions in antioxidant activity, relative water content, photosynthetic pigments, increased malondialdehyde (MDA) and H₂O₂ concentrations, disruption of the cortex, xylem and pith, and inhibition of roots, shoots, and vigour indices. The further decline in *A. esculentus* physiological and biochemical characteristics by SeNPs implies their phytotoxicity. It is evidenced in this study that using goldmine soil and water simultaneously as practised by farmers in gold mining communities harms plant health and also public health.

1. Introduction

The potential risks associated with gold mining have resulted in a significant degree of toxic metals (TEs) contamination being detected in ecological media (Orimoloye and Ololade, 2020; Chetty et al., 2021). Metal contamination during gold mining has been linked to long-term biodiversity loss, particularly during blasting, drilling, tailings and washing (du Plessis and Curtis, 2021; Chen et al., 2022; Gao et al., 2022). Gold mining typically results in pollution, as evidenced by the contamination of various environmental matrices with Hg, As, Pb, U, Th, Cd, and Cr (Gautam and Agrawal, 2021; Zeeshan et al., 2021; Hao et al., 2022). Even trace amounts of these metals can harm public health and the environment due to their persistence, toxicity, mobility, and non-biodegradability (Marrugo-Madrid et al., 2022). These metals have been linked to the induction of oxidative stress, which disrupts cells, cancer, brain, liver, kidney, lung disorders and dermal defects (Alsafran et al., 2021; Qi et al., 2021). Unfortunately, these metal-containing mining ef-

fluents are frequently dumped into bodies of water and soil, polluting them beyond acceptable levels. Mining-related activities can endanger human health in the absence of effective prevention and management (du Plessis and Curtis, 2021; Chen et al., 2022). This is more prevalent in areas where artisanal and small-scale miners use mercury to recover gold through amalgam formation (Gnonsoro et al., 2022; Grant and Wilhelm, 2022). Furthermore, these small-scale gold mining operations take place in areas where self-consumption crops like vegetables, palm trees, cassava, yams, and fruits are grown. Those living in gold mining areas are more likely to suffer from degenerative and non-communicable diseases as they are exposed to different pollutants, particularly lead poisoning. It could happen through ingesting polluted soil or water or consuming vegetables planted with it (Chetty et al., 2021; Azeez et al., 2022).

Toxic metals can cause significant changes in plants, such as the destruction of their morphological, physiological, biochemical, and photosynthetic pigment indices, resulting in phytotoxicity (Zhao et al., 2019;

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Liza et al., 2020; Manara et al., 2020; Qi et al., 2021). Due to metal toxicity, plants usually exhibit chlorosis and stunted growth as warning signs of radical generation. Plants' ability to detoxify or hyperaccumulate toxic metals is the result of a complex adaptation process (Angulo-Bejarano et al., 2021; Pandey et al., 2022). Phytoremediation, which limits the transport of metals and prevents their accumulation and translocation by phytostabilizing metals, is amongst the strategies used by plants to address metal toxicities (Zeeshan et al., 2021; Azeez et al., 2022). Other processes include the modulation of phytochemicals and enzymes. When plant immunity is compromised, oxidative stress is triggered by the excessive generation of radicals without corresponding antioxidants to scavenge them leading to the disruption of biomolecules with metabolism severely disturbed (Angulo-Bejarano et al., 2021; Ogunkunle et al., 2023).

Several strategies, including the use of various nanoparticles (NPs), have been used to mitigate the negative effects of toxic metals in plants and to modulate their biochemical parameters for improved health-promoting ability. Metal and metal oxide nanoparticles such as Ag, Se, Fe, Fe₂O₃, TiO₂, CeO₂, MgO, ZnO, NiO, and others have been shown in studies to be effective adsorbents and stress modulators to mitigate metal toxicity in plants for improved performance (Babajani et al., 2019; Behbahani et al., 2020; Hasanuzzaman et al., 2020; Azeez et al., 2019, 2022; El-Badri et al., 2022; Kamali-Andani et al., 2022; Santhosh et al., 2022; Ogunkunle et al., 2020, 2023).

As an essential metalloid, selenium (Se) has a wide range of applications in modifying hormones, increasing antioxidant activity, reprogramming enzyme transcription, enhancing photosynthetic pigmentation, modulating secondary metabolites, and improving plant defences against biotic/abiotic stresses (Babajani et al., 2019; Oliveira et al., 2019; Zhao et al., 2019; Liu et al., 2022; Sharma et al., 2022). Besides, selenium nanoparticles (SeNPs) have been shown to exhibit the above characteristics in addition to eliciting distinct responses in plants that are quite different from bulk Se (Cittrarasu et al., 2021; Meenambigai et al., 2021). In contrast to metallic and metal oxide nanoparticles, SeNPs are preferred for treating cancer, fibrosis, and metal poisoning in humans. In addition to possessing antioxidant, antimicrobial, and antiproliferative properties, SeNPs also enhance plants' physiological, biochemical, and stress tolerance abilities (Lima et al., 2019; Santhosh et al., 2022). Some studies have documented differences in the morphology, physiology, metabolism, DNA fragmentation, gene expression, and health-promoting characteristics of plants exposed to SeNPs as a result of their phytostimulation and phytotoxicity (Babajani et al., 2019; Behbahani et al., 2020; Kumar and Prasad, 2020; Kamali-Andani et al., 2022). Nanoparticle modulation and phytotoxicity are influenced by factors such as concentration, shape, size, mode of synthesis and application (Safari et al., 2018; El-Badri et al., 2022; Sharma et al., 2022). Additionally, the plant type/development stage, the mode of an experiment, and the environment play critical roles in determining the phytostimulation or phytotoxicity of nanoparticles. There is no doubt that no two plants react exactly the same way to different nanoparticles (Hu et al., 2018; Nazerieh et al., 2018; Sotoodehnia-Korani et al., 2020; Shin et al., 2021).

Okro (*Abelmoschus esculentus* L.) is a multi-use vegetable with leaves and seeds that can be eaten fresh or dried. It is expensive, readily available and cherished for its good nutritional and medicinal profiles (Ogunkunle et al., 2023). It contains vitamins, minerals, and bioactive compounds that are necessary for a healthy diet (Azeez et al., 2019). It consumed as much as 62.5 g/meal daily in Nigeria (Chubike et al., 2013).

Previous studies relied either on simulated polluted soil or primarily on separate soil or water contamination from gold mines as sources of potentially toxic elements. This may have underestimated the compromised plant characteristics and, by extension, the medicinal uses required by residents. The combined effect of goldmine soil and goldmine water on *A. esculentus* morphological and biochemical parameters alongside the metal decontamination ability of SeNPs has not yet been

studied. As a result of the importance of this vegetable and some other vegetables in its category being planted by residents of gold mining areas currently facing existential environmental challenges resulting from mining and exposure to toxic metals, this study examined the simultaneous exposure of *A. esculentus* to goldmine soil and goldmine water with the application of SeNPs for metal decontamination and stimulation of other parameters.

2. Materials and methods

2.1. Biosynthesis and determination of the concentration of selenium nanoparticles

Following the method previously reported by Adibian et al. (2022), selenium nanoparticles (SeNPs) were mediated with the bark extract of *Cola nitida*. A drop-wise addition of 10 mL of *C. nitida* extract was added to 90 mL of 10 mM sodium selenite solution while being magnetically stirred. The resulting solution was kept in the dark for 24 h, resulting in red-coloured SeNPs. The concentration of SeNPs was determined following the procedure described by Azeez et al. (2019).

2.2. Instrumentation and characterization of SeNPs

The maximum absorption peak was identified using UV-Visible spectroscopy scanned from 190 to 900 nm. Fourier transform-infrared (FTIR) spectroscopy was used to identify the functional groups in the biomolecules used as capping and reducing agents in the biosynthesis of SeNPs scanned from 400 to 4000 cm⁻¹. The surface morphology and elemental composition were examined using scanning electron microscopy (SEM) and Energy-Dispersive X-Ray (EDX). The crystallinity and particle (grain) size of SeNPs calculated from the Debye-Scherrer formula (Eq. (1)) were determined by X-ray diffraction (XRD) using an Empyrean X-ray diffractometer operated at 45 kV/40 mA with Cu-K radiation and maintained at = 1.54060 Å over a scanning range of Bragg angles (2θ) from 0° to 80°

$$D = \frac{k\lambda}{\beta \cos \theta} \quad (1)$$

Where $k = 0.94$ stands as a constant value, λ is the wavelength of the X-ray, β is the half-width of the peak, and θ is the irradiation angle (Azeez et al., 2022).

2.3. Sampling location and planting experiment

Sediment and water samples were collected from a gold-mined site at the Odo-Rice community (7°29'19.6"N 4°35'01.0"E), opposite the Nigerian correction centre, off Ife-Ifewara road, Osun State, Southwest, Nigeria at a depth between 0 and 25 cm. This community is renowned for growing rice. Additionally, the control soil sample was collected from a farm near the Olagunsoye Oyinola auditorium (7°36'32.3" N 4°36'07.2"E), Osun State University, Osogbo, Southwest, Nigeria at a depth between 0 and 25 cm. The sampling was done four times and mixed thoroughly to obtain detailed representative samples. The sediment and control soil samples were air-dried for a week and sieved with a mesh size of 2 mm. The map (Fig. 1) details the sampling locations at the goldmine sites

A. esculentus seeds (Batch number 43664CIT0BX) were procured from Premier Seeds Nigeria Limited, Jericho, Ibadan, Oyo State, Nigeria. Five viable seeds were grown in each of the non-perforated plastic buckets (5 L) at the screen house of the Department of Plant Biology, Osun State University, Osogbo, Nigeria for twenty-one days with the following variations: control soil + control water (CSCW), control soil + goldmine water (CSGW), goldmine soil + control water (GSCW), goldmine soil + goldmine water (GSGW), control soil + control water + SeNPs (CSCWSE), control soil + goldmine water + SeNPs (CSGWSE), goldmine soil + control water + SeNPs (GSCWSE) and goldmine soil + goldmine water + SeNPs (GSGWSE). Each treatment had four buckets.

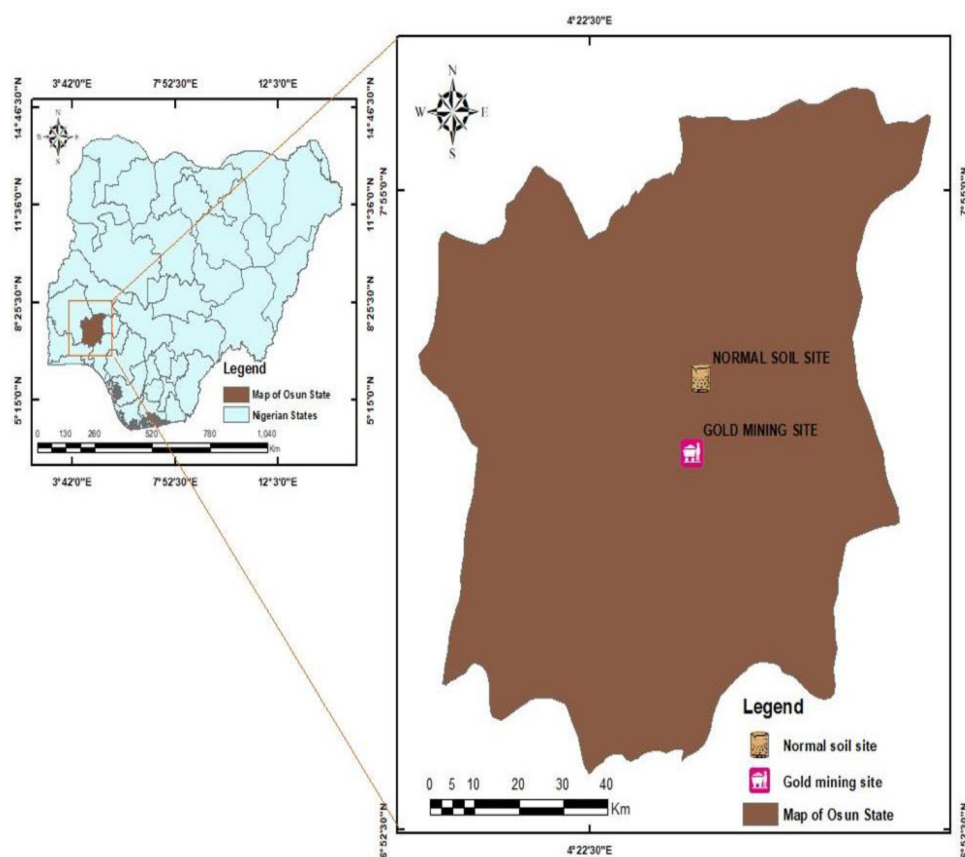


Fig. 1a. The map showing the sampling locations.

2.4. Elemental analysis of goldmine soil, water, *A. esculentus* and TE decontamination

The elemental contents of raw soil (control and goldmine), water (control and goldmine), *A. esculentus* shoot and various post-planting soil components were determined using an inductively coupled plasma with optical emission spectrometer (ICP-OES, Agilent 720-ES, USA) after digestion with digesting 0.5 g of soil/5 mL of water with a 10 mL acid mixture of $\text{HNO}_3\text{:HCl}$ (Azeez et al., 2022). The method described by Motsara and Roy (2008) was used for the physicochemical analysis of soil and water samples.

Absorption of TEs by *A. esculentus* and decontamination ability of SeNPs was determined using Eq. (2)

Metal decontamination

$$TE \text{ concentration in } A. \text{ esculentus shoot (control) - } TE \text{ concentration in } A. \text{ esculentus shoot with SeNPs} = \frac{TE \text{ concentration in } A. \text{ esculentus shoot}}{TE \text{ concentration in } A. \text{ esculentus shoot}} \quad (2)$$

2.5. Determination of physiological, morphological, biochemical and photosynthetic parameters in *A. esculentus*

Seedlings of *A. esculentus* exposed to various treatments were collected after three weeks of planting for sectioning. *A. esculentus* stems and roots from harvested seedlings were chopped with razor blades into tiny fragments and dropped into distilled-filled Petri dishes. Forceps were used to pick up the thinly sliced stems and roots and place them on a binocular microscope slide (Biobase DM 125) for observation. The physiological parameters of roots and shoots, number of leaves, germination percentage, and vigour index were measured as described by Azeez et al. (2022). Moisture and relative water were determined using the method of Azeez et al. (2019). Malondialdehyde (MDA), hydrogen peroxide (H_2O_2) and photosynthetic pigments in fresh

shoots were determined as described by Gupta et al. (2018), Kamali-Andani et al. (2022) and Ogunkunle et al. (2023), respectively, while the remaining samples were oven-dried for heavy metal concentrations and antioxidant activity as described previously by Azeez et al. (2022). MDA was determined by homogenizing 0.2 g of fresh *A. esculentus* shoots and extracting them in 5 mL of chilled 80% ethanol. This was followed by a 20 min centrifugation at 3500 rpm. After that, the extract was mixed with 4 mL of 20% trichloroacetic acid (TCA) and 0.67% thiobarbituric acid (TBA), incubated at 90 °C for 30 min, cooled on ice and centrifuged at 3500 rpm for 30 min. The absorbance of the supernatant was measured at 440, 532, and 600 nm. The H_2O_2 content of fresh *A. esculentus* leaves was determined by homogenizing 0.1 g with 2 mL ice-cold TCA and centrifuging the resulting solution at 12,000 rpm for 15 min. After adding 0.5 mL of 10 mM phosphate buffer (pH 7) and 1 mM KI solution to the supernatant, the absorbance was measured at 390 nm. For photosynthetic pigment contents, fresh *A. esculentus* leaves were homogenized in 5 mL of chilled 80% acetone. The homogenate was centrifuged for 5 min at 5000 rpm and extracted twice more with the same amount of 80% acetone. Chlorophyll a, b, and carotenoids were measured at 470, 645, and 663 nm as previously described by Ogunkunle et al. (2023). The ability of *A. esculentus* subjected to various treatments to scavenge free radicals was assessed by extracting 2 g of dried leaves twice with 70% methanol. The extract was filtered and concentrated. The extract's capacity to bleach 2,2-diphenyl-1-picrylhydrazyl (DPPH) was determined at 517 nm as reported by Azeez et al. (2022).

2.6. Statistical analysis

Data are expressed as mean $\pm$ standard error of the mean (SEM) of three concordant triplicate values. All data were analysed using analysis of variance (ANOVA) followed by Tukey's Post Hoc test for comparison of means. The significant difference was performed at $p < 0.05$ using SPSS 2020.

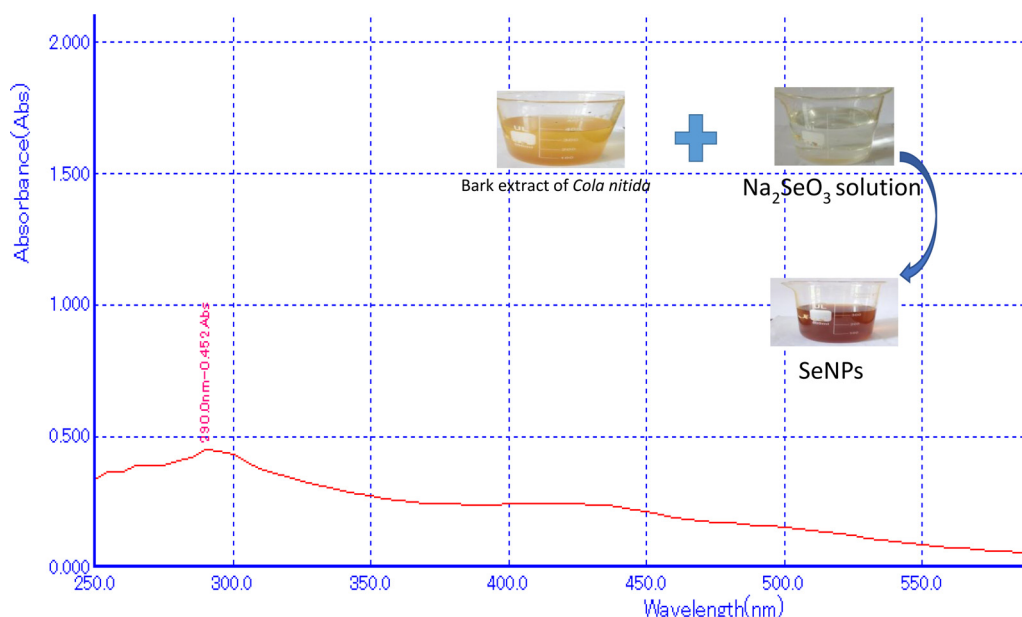


Fig. 2. UV-Visible spectrum of SeNPs (Insert: synthesis of SeNPs).

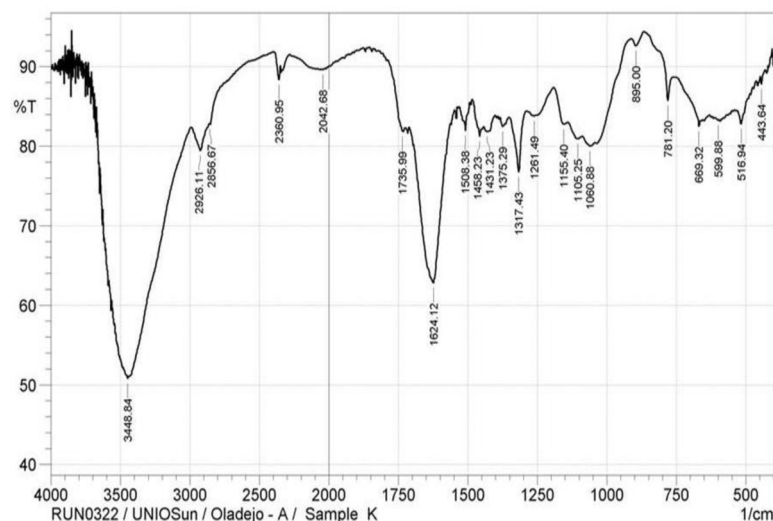


Fig. 3. FTIR spectrum of SeNPs.

3. Results and discussion

3.1. SeNPs characterization

The green synthesized SeNPs mediated with bark extract of *C. nitida* had a colour change from yellow to brick red with maximum absorption at 290 nm (Fig. 2) and a concentration of $42.02 \pm 0.21 \text{ mg L}^{-1}$. The colour change was noticed after 24 h of synthesis, indicating the reduction of Se^{4+} to Se^0 . The colour change to brick red and the maximum absorption at 290 nm are characteristics of SeNPs previously described. Previous studies have reported the maximum absorption of SeNPs appearing within the range of 200–400 nm (Hassanien et al., 2019; Salem et al., 2019; Shin et al., 2021; Adibian et al., 2022; Alhawiti, 2022; Santhosh et al., 2022). The difference in the absorption bands of SeNPs reported by various studies could be related to the size-dependant and shape-proportional characteristics of SeNPs (Hassanien et al., 2019).

The FTIR spectrum of SeNPs scanned within the range of 400 to 4000 cm^{-1} showed some prominent absorption peaks (Fig. 3). The peaks at 3448 and 1624 cm^{-1} are assigned to the NH and C=O groups, respectively suggesting the presence of an amide linkage in the extract. The peaks at 2926 , 2856 and 1060 cm^{-1} belong to C–O stretching vibration,

C–H stretching of methyl and methylene, respectively. These peaks suggest that the amide linkage from protein biomolecules in the *C. nitida* extract could be responsible for capping, reducing and stabilizing SeNPs (Hassanien et al., 2019; Azeez et al., 2022). This result is consistent with the results of Shin et al. (2021) and Adibian et al. (2022) who reported the biosynthesis of SeNPs from *Cirsium setidens* and *Rosmarinus officinalis*, respectively. Moreover, the peaks at 1061 , 781 and 599 cm^{-1} are related to the Se–O bands as reported by Meenambigai et al. (2021) and Salem et al. (2021).

A SEM micrograph (Fig. 4a) revealed that the morphology of the homogeneously dispersed and stable to aggregation SeNPs varied between oval and cylindrical shapes with an average size of $46.63 \pm 16.23 \text{ nm}$; while the EDX result (Fig. 4b) revealed both the quantitative and qualitative elemental composition of the SeNPs. The prominence of Se in the biosynthesized SeNPs as shown by the EDX spectrum implies the reduction of Se^{4+} to Se^0 with high purity (Hassanien et al., 2019; Alhawiti 2022). This result is in agreement with the reports of Cittrarasu et al. (2021), Salem et al. (2021) and Shin et al. (2021).

The XRD pattern of SeNPs (Fig. 5) showed a crystalline monoclinic-shaped material with an average grain size and interplanar spacing of 64.95 nm and 3.093 Å , respectively, matching JCPDS card



Figure 4a. SEM image of SeNPs

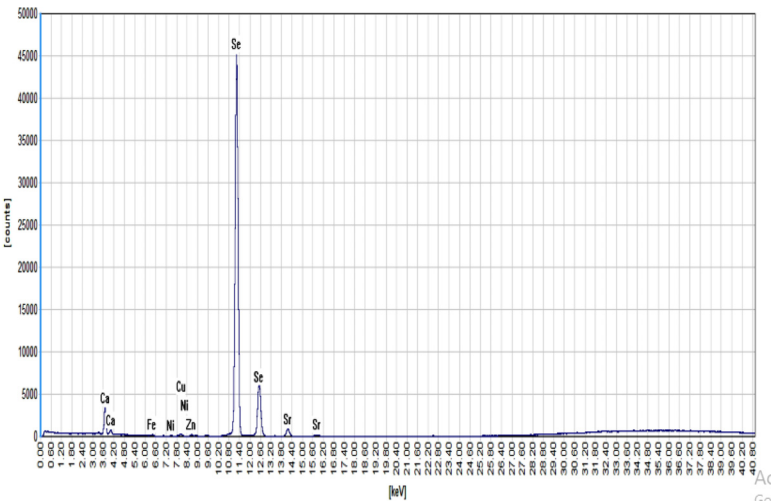


Figure 4b. EDX pattern of SeNPs

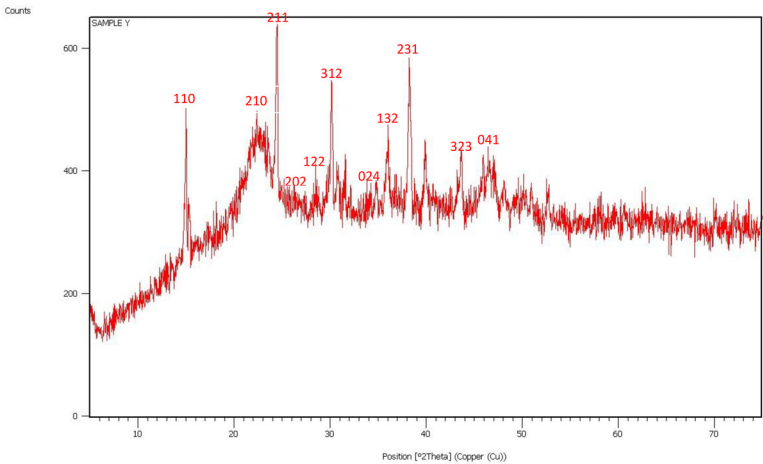


Fig. 5. XRD pattern of SeNPs.

number 00–220–4812. The lattice parameters are; $a = 9.2004 \text{ \AA}$, $b = 8.0000 \text{ \AA}$, $c = 12.7350 \text{ \AA}$, $\beta = 92.950^\circ$ with twelve (12) notable diffraction peak angles at $2\theta = 14.67^\circ$, 22.32° , 23.68° , 24.46° , 28.31° , 30.18° , 34.98° , 36.05° , 38.03° , 39.88° , 43.63° and 45.89° . These peaks correspond to hkl crystal planes of (110), (210), (211), (202), (122), (312), (024), (132), (231), (323) and (041). In this study, the crystallinity and crystal planes obtained are similar to those obtained by Cittrarasu et al. (2021), Meenambigai et al. (2021), Shin et al. (2021) and Adibian et al. (2022) indicating SeNPs to be crystalline. In this study, the average grain size is larger than that previously reported by Adibian et al. (2022) and Alhawiti (2022).

3.2. Physicochemical properties and mineral nutrient contents of soil and water samples

In general, the goldmine soil samples were composed primarily of clay (73.12% clay, 17.62% silt, and 9.26% sand), were strongly acidic ($\text{pH} = 4.73 \pm 0.07$), had an soil organic matter (SOM) content of 7.09 mg kg^{-1} with richness in mineral nutrients as follows: Na ($0.336 \pm 0.002 \text{ mg kg}^{-1}$), K ($71.358 \pm 0.035 \text{ mg kg}^{-1}$), Mg ($42.000 \pm 0.004 \text{ mg kg}^{-1}$), P ($2.016 \pm 0.004 \text{ mg kg}^{-1}$), S ($0.118 \pm 0.045 \text{ mg kg}^{-1}$), Si ($3.549 \pm 0.000 \text{ mg kg}^{-1}$) and Se ($0.378 \pm 0.003 \text{ mg kg}^{-1}$) while Ca was not found in it. The goldmine water samples were extremely acidic ($\text{pH} = 3.55 \pm 0.01$) and included Na ($4.158 \pm 0.004 \text{ mg kg}^{-1}$), K ($26.523 \pm 0.001 \text{ mg kg}^{-1}$), Mg ($1.407 \pm 0.009 \text{ mg kg}^{-1}$), Ca ($2.247 \pm 0.017 \text{ mg kg}^{-1}$), P ($0.672 \pm 0.005 \text{ mg kg}^{-1}$), S ($0.133 \pm 0.003 \text{ mg kg}^{-1}$), Si ($2.667 \pm 0.000 \text{ mg kg}^{-1}$) and Se ($0.441 \pm 0.004 \text{ mg kg}^{-1}$). The control soil samples were primarily sandy-loamy (sand: 60.02%, silt: 24.51%, and clay: 15.47%), moderately acidic ($\text{pH} = 5.63 \pm 0.14$), and had an soil organic matter (SOM) content of 11.43 mg kg^{-1} containing mineral components Na ($0.588 \pm 0.005 \text{ mg kg}^{-1}$), K ($17.682 \pm 1.679 \text{ mg kg}^{-1}$), Mg ($1.785 \pm 0.171 \text{ mg kg}^{-1}$), Ca ($27.048 \pm 2.584 \text{ mg kg}^{-1}$), P ($0.945 \pm 0.003 \text{ mg kg}^{-1}$), S ($0.151 \pm 0.007 \text{ mg kg}^{-1}$), and Si ($2.058 \pm 0.000 \text{ mg kg}^{-1}$). The control water samples were mildly alkaline/neutral ($\text{pH} = 7.12 \pm 1.02$) and included Na ($3.741 \pm 0.002 \text{ mg kg}^{-1}$), K ($2.278 \pm 0.085 \text{ mg kg}^{-1}$), Mg ($1.284 \pm 0.059 \text{ mg kg}^{-1}$), Ca ($3.053 \pm 0.157 \text{ mg kg}^{-1}$), P ($0.047 \pm 0.005 \text{ mg kg}^{-1}$), S ($0.129 \pm 0.004 \text{ mg kg}^{-1}$), Si ($4.708 \pm 0.009 \text{ mg kg}^{-1}$). Se was not found in both control soil and water. The physicochemical results of goldmine and control soils demonstrate that control soil was more fertile, sandy, and could hold more nutrients, while goldmine soil's pH was excessively acidic and would allow toxic metal mobility (Mukhopadhyay et al., 2019; Azeez et al., 2021). A soil quality indicator is crucial for monitoring fertility and its impacts on plant growth as well as other aspects of plant germination and sustenance. The fact that the control soil is sandy indicates that it is more porous, which may aid in nutrient transport and absorption (Hayes et al., 2019).

Soil pH affects soil nutrient availability and metal mobility. Mineral nutrients are more mobile and therefore phytoabsorbed at pH levels between 6.5 and 7.5, while toxic metals are inhibited at this pH but more mobile at pH levels between 3 and 5 (Mukhopadhyay et al., 2019; Azeez et al., 2021). Based on the findings of this study, pH played a critical role in permitting toxic metals to be translocated at pH 3.55 into plants more readily in goldmine soil and water combinations. This led to higher phytotoxicity. The presence of calcium modulates soil salinity stress, and its absence in goldmine soil indicates additional stress (Hosseini et al., 2019).

Soil organic matter (SOM) is a reservoir of soil fertility and therefore has a significant impact on soil ecosystems. It is an important source of nitrogen (N) and phosphorus (P) in the soil. SOM contains over 99% of soil N (Hatten and Liles, 2019; Schleuss et al., 2020). Sustaining plant growth and the production of food depends on its preservation and further accumulation (Azeez et al., 2020). Therefore, as determined for both control and goldmine soils in this study, the control soil had higher SOM. This indicates that it would supply more nutrients and support better growth of *A. esculentus*. This played a key role in modulating

A. esculentus physiological and biochemical parameters better in control soil than in goldmine soil. Soil organic matter (SOM) can also have a significant impact on metal sorption, which can reduce the solubility of toxic metals by forming complexes with organic functional groups (Hatten and Liles, 2019). Specifically, nutrients in SOM play a significant role in supporting the ability to detoxify pollutants resulting from contamination through their availability. Both nutrient availability and elemental toxicity decline as soils become more acidic, since acidic pH has a strong influence on nutrient supply and elemental toxicity, especially toxic metals due to their high mobility at this pH (Mukhopadhyay et al., 2019). According to the findings of this study, the acidic pH of goldmine soil and the addition of goldmine water with acidic pH could have influenced stunted growth and low *A. esculentus* levels.

3.3. Influence of different soil compositions and SeNPs on elemental contents of *A. esculentus* and decontamination

Significant ($p < 0.05$) variations in toxic and radioactive metal contents were found amongst goldmine water, goldmine soil, and control water, with goldmine water having the highest concentrations (Table 1). Compared to control soil, goldmine soil contained significantly ($p < 0.05$) higher levels of Fe and Cu while goldmine water contained significantly ($p < 0.05$) higher levels of Zn and Mn (Table 1). The content of Al was significantly higher in goldmine soil and lower in control water. For As, Cd, and U, the trend follows goldmine water > goldmine soil > control soil > control water. In all soil samples, heavy metal concentrations were below the WHO threshold limits of 10 mg g^{-1} for Mn, 3 mg g^{-1} for Zn, 0.1 mg g^{-1} for Cd, Se and Ti and 1 mg g^{-1} for As, Pb, Ni and Cr in soil. However, in goldmine water, As, Ni, Cr, and Cd were higher than the WHO limits of 0.01, 0.2, 0.1, and 0.003 mg L^{-1} , respectively (Angulo-Bejarano et al., 2021). In most cases, the synergy amongst the toxic metals in soil is responsible for the inhibition of plant characteristics even when the individual metal contents are below the permissible limits (du Plessis and Curtis, 2021; Zeeshan et al., 2021). While plants have mechanisms to delimit, adapt, and tolerate toxic metals, prolonged exposure alters their physiology, morphology, biochemistry, and health attributes, especially edible ones (Lima et al., 2019; Gautam and Agrawal, 2021; Ogunkunle et al., 2023).

Relative to the control (CSCW), Au contents were 85.96, 86.44 and 85.86% higher in the shoots of *A. esculentus* grown on CSGW, GSCW and GSGW, respectively. Application of SeNPs reduced Au contents by 50, 8.77, 1.69 and 1.75% in CSCWSE, CSGWSE, GSCWSE and GSGWSE in relation to the corresponding soil compositions (Table 2). As for Cd, although its content was not significant, it increased by 40 and 25% in CSGW and GSCW, respectively, while Ni increased by 75 and 50%, respectively. Applications of SeNPs reduced their concentrations by 50 and 33.33% in GSGWSE in comparison with GSGW. The concentrations of As decreased in CSGW by 80% when compared with the CSCW but increased by 75 and 66.67% in GSCW and GSGW, respectively (Table 2). The concentrations of Cr, Fe, W, Th, Al, Ti, U, Cu, Mn and Zn did not differ significantly in *A. esculentus* shoots in CSCW from those grown on other soil compositions. However, the concentrations of for Fe, As, Cd, Ni, Cu, Zn, U and Th are not recommended above the WHO/FAO limits of 5.0, 0.15, 0.2, 10.0, 2.0, 1.5, 0.00012 and 0.00014 mg/kg , respectively in vegetables (El-Gamal et al., 2019; Atikpo et al., 2021; Dai et al., 2022; Peirovi-Minaee et al., 2022). The addition of SeNPs increased the concentrations of Se by 91.89, 95.38, 77.94 and 79.73% in CSCWSE, CSGWSE, GSCWSE and GSGWSE, respectively. Toxic metals and metalloids present in soil and water interfere with growth hormones inhibiting physiological indices and morphological parameters in plants (Ogunkunle et al., 2020, 2023). Zn, Cd, As, Al and Cr have been found to hinder photosynthesis and growth, thwart nutrient balance and create reactive oxygen radicals (Angulo-Bejarano et al., 2021; Azeez et al., 2022). The application of SeNPs reduced the availability of these metals and completely decontaminated Cr. Studies by Lima et al. (2019) and Zhao et al. (2019) showed that SeNPs decontaminated soil containing

Table 1

Toxic and radioactive metal concentrations in different pre-planting soil and water samples.

Groups	Control soil (mgkg ⁻¹)	Control water (mgL ⁻¹)	Goldmine soil (mgkg ⁻¹)	Goldmine water (mgL ⁻¹)
Au	0.420±0.004 ^a	0.046±0.000 ^b	0.441±0.003 ^a	1.008±0.005 ^c
Si	2.058±0.000 ^a	4.708±0.01 ^b	3.549±0.000 ^c	2.667±0.000 ^d
Se	nd	nd	0.378±0.003 ^a	0.441±0.004 ^a
Al	2.667±0.000 ^a	0.137±0.010 ^b	12.726±0.001 ^a	4.158±0.000 ^d
Fe	2.898±0.268 ^a	0.141±0.000 ^b	30.072±0.015 ^c	2.436±0.004 ^a
Cd	0.000±0.000 ^a	0.002±0.000 ^a	0.042±0.000 ^b	0.021±0.000 ^c
Ni	0.021±0.002 ^a	0.002±0.000 ^b	0.651±0.002 ^c	0.756±0.001 ^c
As	0.010±0.003 ^a	0.007±0.000 ^b	0.420±0.014 ^c	0.084±0.000 ^d
Cr	0.042±0.001 ^a	0.009±0.000 ^b	0.084±0.001 ^c	0.105±0.001 ^d
Cu	0.080±0.006 ^a	0.042±0.000 ^b	0.903±0.001 ^c	0.315±0.002 ^d
Zn	0.063±0.011 ^a	0.077±0.000 ^a	0.147±0.001 ^b	0.357±0.000 ^c
Mn	0.189±0.025 ^a	0.003±0.000 ^b	0.105±0.000 ^c	0.021±0.000 ^d
Ti	0.250±0.062 ^a	0.018±0.000 ^b	0.840±0.001 ^c	0.042±0.000 ^d
W	nd	0.009±0.000 ^a	0.147±0.001 ^b	0.105±0.002 ^c
U	0.357±0.008 ^a	0.000±0.000 ^b	1.554±0.066 ^c	0.693±0.100 ^d
Th	3.150±0.040 ^a	0.094±0.010 ^b	4.242±0.013 ^c	4.641±0.026 ^a

Data expressed as mean ± standard error of mean of three triplicate concordant values. Data with different superscripts for a particular metal across the row (horizontally) are significantly different at $p < 0.05$.

Table 2Concentrations of toxic and radioactive metals in *A. esculentus* planted on different soil compositions (mgkg⁻¹).

Elements	CSCW	CSGW	GSCW	GSGW	CSCWSE	CSGWSE	GSCWSE	GSGWSE
Au	0.008±0.001 ^a	0.057±0.005 ^b	0.059±0.002 ^b	0.057±0.002 ^b	0.004±0.000 ^a	0.052±0.001 ^b	0.058±0.001 ^b	0.056±0.000 ^b
Si	1.914±0.024 ^a	1.723±0.015 ^b	1.421±0.020 ^c	1.010±0.017 ^d	1.049±0.024 ^c	1.457±0.006 ^f	1.482±0.006 ^g	0.947±0.011 ^h
Se	0.015±0.009 ^a	0.012±0.006 ^a	0.004±0.003 ^b	0.001±0.000 ^b	0.185±0.000 ^c	0.325±0.004 ^d	0.068±0.002 ^e	0.074±0.002 ^e
Al	0.114±0.002 ^a	0.114±0.001 ^a	0.120±0.002 ^b	0.117±0.002 ^{a,b}	0.094±0.001 ^c	0.106±0.001 ^d	0.112±0.000 ^a	0.042±0.015 ^f
Fe	0.146±0.001 ^a	0.157±0.001 ^b	0.114±0.001 ^c	0.102±0.001 ^d	0.125±0.000 ^e	0.128±0.001 ^e	0.108±0.001 ^{df}	0.111±0.005 ^{cf}
Cd	0.003±0.000 ^a	0.005±0.000 ^a	0.004±0.000 ^a	0.002±0.000 ^a	0.002±0.000 ^a	0.004±0.000 ^a	0.004±0.000 ^a	0.001±0.000 ^a
Ni	0.001±0.000 ^a	0.004±0.002 ^a	0.002±0.000 ^a	0.003±0.000 ^a	0.002±0.000 ^a	0.004±0.000 ^a	0.003±0.001 ^a	0.002±0.000 ^a
As	0.005±0.000 ^{ac}	0.001±0.000 ^a	0.020±0.001 ^b	0.015±0.001 ^b	0.004±0.001 ^{ac}	0.001±0.000 ^a	0.016±0.005 ^b	0.007±0.002 ^c
Cr	0.001±0.000 ^a	0.001±0.000 ^a	0.001±0.000 ^a	0.002±0.000 ^a	0.002±0.000 ^a	0.005±0.000 ^a	0.001±0.000 ^a	0.001±0.000 ^a
Cu	0.055±0.000 ^a	0.069±0.001 ^b	0.005±0.000 ^c	0.041±0.001 ^d	0.036±0.000	0.060±0.001	0.090±0.001	0.051±0.000
Zn	0.082±0.000 ^a	0.092±0.001 ^b	0.061±0.001 ^c	0.050±0.001 ^d	0.056±0.001 ^{cd}	0.102±0.001 ^e	0.102±0.000 ^e	0.067±0.000 ^f
Mn	0.085±0.000 ^a	0.091±0.001 ^a	0.056±0.001 ^b	0.056±0.001 ^b	0.071±0.000 ^c	0.100±0.000 ^d	0.047±0.000 ^e	0.067±0.001 ^c
Ti	0.008±0.000 ^a	0.009±0.000 ^a	0.005±0.000 ^a	0.009±0.000 ^a	0.006±0.000 ^a	0.006±0.000 ^a	0.006±0.000 ^a	0.008±0.000 ^a
W	0.011±0.005 ^a	0.009±0.00 ^a	0.010±0.002 ^a	0.009±0.001 ^a	0.006±0.000 ^a	0.009±0.001 ^a	0.010±0.001 ^a	0.010±0.001 ^a
U	0.001±0.000 ^a	0.001±0.000 ^a	0.002±0.000 ^a	0.003±0.001 ^a	0.000±0.000 ^a	0.002±0.000 ^a	0.000±0.000 ^a	0.001±0.001 ^a
Th	0.118±0.007 ^a	0.105±0.009 ^{bc}	0.115±0.007 ^a	0.113±0.002 ^{ab}	0.102±0.001 ^b	0.108±0.002 ^b	0.109±0.000 ^b	0.098±0.004 ^c

Data expressed as mean ± standard error of mean of three triplicate concordant values. Data with different superscripts for a particular metal across the row (horizontally) are significantly different at $p < 0.05$. CSCW, CSGW, GSCW, GSGW, CSCWSE, GSCWSE, CSGWSE, GSGWSE are control soil + goldmine water (CSGW), goldmine soil + control water (GSCW), goldmine soil + goldmine water (GSGW), control soil + control water + SeNPs (CSCWSE), control soil + goldmine water + SeNPs (CSGWSE), goldmine soil + control water + SeNPs (GSCWSE) and goldmine soil + goldmine water + SeNPs (GSGWSE).

Cr, Cd and Pb to reduce their phytoabsorption in *Lycopersicon esculentus* and *Brassica campestris*. This is consistent with results in this study.

3.4. Influence of soil compositions and SeNPs on *A. esculentus* physiological and morphological parameters

The results of physiological parameters (Fig. 6 and Table 3) showed significant ($p < 0.05$) reductions in shoot lengths by 12.30, 28.09, 48.39, 53.86, 63.68 and 76.48% in groups CSGW, GSCW, GSGW, CSCWSE, GSCWSE, CSGWSE and GSGWSE, respectively compared to CSCW. Likewise, the root lengths were significantly ($p < 0.05$) reduced by 4.86, 12.86, 14.29, 27.14, 30.57, 32.86 and 70.57% in samples CSGW, GSCW, GSGW, CSCWSE, GSCWSE, CSGWSE and GSGWSE, respectively relative to CSCW. These growth parameters measure how sensitive plants are to harsh environmental conditions, toxins, and pathogens (Azeez et al., 2019; Ogunkunle et al., 2023). The results of physiological parameters (Table 3) also revealed that there were significant ($p < 0.05$) declines in vigour indices by 11.05, 25.56, 15.74, 55.91, 57.52, 66.88 and 77.96% in samples CSGW, GSCW, GSGW, CSCWSE, GSCWSE, CSGWSE and GSGWSE, respectively compared to CSCW while no significant ($p > 0.05$) difference was obtained for germination percentage. The reductions in the number of leaves, percentage germination, shoot

and root lengths in CSGW, GSCW and GSGW could indicate that the presence of toxic metals in goldmine soil and water had interfered with the growth hormones in *A. esculentus*, thus the inhibition of physiological indices. The toxicity of metals such as Cd, Pb and Cr manifests with threatening signs like chlorosis, inhibited growth, reduced seed germination and decreased shoot length. Toxic metals are known to be hazardous to plants even at minute levels inhibiting their growth hormones (Raklami et al., 2021). This was equally previously reported by Azeez et al. (2020) and Ogunkunle et al. (2020) that toxic metals inhibited physiological parameters of *A. esculentus* and *Moringa oleifera*. Moreover, the reports of Azeez et al. (2019) and Gupta et al. (2018) also support the assertion that toxic metals negatively impact plant growth and metabolism. Vigour indices reflect the influence of the additive effects of various growth regulators on *A. esculentus* and how physiologically tolerant the seedlings were to biotic and abiotic stresses (El-Gamal et al., 2019). Besides providing information about seed resistance or tolerance, vigour indices additionally provide information about seed viability. Seeds and seedlings with a high vigour index are more viable (Dai et al., 2022). Azeez et al. (2019, 2020) reported that phytohormones that regulate endogenous pathways for plant development can also be distorted by toxic metals. This is because vigour indices are reduced due to water deficit, imbalanced nutrient absorption,

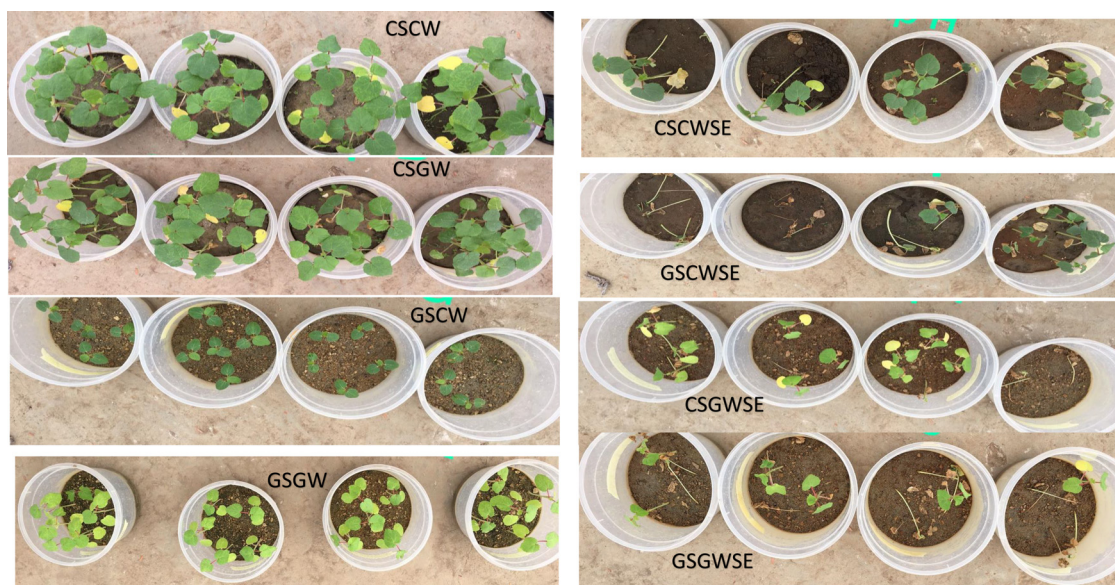


Fig. 6. Physiological response of *A. esculentus* different soil compositions. CSCW, CSGW, GSCW, GSGW, CSCWSE, GSCWSE, CSGWSE, GSGWSE are control soil + goldmine water (CSGW), goldmine soil + control water (GSCW), goldmine soil + goldmine water (GSGW), control soil + control water + SeNPs (CSCWSE), control soil + goldmine water + SeNPs (CSGWSE), goldmine soil + control water + SeNPs (GSCWSE) and goldmine soil + goldmine water + SeNPs (GSGWSE).

Table 3

Influence of different soil compositions on physiological parameters of *A. esculentus*.

Groups	Shoot Length (cm)	Root Length (cm)	No. of Leaves	Percentage Germination (%)	Vigour Index (%)
CSCW	17.73±0.98 ^a	3.50±0.17 ^a	4.85±0.29 ^a	100.00±0.05 ^a	2123.10±27.42 ^a
CSGW	15.55±0.40 ^b	3.33±0.21 ^b	4.75±0.08 ^b	100.00±0.04 ^a	1888.50±21.32 ^b
GSCW	12.75±0.26 ^c	3.05±0.09 ^c	4.10±0.07 ^c	100.00±0.06 ^a	1580.50±23.39 ^c
GSGW	14.89±0.34 ^d	3.00±0.05 ^c	4.20±0.12 ^d	100.00±0.01 ^a	1789.00±19.29 ^d
CSCWSE	9.15±1.42 ^e	2.55±0.28 ^d	3.10±0.48 ^e	80.00±0.08 ^b	936.00±20.31 ^e
GSCWSE	8.18±0.90 ^f	2.43±0.24 ^e	3.00±0.32 ^f	85.00±0.57 ^c	901.90±17.71 ^f
CSGWSE	6.44±1.38 ^g	2.35±0.22 ^f	2.00±0.43 ^g	80.00±0.16 ^b	703.20±10.18 ^g
GSGWSE	4.17±0.87 ^h	1.03±0.20 ^g	2.85±0.28 ^h	90.00±0.77 ^c	468.003±11.28 ^h

Result: mean ± standard error of mean (SEM). Results with different superscripts down the group (vertically) are significantly different ($p < 0.05$). CSCW – control soil + control water. CSCW, CSGW, GSCW, GSGW, CSCWSE, GSCWSE, CSGWSE, GSGWSE are control soil + goldmine water (CSGW), goldmine soil + control water (GSCW), goldmine soil + goldmine water (GSGW), control soil + control water + SeNPs (CSCWSE), control soil + goldmine water + SeNPs (CSGWSE), goldmine soil + control water + SeNPs (GSCWSE) and goldmine soil + goldmine water + SeNPs (GSGWSE).

and delimitation of enzymes caused by toxic metals. This study found that decreased vigour indices in *A. esculentus* exposed to soil compositions other than the CSCW reflect the toxicity of the metals. This was previously reported by Pandey et al. (2022). Further decreases in vigour indices and other physiological parameters of *A. esculentus* exposed to SeNPs are a function of high SeNP concentration (42 mg L^{-1}), as has been demonstrated in previous studies by Babajani et al. (2019), Behbahani et al. (2020) and Kamali-Andani et al. (2022). SeNPs have a range of inhibitory and growth-modulating properties depending on the dose, application procedure, the plant species, and the stage of development of the plants (Hu et al., 2018; Nazerieh et al., 2018; Babajani et al., 2019; Zhao et al., 2019; Liu et al., 2022; Sharma et al., 2022). The study published by Safari et al. (2018) showed that nanoselenium caused growth hormones, fresh and dry masses, gene expression, heat stress factors and enzymes to decrease in *Triticum aestivum* exposed to high concentrations ($30\text{--}50 \text{ mg L}^{-1}$). Moreover, Behbahani et al. (2019) and Sotoodehnia-Korani et al. (2020) found variations in SeNP activities such that at lower concentrations, roots and shoots were lengthened, gene expression increased, while toxicity and abnormal growth resulted from high concentration SeNPs application in *Momordica charantia* and *Capsicum annum*. In this study, SeNPs were found to impair *A. esculentus* function possibly due to the alteration of phytohormones that

promote signalling pathways and cell differentiation by accumulating in the plant's shoots/roots and declining the anatomical characteristics of *A. esculentus* through radical production. This is in agreement with previous reports by Oliveira et al. (2019), Lima et al. (2019) and Hasanuzzaman et al. (2020).

An examination of the cross-sections of stems and roots of *A. esculentus* under the binocular microscope revealed changes in morphological features, such as the pith, cortex, xylem, epidermis, endodermis, and pericycle (Fig. 7a and b), which were evidences of the different treatments applied. The stem and root epidermis were distorted in all treatments except the CSCW. The stems of *A. esculentus* in CSCW, CSGW and GSCW had thick cortexes while groups GSGW, CSCWSE, GSCWSE, CSGWSE and GSGWSE had thin cortexes (Fig. 7a). Similarly, xylems and pith were distorted in GSGW, CSCWSE, GSCWSE, CSGWSE and GSGWSE in comparison to CSCW with the greatest distortion/disappearance recorded in the stem of *A. esculentus* in GSGWSE. In some instances, there was a disappearance of the pith in stems of *A. esculentus* exposed to other compositions besides water. Moreover, the pigmentation of the stems also differed when CSCW was compared with other treatments (Fig. 7a). In the roots of *A. esculentus*, GSGW and GSGWSE distorted the pith and xylem, and changed the colouration in comparison to others while the highest distortion was observed in GSGWSE (Fig. 7b).

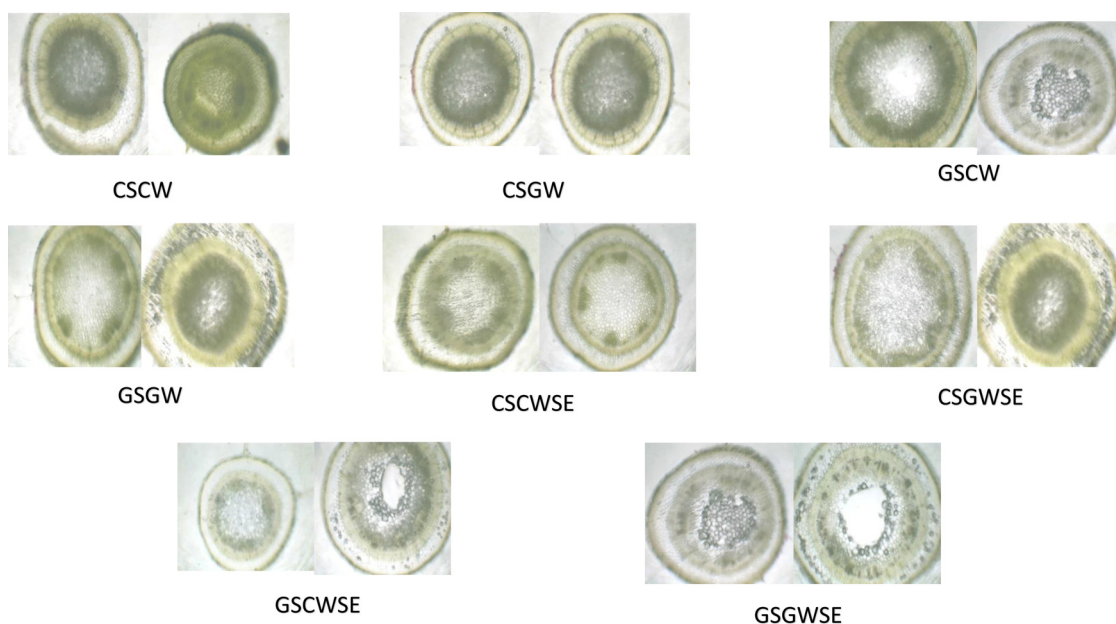


Figure 7a. Morphological characteristics of stems of *A. esculentus* exposed to different treatments. CSCW, CSGW, GSCW, GSGW, CSCWSE, GSCWSE, CSGWSE, GSGWSE are control soil + goldmine water (CSGW), goldmine soil + control water (GSCW), goldmine soil + goldmine water (GSGW), control soil + control water + SeNPs (CSCWSE), control soil + goldmine water + SeNPs (CSGWSE), goldmine soil + control water + SeNPs (GSCWSE) and goldmine soil + goldmine water + SeNPs (GSGWSE).

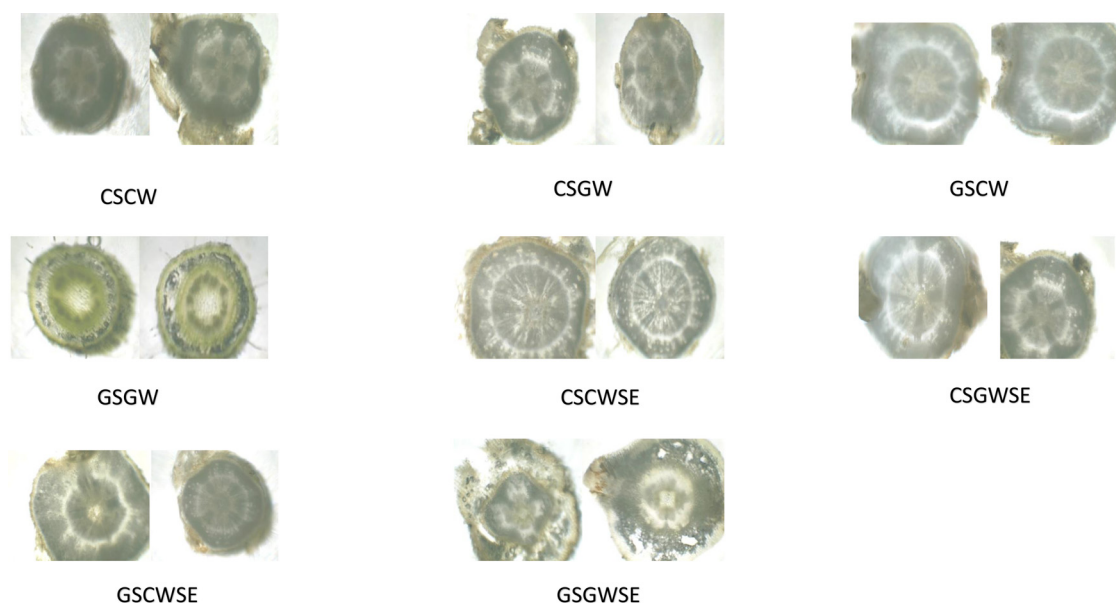


Figure 7b. Morphological characteristics of roots of *A. esculentus* exposed to different treatments. CSCW, CSGW, GSCW, GSGW, CSCWSE, GSCWSE, CSGWSE, GSGWSE are control soil + goldmine water (CSGW), goldmine soil + control water (GSCW), goldmine soil + goldmine water (GSGW), control soil + control water + SeNPs (CSCWSE), control soil + goldmine water + SeNPs (CSGWSE), goldmine soil + control water + SeNPs (GSCWSE) and goldmine soil + goldmine water + SeNPs (GSGWSE).

The cortex is known to transport and store nutrients in addition to providing mechanical support to plants (Pandey et al., 2022). Comparatively to the CSCW, the cortices of these groups (treatment groups) were so thin, making them susceptible to mechanical damage, which resulted in a reduction in resistance to fall-off (Fig. 6) (Zhao et al., 2019). Exposure of plants to toxic metals and sometimes metalloids can compromise and alter the cortex tissues, creating intracellular spaces that reduce the strength of the plant (Angulo-Bejarano et al., 2021). This is in agreement with the decreased values of vigour indices that decreased with different soil compositions and further with the application of SeNPs. In addition, more distortion was observed in the xylems of the treatment groups,

which may indicate lesser support for the plant structure (Liza et al., 2020). This could also indicate less effective storage and lower translocation of nutrients when compared to groups without distorted xylems (Babajani et al., 2019; Behbahani et al., 2020; Pandey et al., 2022). Distortions observed in the treatment group are more likely to lead to water stress in the plant (Kamali-Andani et al., 2022). Variations and alterations in the xylem and epidermis of roots and shoots exposed to toxic metals have previously been reported to negatively modify plant structures causing disruption to cell division thus preventing adequate transportation of nutrients which can eventually lead to plant death (Oliviera et al., 2019; Lima et al., 2019; Liza et al., 2020; Manara et al.,

Table 4
Biochemical parameters of *A. esculentus* exposed to different soil compositions.

Groups	MDA (nmol/g)	H ₂ O ₂ (μmol/g)	DPPH (%)	Moisture Content (%)	Relative Water content (%)
CSCW	1.85±0.69 ^a	5.61±1.70 ^a	42.79±1.03 ^a	81.94±0.07 ^a	37.93±0.05 ^a
CSGW	2.17±0.82 ^b	7.87±1.74 ^b	37.10±1.27 ^b	86.66±0.04 ^b	35.18±0.09 ^{ab}
GSCW	2.44±0.28 ^c	7.93±1.92 ^b	33.99±1.01 ^c	86.08±0.02 ^b	33.71±0.06 ^b
GSGW	2.62±0.25 ^d	8.16±1.87 ^b	31.47±1.97 ^c	86.24±0.06 ^b	30.96±0.03 ^c
CSCWSE	2.70±0.17 ^{de}	8.41±0.60 ^c	27.89±1.48 ^d	89.38±0.09 ^c	26.67±0.04 ^d
GSCWSE	2.79±0.42 ^e	8.78±0.81 ^f	25.71±0.97 ^{de}	85.00±0.08 ^b	25.77±0.06 ^{de}
CSGWSE	2.90±0.29 ^g	8.89±0.84 ^g	24.74±1.03 ^e	91.70±0.05 ^d	23.29±0.08 ^e
GSGWSE	3.35±0.77 ⁱ	9.09±1.36 ^f	13.85±0.28 ^f	94.46±0.02 ^e	15.85±0.07 ^f

Result: mean ± standard error of mean (SEM). Results with different superscripts down the group (vertically) are significantly different ($p < 0.05$). CSCW – control soil + control water. MDA – Malondialdehyde content, DPPH - 2,2-diphenyl-1-picrylhydrazyl for antioxidant activity, CSGW, GSCW, GSGW, CSCWSE, GSCWSE, CSGWSE, GSGWSE are control soil + goldmine water (CSGW), goldmine soil + control water (GSCW), goldmine soil + goldmine water (GSGW), control soil + control water + SeNPs (CSCWSE), control soil + goldmine water + SeNPs (CSGWSE), goldmine soil + control water + SeNPs (GSCWSE) and goldmine soil + goldmine water + SeNPs (GSGWSE).

2020). Sotoodehnia-Korani et al. (2020) reported morphological alterations and inhibitions in the xylem following the application of high concentrations of SeNPs as observed in this study.

3.5. Influence of soil compositions and SeNPs on *A. esculentus* biochemical and photosynthetic pigment parameters

In comparison to CSCW, moisture contents of *A. esculentus* planted on goldmine soil and goldmine water with and without SeNPs increased significantly ($p < 0.05$) by 5.44, 4.81, 4.99, 8.32, 3.60, 10.64 and 13.25% in CSGW, GSCW, GSGW, CSCWSE, GSCWSE, CSGWSE and GSGWSE, respectively with a further 5.95 and 5.38% increase in *A. esculentus* in CSGWSE and GSGWSE over CSGW and GSGW (Table 4). In addition, *A. esculentus* planted on CSGW, GSCW, GSGW, CSCWSE, GSCWSE, CSGWSE and GSGWSE showed significant ($p < 0.05$) reductions in relative water contents by 7.25, 11.13, 18.37, 29.69, 32.06, 38.59 and 58.21%, respectively relative to CSCW, and further reductions by 23.55, 24.77 and 40.57% were recorded for GSCWSE, CSGWSE and GSGWSE when compared to GSCW, CSGW and GSGW (Table 4). *A. esculentus* shoots exposed to different soil compositions except CSCW had high moisture contents that increased with increasing toxic metal and SeNPs contents in soil, suggesting probable susceptibility to rottenness, accelerated deterioration, and reduced shelf-life (Azeez et al., 2020). Furthermore, the higher relative water content in CSCW with respect to other compositions indicates the better water tolerance status of *A. esculentus* against unfavourable environmental stresses such as drought (Azeez et al., 2019). Additionally, the balance between water absorption from the soil and loss through transpiration was not compromised in the CSCW group. However, lower relative water contents in other soil compositions suggest water stress in the plant, with further declines in the SeNPs-supplemented group possibly due to radical clogging of root pores caused by high Se concentration (Lima et al., 2019). Previous studies have demonstrated that toxic metals such as Cr, Cd, Pb and As amongst other pollutants compromised the relative water contents of vegetables. They caused water stress that eventually led to stunted growth of plants (Ogunkunle et al., 2023). There is also a possibility that the alterations in morphology and physiological traits were due to water deficit (Azeez et al., 2019). The additional reduction observed in SeNPs-supplemented *A. esculentus* implies that the nanoparticles have differential properties, particularly at high concentrations (Hasanuzzaman et al., 2020). There is also a possibility that these reductions were caused by SeNPs clogging root pores, which could be results of phytotoxic signals (Oliviera et al., 2019; Kamali-Andani et al., 2022).

A. esculentus exposed to different treatments showed significantly ($p < 0.05$) increased malondialdehyde (MDA) levels by 14.74, 24.18, 29.39, 31.48, 33.69, 36.20, and 44.74% relative to CSCW for CSGW, GSCW, GSGW, GSCWSE, GSCWSE, CSGWSE and GSGWSE, respectively

(Table 4). The MDA contents further increased by 12.54, 25.17, and 21.79 in GSCWSE, CSGWSE, and GSGWSE in comparison with *A. esculentus* planted on goldmine soil and water without SeNPs (Table 4). The H₂O₂ contents in *A. esculentus* in other soil compositions aside from CSCW were significantly ($p < 0.05$) higher by 3.64, 4.81, 5.68, 10.10, 13.37, 14.99 and 16.86% in CSGW, GSCW, GSGW, GSCWSE, GSCWSE, CSGWSE and GSGWSE, respectively (Table 4). As biomarkers for lipid peroxidation and radical generation, malondialdehyde (MDA) and hydrogen peroxide (H₂O₂) contents can be used to appraise and predict oxidative stress (Qi et al., 2021). The significantly elevated levels of MDA and H₂O₂ in *A. esculentus* exposed to different soil compositions compared with the CSCW reflect the toxic effects of peroxide radicals generated by toxic metals on the plant. At high doses, Se and heavy metals can cause excessive MDA and H₂O₂ production due to their prooxidant nature (Oliviera et al., 2019; Kamali-Andani et al., 2022). Azeez et al. (2019) and Ogunkunle et al. (2023) reported that Cd-supplemented soil increased MDA contents in *Moringa oleifera* and *A. esculentus* while the significantly higher MDA contents obtained in SeNPs-supplemented samples in comparison to others could indicate that SeNPs had inhibitory effects on the phytochemicals responsible for the prevention of the oxidation of biomolecules, thus causing oxidative damage (Sharma et al., 2022). Babajani et al. (2019) and Sotoodehnia-Korani et al. (2020) noted that the application of high concentrations of SeNPs was severely toxic to *Melissa officinalis* and *Capsicum annum* negatively modifying the plants' characteristics.

The antioxidant activities of *A. esculentus* were significantly ($p < 0.05$) reduced by 13.30, 20.57, 26.45, 34.82, 39.91, 42.18 and 67.63% below the CSCW in CSGW, GSCW, GSGW, GSCWSE, GSCWSE, CSGWSE and GSGWSE, respectively while there were sustained reductions in GSCWSE, CSGWSE and GSGWSE by 24.36, 21.38 and 50.34% when compared to GSCW, CSGW and GSGW (Table 4). A significant reduction ($p < 0.05$) in antioxidant activities could be attributed to enzyme inhibition, gene deactivation, and decreased induction of polyphenols to counteract toxic metals' toxicity (Babajani et al., 2019). Moreover, the lower antioxidant activity of *A. esculentus* was more pronounced in SeNPs-supplemented groups, implying that SeNPs caused oxidative stress damage by promoting free radical production (Oliviera et al., 2019). The reports of Babajani et al. (2019), Behbahani et al. (2020) and Sotoodehnia-Korani et al. (2020) found that high concentrations of SeNPs were inhibitory to transcription genes, polyphenols, ascorbate content, nitrate reductase and peroxidase in *Melissa officinalis* and *Capsicum annum*.

When compared to the CSCW, chlorophyll a and chlorophyll b contents of *A. esculentus* were significantly ($p < 0.05$) lowered by 8.59 and 4.18, 14.74 and 11.79, 21.54 and 12.04, 28.97 and 25.06, 29.48 and 31.45, 34.74 and 31.70, and 46.54 and 39.07% in CSGW, GSCW, GSGW, GSCWSE, GSCWSE, CSGWSE and GSGWSE, respectively (Table 5). In

Table 5
Photosynthetic parameters of *A. esculentus* exposed to different treatments.

Groups	Chlorophyll A (mg/g of fresh weight)	Chlorophyll B (mg/g of fresh weight)	Carotenoids (mg/g of fresh weight)
CSCW	7.80±0.81 ^a	4.07±0.21 ^a	5.28±0.48 ^a
CSGW	7.13±0.64 ^a	3.90±0.78 ^b	5.00±0.43 ^b
GSCW	6.65±0.52 ^b	3.59±0.85 ^c	4.51±0.25 ^c
GSGW	6.12±0.73 ^b	3.58±0.69 ^c	4.24±0.30 ^d
CSCWSE	5.54±0.22 ^c	3.05±0.57 ^d	3.99±0.22 ^e
GSCWSE	5.50±0.64 ^c	2.79±0.17 ^e	3.88±0.31 ^e
CSGWSE	5.09±0.08 ^c	2.78±0.94 ^e	3.86±0.95 ^e
GSGWSE	4.17±0.15 ^d	2.48±0.81 ^g	3.27±0.67 ^f

Result: mean ± standard error of mean (SEM). Results with different superscripts down the group (vertically) are significantly different ($p < 0.05$). CSCW – control soil + control water. CSGW, CSGW, GSCW, GSGW, CSCWSE, GSCWSE, CSGWSE, GSGWSE are control soil + goldmine water (CSGW), goldmine soil + control water (GSCW), goldmine soil + goldmine water (GSGW), control soil + control water + SeNPs (CSCWSE), control soil + goldmine water + SeNPs (CSGWSE), goldmine soil + control water + SeNPs (GSCWSE) and goldmine soil + goldmine water + SeNPs (GSGWSE).

comparison with GSCW, CSGW and GSGW, further reductions of 17.29 and 22.28, 28.61 and 28.72, and 31.86 and 30.72% were observed for GSCWSE, CSGWSE and GSGWSE, respectively. The carotenoid contents of *A. esculentus* in CSGW, GSCW, GSGW, GSCWSE, GSCWSE, CSGWSE and GSGWSE significantly ($p < 0.05$) decreased by 5.30, 14.58, 19.70, 24.43, 26.52, 26.89 and 38.07% compared to CSCW while GSGWSE, CSGWSE and GSGWSE further reduced carotenoid contents by 13.97, 22.8 and 22.88% compared with GSCW, CSGW and GSGW.

Photosynthesis pigments are expressions of plants' healthy functions, while carotenoids serve as cellular antioxidants (Qi et al., 2021; Zeeshan et al., 2021). The decrease in photosynthetic pigment contents observed in *A. esculentus* in other soil compositions compared to the CSCW indicates disruption of the photosynthetic pathway, especially chlorophyll a, which has been used as a measure of photosynthetic rate. As observed in SeNPs-supplemented groups, there were significant reductions in photosynthetic pigments, indicating that SeNPs further added to the toxicity of toxic metals by inhibiting pigment synthesis, resulting in growth retardation of *A. esculentus* (Qi et al., 2021). Many heavy metals are known to stress chlorophyll a and b, as well as carotenoids, while SeNPs can act as pro-oxidants that damage cell membranes, disrupt chloroplasts, and desynchronize antioxidant systems (Oliviera et al., 2019; Hasanuzzaman et al., 2020). Similar observations were recorded by Azeez et al. (2019), Ogunkunle et al. (2020; 2023) and Kamali-Andani et al. (2022).

4. Conclusion

This study assessed the influence of decommissioned goldmine soil, goldmine water and SeNPs on *A. esculentus* physiology, morphology and biochemistry. The SeNPs were successfully mediated with bark extract of *C. nitida* and characterized with UV–Vis, FTIR, SEM-EDX and XRD analyses. The SeNPs with a concentration of 42 mgL⁻¹ were brick-red crystalline with a grain size of 64.95 nm, absorbed maximally at 290 nm and were capped by protein molecules in the extract. Both goldmine soil and goldmine water contained toxic metals while the contents in goldmine water were higher than WHO limits. The combined effects of goldmine soil and goldmine water on compacting different soil compositions were investigated in this study in which seeds of *A. esculentus* were planted for 21 days. Decreased antioxidant activity, relative water contents, photosynthetic pigments, increased radical production as demonstrated by MDA and H₂O₂ contents, disrupted shoot and root systems as shown in the micrographs of the cortex, xylems and piths in addition to inhibition of roots, shoots and vigour indices were recorded in *A. esculentus* exposed to other soil compositions beside CSCW. Further decline in *A. esculentus* useful characteristics and increase in radical generation were obtained with the addition of SeNPs eliciting phytotoxicity.

Study findings indicate that the simultaneous use of goldmine soil and goldmine water, as practised by farmers in gold mining communities, is harmful to plant health and by extension public health. It also shows that SeNPs can be phytotoxic to plants at high doses.

Authors' contribution

Azeez L and Oladejo AA – conceptualization, methodology, planting, data curation, validation and manuscript writing. Adejumo AL and Kolawole TO – metal analysis, result interpretation and data curation. Aremu, HK, Busari HK and Oyedede OA – biochemical analysis, supervision, manuscript review and editing.

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Declaration of Competing Interest

The authors declare that they have no competing interests.

Data availability

Data will be made available on request.

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