Foliar-applied selenium nanoparticles alleviate cadmium stress through changes in physio-biochemical status and essential oil profile of coriander (*Coriandrum sativum* L.) leaves

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Abstract

Since large areas of agricultural soils around the world are contaminated by Cd, a cost-effective and practical method is needed for the safe production of edible plants. The effective role of many nanomaterials to improve plant yield by mitigating environmental pollutions is addressed; however, the impacts of selenium nanoparticles (Se-NPs) have not been well-known yet. The aim of this work was to investigate foliar application of Se-NPs on yield, water content, proline concentration, phenolic content, lipid peroxidation, and essential oil (EO) attributes of coriander (*Coriandrum sativum* L.) under Cd stress. The plants were exposed to Cd contamination (0, 4, and 8 mg L⁻¹) and foliar application of Se-NPs (0, 20, 40, and 60 mg L⁻¹). The results showed increased Cd accumulation in roots and shoots of coriander plants upon Cd stress; however, Se-NPs alleviated the uptake of Cd. Cd toxicity, particularly 8 mg L⁻¹, decreased shoot and root weight, chlorophyll (Chl), and relative water content (RWC), while Se-NPs improved these attributes. The Cd concentration at 4 mg L⁻¹ and Se-NPs at 40 or 60 mg L⁻¹ increased phenolic and flavonoid contents as well as EO yield. Proline concentration and malondialdehyde (MDA) increased by enhancing Cd stress, but Se-NPs decreased MDA. The GC/MS analysis showed that the main EO constitutes were n-decanal (18.80–29.70%), 2E-dodecanal (14.23–19.87%), 2E-decanal (12.60–19.40%), and n-nonane (7.23–12.87%), representing different amounts under Cd pollution and Se-NPs. To sum up, Se-NPs at 40–60 mg L⁻¹ are effective in alleviating Cd stress.

Keywords Heavy metals · Nanotechnology · Essential oil composition · Phenolic content

Introduction

Soil contamination with trace metals is a main environmental concern, which threatens food security and agricultural production (Hussain et al. 2020). Despite plants requiring some microelements like selenium (Se), copper (Cu), cobalt (Co), zinc (Zn), and iron (Fe), others such as lead (Pb) and cadmium (Cd) are virulent to plants (Rizwan et al. 2019). Cd is addressed as the most harmful element for animals and humans (Khosropour et al. 2019), which releases in soil environment through different anthropogenic actions like mining wastes, sewage sludge, synthesis fertilizers, and industrial waste (Hussain et al. 2020; Khosropour et al. 2021). There is an increasing contamination of Cd in developing countries due to noticeable urbanization and industrialization (Hussain et al. 2020). Plants uptake heavy elements from soil and accumulate in their tissues, and thereby enhance the health risk for humans through consuming the edible parts (Gall et al. 2015). Plants adjust their physiological and molecular processes to reach the normal growth when exposed to Cd stress (Wang et al. 2020; Khosropour et al. 2021). Cd enhances the oxidative damages in plants by stimulating the production of the reactive oxygen species (ROS), where the overproduction of ROS leads to the photosynthesis damage and growth reduction through disturbing the plant defense system (Rizwan et al. 2019).
Nanoparticles (NPs), as a main part of nanotechnology, have received increasing attention on mitigating the contamination rate of the environment (El-Saadony et al. 2021) and thereby to improve human life (Fatemi et al. 2021). NPs are considered effective materials in the field of nutrition because they have high adsorption capacity and large surface area (Fatemi et al. 2021). Regarding their shape, size, and application method, NPs have different impacts on plants (Rastogi et al. 2019). Since the diameter of stomata pores is ~10 nm, NPs can easily penetrate through this gate under foliar spray techniques (Singh et al. 2021). After penetration and translocation, NPs induce the physiological and biochemical changes of plants which can be either beneficial or harmful (Singh et al. 2021). They can eliminate ROS generated under abnormal conditions such as heavy metals (Rubio et al. 2019). Recently, the NP forms of metals have been widely used in agriculture. Selenium (Se) is a beneficial and essential micronutrient for humans and animals, which acts as the cofactor and coenzyme in improving the immune system of human body (Ikram et al. 2021). According to the World Health Organization (WHO) reports, around 15% of the global population suffer from Se deficiency (Tan et al. 2016; Husain et al. 2020). In addition, the positive effects of Se on plants have been recently reported in some plants during biotic and abiotic stress such as drought (Rady et al. 2020; El-Saadony et al. 2021), salinity (Zahedi et al. 2019; Sheikhalipour et al. 2021; Soleymanzadeh et al. 2020), and heavy metals (Zhao et al. 2019; Wu et al. 2020; Zahedi et al. 2021). In plants under the interaction of Cd and Se application, Se usually mitigates Cd toxicity through subsiding oxidative stress, forms an insert complex or reduces Cd uptake, and rehabilitates damaged cells (Hussain et al. 2020; Wu et al. 2020). Vital biological processes are exerted by Se through activating selenoenzymes, which can boost antioxidant capacity, fortify ROS scavenging, and protect cell membrane (Hussain et al. 2020).

Coriander (Coriandrum sativum L.) is a herbaceous plant of the Apiaceae family. It can grow between 30 and 120 cm depending on the growth conditions such as temperature, water, and soil. Coriander is widely used as a vegetable and in food preparation (Amiripour et al. 2021). In addition to giving a pleasant taste and smell to food, coriander also has a high nutritional value (Memari-Tabrizi et al. 2021). Recently, there is an interest to use the coriander as medicinal plants due to its high quality of fatty acids (Amiripour et al. 2021) and valuable essential oil (EO) compounds (Memari-Tabrizi et al. 2021), which has a noticeable role on controlling a broad range of human diseases such as skin and digestive problems (Wei et al. 2019; Sardar et al. 2021b).

Phytochemicals are natural compounds in plants with a wide range of primary (amino acids, sugars, proteins, etc.) and secondary (phenols, EOs, etc.) compounds. Secondary metabolites are the outstanding traits of medicinal plants (Li et al. 2020). The antioxidant activity of plants is closely related to phenolic compounds such as flavonoids, phenolic acids, coumarins, tannins, and lignins. In fact, phenolic compounds are made from aromatic cores and OH groups, and due to their redox properties exert high antioxidant capacity in plants (Ali-Arab et al. 2022). EOs are complex mixtures of volatile organic compounds, which are mainly responsible for odor of plants and widely used in the cosmetic, food, and pharmaceutical industries (Afshari et al. 2021; Ali-Arab et al. 2022).

Recently, NPs have been emphasized as useful mechanisms for enhancement in yield of plant products. The beneficial role of NPs in the presence of heavy metals has been explained on coriander plants (Fatemi et al. 2021; Cordoba et al. 2021; Afshari et al. 2021; Sardar et al. 2021b; Sardar et al. 2022). However, there are a few reports about participation of Se-NPs as a foliar application in the mitigation of Cd stress in terms of biochemical traits in coriander plants. We hypothesized that foliar-applied Se-NPs can modulate Cd stress by improving plant growth and minimizing Cd uptake. Accordingly, the objectives of this study were (1) to explore Cd concentration in plant tissue, leaf water and chlorophyll (Chl) content, proline and malondialdehyde (MDA) concentration, and phenolic content with spraying Se-NPs and exposing to Cd stress; (2) to quantify and qualify leaf EO of coriander plants in the presence of Cd and Se-NPs; and (3) to find the best level of Se-NPs for subsiding the undesirable function of Cd in coriander. These results can discover appropriate levels of Se-NPs to control the Cd stress on coriander plants in terms of optimum yield and EO composition.

Material and methods

Growth conditions

The coriander seeds were obtained from the Pakan Bazr Company, Isfahan, Iran. The experiment was carried out in a greenhouse with a relative humidity of 65–75% and a photoperiod of 16/8 (lightness/darkness) in Islamic Azad University of Maragheh, Iran. The growing medium was coco peat and perlite at a ratio of 2:1, which was applied in 3-L pots.

Experimental design and treatments

The Cd stress and Se-NPs, as treatments of the study, were carried out in a factorial based on completely randomized design (RCD) with four replicates. Ten seeds were cultivated in each pot and then thinned to three seedlings after the four-leaf stage. Each pot contains three plants of coriander. Three different Cd stress were 0 (control), 4 mg L$^{-1}$, and 8 mg L$^{-1}$.
applied at the 4-leaf growth stage. The irrigation with Cd solution (250 mL in each pot) occurred five times. Se-NPs (Sigma-Aldrich, USA) were purchased from Bis-moot Company (Tehran, Iran) in the powder form with the source of SeO₂. They were spherical with average particle size of 10–40 nm, specific surface area of 30–50 m² g⁻¹, true density of 3.89 g cm⁻³, CAS number of 7446-08-4, and purity of 99.9%. The Se-NPs at levels of 0 (control), 20, 40, and 60 mg L⁻¹ were sprayed on plants two times in the 6-leaf stage (first time) and after 15 days (second time). All coriander plants were nourished by 400 mL of Hoagland’s nutrient solution (Hoagland and Arnon 1950) per pot in 3-day intervals. This nutrient solution included macronutrients in mM (N 3.75, K 3.0, Ca 2.5, Mg 1.0, S 1.0) and micronutrients in μM (B 23.15, Fe 26.0; Mn 4.55, Cl 9.0, Zn 0.38, Mo 0.25, Cu 0.16). After the flowering stage, the leaves were sampled to measure the physiological and biochemical attributes.

Cd concentration

Inductively coupled plasma mass spectrometry (ICP/MS) (Agilent 4500 series, USA) was used to measure Cd concentration in coriander tissues. The 0.2 g of dry matter was mixed with 4 mL of 65% nitric acid (HNO₃) and kept at 25 °C for 24 h. Thereafter, the sample was placed in an oven at 90 °C until evaporating NO₂. The volume was made up to 10 mL with distilled water (Khosropour et al. 2019).

Relative water content determination

The developed leaves were applied to measure relative water content (RWC). After measuring the fresh weight (FW), saturation weight (SW) was obtained by immersing the leaves in distilled water for 24 h. After that, the leaf samples were dried at 70 °C for 24 h to get their dry weight (DW). Eventually, RWC was calculated based on the following equation (Dhopte and Manuel 2002).

\[ RWC = \left( \frac{FW - DW}{SW - DW} \right) \times 100 \]

Malondialdehyde measurement

To determine MDA, 0.2 g fresh leaf tissue was grinded with 5 mL of trichloroacetic acid (TCA, 1%) and centrifuged for 5 min at 10,000 rpm. Moreover, 5 mL of TCA (20%) containing 0.5 mL thiobarbituric acid was added to 1 mL of supernatant and placed in a 95 °C water bath for 30 min, and followed by centrifuging for 10 min at 10,000 rpm. The absorbance wavelength was 520 nm (Heath and Packer 1968).

Chlorophyll assay

To determine chlorophyll (Chl) content, 0.5 g of leaf tissue was mixed with 4 mL of acetone (80%). The supernatant was prepared after centrifuging at 4000 rpm for 5 min. To measure total Chl, a spectrophotometer (T80 model) was calibrated and zeroed using acetone 80% in 630-, 647-, and 664-nm wavelengths. The absorbance of the solutions was read and the concentration Chl was calculated (Arnon 1949).

Proline concentration

To determine the proline content, 0.1 g of fresh leaf tissue was mixed with 10 mL of sulfosalicylic acid (3% w/v) and centrifuged at 4000×g for 20 min. Then, the mixture was supplied with 2 mL of nihydorn acid and 2 mL of glacial acetic acid. Simultaneously, 2 mL of standard 0, 4, 8, 12, 16, and 20 mg of proline was mixed with 2 mL of nihydirnic acid and 2 mL of acetic acid. The samples were read at 520 nm using a spectrophotometer (Bates et al. 1973).

Total phenolic content

The total phenolic content (TPC) was measured with Folin-Ciocalteu as a reagent and gallic acid (GA) as a standard. For this, 2 g of leaf sample was homogenized with 8 mL of 80% ethanol and centrifuged at 12,000×g for 20 min. After that, 0.5 mL of supernatant was transferred into 15-mL Falcon. Then 500 μL Folin-Ciocalteu was added to the mixture and after 2 min, 1 mL sodium carbonate (7%) was added to the reaction mixture and the final volume reached 6 mL using distilled water. The mixture remained in a 30 °C (dark condition) bath for 90 min. The absorbance of the samples was measured in a 725-nm wavelength with a spectrophotometer (McDonald et al. 2001).

Total flavonoid content

The amount of total flavonoid content (TFC) was measured by aluminum chloride colorimetric method. In this method, 0.5 mL of the extract solution was mixed with 1.5 mL of 95% ethanol, 0.1 mL of 10% aluminum chloride, 0.1 mL of 1 M potassium acetate, and 2.8 mL of distilled water. After keeping the samples at room temperature for 30 min, the adsorption of the mixture was read at 415 nm. The quercetin standard was used to draw the curve (Chang et al. 2002).

Essential oil content and composition

To obtain essential oil (EO) content, dried leaves were hydro-distillated for 3 h using a Clevenger-type apparatus (Sefidkon et al. 2006). The EO samples were dehydrated by placing them in dark glass bottles containing anhydrous
sodium sulfate. The samples were maintained at 4 °C until they were analyzed by gas chromatography and/or mass spectroscopy. EO yield was determined as the amount of EO extracted from total dry weight per pot. The EO compositions were analyzed by Varian 3400 GC-MS system equipment with AOC-5000 auto injector and DB-5 fused silica capillary column (30 m × 0.25 mm i.d.; film thicknesses 0.25 μm).

**Results**

**Cadmium concentration in root and shoot**

The increased cadmium (Cd) concentrations in roots and shoots of coriander plants were observed when exposed to Cd stress, but Se-NPs reduced Cd content in these tissues. Approximately 2.5-fold increases of Cd content in shoot and root were obtained in plants experiencing 8 mg L⁻¹ Cd relative to 4 mg L⁻¹ Cd. Under Cd concentration at 8 mg L⁻¹ Cd, Se-NPs at 20, 40, and 60 mg L⁻¹ decreased the Cd concentration of roots by 20, 60, and 50% compared with non-foliar applied plants (Fig. 1a). The declines of Cd concentration in shoot (Fig. 1b) were 17, 64, and 61% for 20, 40, and 60 mg L⁻¹, respectively. Although all levels of Se-NPs prevented

![Fig. 1](image-url)
the uptake of Cd in coriander plants, the effect of 40 mg L\(^{-1}\) was more effective.

**Shoot dry weight and root dry weight**

The dry weight of shoots and roots significantly \((P \leq 0.05)\) decreased by Cd stress over control; however, Se-NPs improved these attributes. Under 8 mg L\(^{-1}\) Cd stress, 40 and 60 mg L\(^{-1}\) Se-NPs increased shoot weight by ~50% when compared to control (Fig. 1c). Like shoot weight, root weight showed the significant enhancement when plants were sprayed with Se-NPs at Cd-stressed conditions. Under non-foliar application of Se-NPs, 4 and 8 mg L\(^{-1}\) Cd decreased root dry weight by 24 and 50% as compared to control (Fig. 1d).

**Relative water content and chlorophyll content**

The remarkable increase of RWC was observed at non-stressful treatment when plants were sprayed with 40 and 60 mg L\(^{-1}\) Se-NPs. The main changes of RWC corresponded to Cd stress so that the minimum amount was reported in plants exposed to 8 mg L\(^{-1}\) Cd and non-foliar application of Se-NPs (Fig. 2a). Like RWC, Chl content decreased with Cd stress but increased with foliar application of Se-NPs. At non-Se application, 34% reduction of total Chl content was obtained in plants exposed to 8 mg L\(^{-1}\) Cd (Fig. 2b).

**Proline and malondialdehyde**

Proline concentration increased with Cd and Se-NPs, but the effect of Cd stress was stronger in increasing the proline

![Graphs showing RWC, chlorophyll content, proline concentration, and malondialdehyde concentration under different treatments.](image)
accumulation. At non-sprayed plants, 8 mg L\(^{-1}\) Cd increased proline concentration by 73% when compared with control. The role of Se-NPs was highlighted in low Cd-stressed plants (Fig. 2c). In addition, Cd stress increased MDA, while Se-NPs decreased it. The highest MDA (34.1 nM g\(^{-1}\) FW) was observed in plants exposed to 8 mg L\(^{-1}\) Cd stress with non-foliar application of Se-NPs. Under 8 mg L\(^{-1}\) Cd, the 55% decline of MDA was recorded when plants were sprayed with 60 mg L\(^{-1}\) Se-NPs (Fig. 2d).

**Total phenolic content and total flavonoid content**

TPC and TFC significantly increased with Se-NPS. However, their amounts were different under Cd stress. The highest amount of TPC (Fig. 3a) and TFC (Fig. 3b) was recorded in 4 mg L\(^{-1}\) Cd and when plants were sprayed with 40 or 60 mg L\(^{-1}\) Se-NPs. In plants treated with 60 mg L\(^{-1}\) Se-NPs, Cd stress at 4 mg L\(^{-1}\) enhanced TPC and TFC by 41 and 19%, respectively, compared with control. However, Cd level at 8 mg L\(^{-1}\) decreased TPC and TFC relative to the non-stressed treatment. On the other hand, Se-NPs improved the antioxidant capacity of coriander plants via increasing the TPC and TFC. Under 4 mg L\(^{-1}\) Cd, 40 mg L\(^{-1}\) Se-NPs elevated TPC and TFC by 39 and 36% when compared with non-foliar application.

**Essential oil content and essential oil yield**

The EO of coriander leaves was raised by Cd level at 4 mg L\(^{-1}\). Under 60 mg L\(^{-1}\) Se-NPs, 4 mg L\(^{-1}\) Cd increased EO by
37%, while there was no significant change between control and Cd concentration at 8 mg L\(^{-1}\) on EO content. On the other hand, 40 and 60 mg L\(^{-1}\) Se-NPs significantly improved EO. Under 4 mg L\(^{-1}\) Cd stress, 40 and 60 mg L\(^{-1}\) Se-NPs increased EO by 52 and 58% as compared with non-foliar applied Se-NPs (Fig. 3c). Although there was no significant change of EO yield between control and Cd concentration at 4 mg L\(^{-1}\), the 8 mg L\(^{-1}\) Cd stress remarkably decreased EO yield. In plants without Se-NPs, the 2-fold reduction of EO yield was observed at 8 mg L\(^{-1}\) Cd relative to control (Fig. 3d).

**Essential oil composition**

The GC/MS analysis showed 24 compounds of EO coriander leaves, which represent more than 97% of total oil for all treatments (Table 1). The main EO constitutes were n-decanal, 2E-dodecanal, 2E-decanal, and n-nonane. The n-decanal decreased by Cd stress and increased by Se-NPs. The minimum amount of n-decanal was reported in 8 mg L\(^{-1}\) Cd stress as 15.9%, while its maximum amount obtained in plants that experienced non-Cd stress and 40 mg L\(^{-1}\) Se-NPs was to be 28.7%. However, Cd stress increased 2E-decanal. Under non-foliar application of Se-NPs, Cd concentration at 8 mg L\(^{-1}\) increased 2E-decanal by 31% compared to control. 2E-decanal differed from 14.23% in 4 mg L\(^{-1}\) Cd stress and 60 mg L\(^{-1}\) Se-NPs to 19.87% in 8 mg L\(^{-1}\) Cd stress and 40 mg L\(^{-1}\) Se-NPs. The n-nonane showed no significant change under Cd stress and foliar application of Se-NPs. It was obtained in a range of 7.23–12.87% of total coriander leaf EO.

**Discussion**

Soil Cd contamination is a main restricting factor on medicinal plants through inhibiting plant growth and development and increasing the Cd concentrations in edible parts of plants (Abbas et al. 2017). Coriander is the most eminent vegetable with high medicinal attributes (Amiripour et al. 2021). To minimize Cd accumulation in medicinal plants is a key factor to reduce Cd toxicity and guarantee food safety (Memari-Tabrizi et al. 2021; Sardar et al. 2022). In this work, Cd stress led to accumulation of Cd in coriander tissues, and also this accumulation in roots was higher than that in shoots. Similarly, compared with shoots, the greater

| Table 1 | Essential oil composition of coriander leaves under cadmium stress and selenium nanoparticles |
|---------|--------------------------------------------------------------------------------------------|
| Compound | RI | Non-Cd stress | 4 mg L\(^{-1}\) Cd | 8 mg L\(^{-1}\) Cd |
|         |    | Se 0 | Se 20 | Se 40 | Se 60 | Se 0 | Se 20 | Se 40 | Se 60 | Se 0 | Se 20 | Se 40 | Se 60 |
| n-Nonane | 900 | 10.23 | 9.34 | 9.80 | 7.23 | 9.20 | 9.43 | 9.93 | 9.43 | 11.89 | 12.87 | 9.78 | 10.32 |
| α-Pinene | 933 | 0.23 | 0.15 | 0.24 | 0.18 | 0.32 | 0.37 | 0.25 | 0.17 | 0.31 | 0.36 | 0.37 | 0.48 |
| n-Decane | 996 | 0.56 | 0.67 | 0.53 | 0.62 | 8.23 | 0.98 | 0.78 | 0.45 | 0.98 | 0.56 | 0.75 | 1.02 |
| n-Octanal | 1005 | 0.56 | 0.53 | 0.65 | 0.34 | 0.34 | 0.00 | 0.54 | 0.00 | 0.32 | 0.00 | 0.00 | 0.23 |
| p-Cymene | 1027 | 0.00 | 0.23 | 0.34 | 0.27 | 0.12 | 1.20 | 0.00 | 0.15 | 0.45 | 0.76 | 0.02 | 0.00 |
| Limonene | 1030 | 0.54 | 0.23 | 0.34 | 0.45 | 0.65 | 0.23 | 0.76 | 0.23 | 0.16 | 0.54 | 0.22 | 0.47 |
| Linalool | 1102 | 0.40 | 0.67 | 0.47 | 1.55 | 0.90 | 0.84 | 0.15 | 0.33 | 0.98 | 0.17 | 0.19 | 0.51 |
| n-Nonanal | 1107 | 1.54 | 1.20 | 1.02 | 1.65 | 1.56 | 1.43 | 1.22 | 0.89 | 1.05 | 0.00 | 1.23 | 2.18 |
| n-Decanal | 1219 | 23.90 | 25.40 | 28.70 | 29.70 | 17.60 | 22.50 | 24.70 | 19.22 | 15.80 | 15.90 | 17.60 | 16.50 |
| 2E-Decanal | 1273 | 13.20 | 14.20 | 15.20 | 14.80 | 13.60 | 14.60 | 12.60 | 15.30 | 17.34 | 19.40 | 16.70 | 18.30 |
| 1-Decanol | 1277 | 0.54 | 1.65 | 0.76 | 0.45 | 2.12 | 0.54 | 0.34 | 0.64 | 0.76 | 0.34 | 0.35 | 0.60 |
| Undecanal | 1311 | 3.12 | 3.15 | 2.65 | 3.43 | 3.56 | 4.32 | 1.45 | 4.09 | 2.15 | 4.21 | 3.65 | 3.21 |
| 2E-Undecanal | 1370 | 3.65 | 2.76 | 2.43 | 4.12 | 3.50 | 4.12 | 3.87 | 3.70 | 3.76 | 2.65 | 3.12 | 4.32 |
| Dodecanal | 1413 | 6.35 | 5.20 | 6.40 | 5.70 | 4.80 | 6.40 | 6.70 | 5.20 | 8.78 | 7.60 | 5.40 | 5.80 |
| 2E-Dodecanal | 1476 | 16.22 | 18.03 | 17.60 | 14.23 | 16.70 | 18.60 | 15.70 | 18.42 | 18.60 | 17.54 | 19.87 | 18.34 |
| (E)-β ionone | 1483 | 0.76 | 0.23 | 0.14 | 0.00 | 0.87 | 0.34 | 0.12 | 1.45 | 0.87 | 0.34 | 0.43 | 0.12 |
| Tridecanal | 1511 | 0.34 | 0.65 | 0.76 | 0.23 | 0.05 | 0.67 | 0.76 | 0.05 | 0.77 | 0.49 | 0.72 | 0.00 |
| E-Nerolidol | 1560 | 0.54 | 0.12 | 0.87 | 0.13 | 0.13 | 0.67 | 0.18 | 0.98 | 0.45 | 0.12 | 0.22 | 0.78 |
| 2E-Tridecan-1-al | 1572 | 1.76 | 1.43 | 0.95 | 1.22 | 1.34 | 0.15 | 0.76 | 0.23 | 0.34 | 1.02 | 1.20 | 0.00 |
| Tetradecanal | 1614 | 1.28 | 1.28 | 1.14 | 1.28 | 1.78 | 1.10 | 1.28 | 1.28 | 1.23 | 1.28 | 1.43 | 3.20 |
| 2E-Tridecan-1-al | 1680 | 8.21 | 7.12 | 5.40 | 7.21 | 6.50 | 3.55 | 9.34 | 7.12 | 5.21 | 7.52 | 5.60 | 5.89 |
| Neocnidilide | 1739 | 3.12 | 2.54 | 2.65 | 3.76 | 1.23 | 3.45 | 4.34 | 4.23 | 5.67 | 1.50 | 6.23 | 4.56 |
| Tridecan-1-al<2E-> | 1780 | 2.34 | 2.34 | 0.94 | 1.43 | 2.76 | 1.23 | 2.76 | 4.37 | 1.89 | 3.67 | 2.87 | 2.76 |
| Total | 99.39 | 99.12 | 99.98 | 99.97 | 99.16 | 99.72 | 98.53 | 97.93 | 99.74 | 98.84 | 97.95 | 99.59 |
Cd accumulation in roots was reported in basil (Gheshlaghpour et al. 2021) and summer savory (Memari-Tabrizi et al. 2021) under Cd stress. It is well documented that enhanced Cd accumulation leads to acidification of rhizosphere, which can improve Cd bioavailability and mobility (Khosropour et al. 2021). In acidic soil, Cd appeared in free Cd$^{2+}$ ions, but in the lower acidity (pH 6–7), Cd is available in the forms of CdCl$^{-}$, CdHCO$_3^-$, and hydrated CdCO$_3$ (Ismael et al. 2019). Generally, Cd accumulation in aerial parts is lower relative to that in the root (Seregin and Kozhevnikova 2008). Apoplast and symplast are the main routes of Cd translocation due to its high mobility and water solubility (Ismael et al. 2019). Plants due to their phytoremediation potential attempt to accumulate Cd in different parts of the plant, subsequently contaminating the food chain and jeopardizing human health (Wang et al. 2019). Hence, minimizing Cd uptake and accumulation in edible parts of plants is important. The present study represented the useful role of foliar-applied Se-NPs to mitigate the Cd accumulation of coriander. However, Se-NPs may mitigate Cd accumulation at Cd-stressed plants through downregulation of Heavy Metal ATPase (HMA) gene (Greger et al. 2016). The HMA is overexpressed under hyper-accumulation of Cd in different plant parts (Gheshlaghpour et al. 2021). Recently, the foliar application of Se has been widely used in most plants to prevent or mitigate the adverse effects of heavy metals (Zhou et al. 2021). The more appropriate mechanism of foliar Se application relative to soil application has been reported (Ismael et al. 2019).

The shoot and root weights of coriander plants increased by Se-NPs (Fig. 2), which confirms the beneficial role of Se-NPs in alleviating trace element stress in plants (Wan et al. 2019; Qi et al. 2021). The restriction of plant growth may be observed due to the Cd accumulation in the tissues via degradation of functional mechanisms, where reactive oxygen species (ROS) is largely generated (Rizwan et al. 2019; Qi et al. 2021). Se-NPs particularly 40 and 60 mg L$^{-1}$ showed the advantageous role of Se-NPs in ameliorating the Cd uptake. In line with our study, the positive role of Se on plant weight through reducing Cd uptake has been previously reported in different plants (Huang et al. 2017; Hussain et al. 2020). However, the information on nanoparticle form of Se to alleviate Cd stress is low. Tripathi et al. (2016) showed the NPs form of Si more efficiently mitigates heavy metal toxicity than its simple form in maize. Sardar et al. (2022) showed increased growth of coriander when seeds were primed with Se-NPs at 5–15 mg L$^{-1}$. Moreover, Qi et al. (2021) showed improvement of *Brassica napus* L. growth via improving the antioxidant capacity of plants under Cd stress.

The decreased RWC and Chl contents under Cd stress were obtained in coriander plants. The RWC is used to assess the water status of plants as the main physiological response to stress (Sarker and Oba 2018). Minimal RWC was observed in plants exposed to high Cd stress (Fig. 3a). The decline in RWC is a strategy for plants to limit certain biochemical processes by preserving the energy needed for survival (Sarker and Oba 2018; Khosropour et al. 2021). The size of Se-NP used in this study was less than 50 nm, and this size was appropriate to penetrate plant cells (Sabo-Attwood et al. 2012; Taylor et al. 2014; Pérez-de-Luque 2017). Se-NP can increase the water content, thereby improving the biochemical process of plant cells, and finally improving plant growth and performance (Merwad et al. 2018). Increased RWC in coriander plants upon seed priming with Se-NPs was reported by Sardar et al. (2021b). Like RWC, Chl content increased by Se-NPs but decreased by Cd stress. Under stress conditions, plants reduce photosynthesis rate to remain surviving. The reduced Chl concentrations under heavy metals have been reported in different plants (Khosropour et al. 2021; Zhang et al. 2020; Sardar et al. 2021b).

Proline concentration increased over control in plants exposed to Cd stress. Plants change the concentration of proline to regulate cell penetration and protect plants from different types of stress (Bhagyawant et al. 2019). Elevated proline content was observed when Se-NPs were used alone or in interaction with Cd stress. Enhanced proline of coriander leaves is a strategy of these plants to overcome Cd stress. The Se-NPs foliar application and Cd stress increased proline level owing to enhancement in the expression of genes related to proline (La et al. 2019). The results of this study indicate that Cd stress causes proline accumulation, which has been previously confirmed by La et al. (2019) and Bhagyawant et al. (2019). Accumulated proline is a mechanism that removes cellular ROS in order to enhance antioxidant potential by stabilizing cell membranes and enzyme activities in stressful plants (Asfand and Foolad 2007; Sardar et al. 2021a). Se foliar spray can promote proline by enhancing the activity of glutamyl kinase, which controls proline accumulation in plants (Khan et al. 2015). Similar to our study, Ghasemian et al. (2021) showed the increased proline content with Se-NPs. Cd stress led to increased accumulation of MDA in coriander plants, whereas both Se-NPs reduced its concentration (Fig. 1). The elevated oxidative stress is due to Cd concentrations in coriander plants because of oxidative stress induced by Cd stress as well previously documented (Sardar et al. 2021a; Sardar et al. 2022). Oxidative stress negatively affects metabolic process, which can damage membrane structure in plants (Wu et al. 2020; Sardar et al. 2021a). Lower production of MDA with Se might be because of the Se-NPs role in reducing Cd accumulation in leaves. The decreased MDA with Se application has been reported on wheat plants under Cd stress (Wu et al. 2020).

Phenolic compounds possess a noticeable role on modulating oxidative stress in medicinal plants (Afshari et al. 2021). We observed that Cd stress at 4 mg L$^{-1}$ leads to enhanced TPC and TFC, but they decreased under 8 mg L$^{-1}$.
Cd stress. Under heavy metals, phenolic metabolites play a significant role in scavenging ROS (Khosropour et al. 2019). Similar to our results, Memari-Tabrizi et al. (2021) showed the increased TPC and TFC of summer savory plants upon Cd concentration at 10 mg kg\(^{-1}\) soil and their reduction when experiencing high Cd concentration at 20 mg kg\(^{-1}\) soil. Therefore, the phenolic compounds due to their antioxidant potential had a remarkable function on alleviating Cd stress in coriander plants.

The improved EO content of coriander leaves was observed upon Cd concentration at 4 mg L\(^{-1}\). In contrast, Cd level at 8 mg L\(^{-1}\) exerted the significant decline of EO yield as it can be due to the noticeable reduction of dry weight at 8 mg L\(^{-1}\) Cd concentration (Memari-Tabrizi et al. 2021). The deleterious impacts of Cd stress were modulated by Se-NPs in terms of improved EO yield (Fig. 3d). Heavy metals can affect EO production in aromatic plants (Memari-Tabrizi et al. 2021). The 4 mg L\(^{-1}\) Cd along with all levels of Se-NPs resulted in the desirable EO yield, which was in line with the results of Memari-Tabrizi et al. (2021) on summer savory because of Si-NPs and Cd level at 4 mg L\(^{-1}\). The reduced EO contents due to Cd stress at 8 mg L\(^{-1}\) were reported on peppermint (Ahmad et al. 2018) and summer savory (Memari-Tabrizi et al. 2021). The decreased leaf surface and increased number of EO glands per leaf area lead to increased EO production (Mirzaie et al. 2020). The EO production can be affected by various abiotic stresses through changes in the density of EO glands (Es-sbhi et al. 2020 Farouk et al. 2020). This study addressed the improved EO yield by foliar application of Se-NPs. Microelements like Se and Si may increase EO yield through improvement of ion uptake and cell development (Memari-Tabrizi et al. 2021).

The main EO compounds of coriander leaves were decanal, 2E-dodecanal, 2E-decanal, and n-nonane, which was confirmed by Amiripour et al. (2021) in leaves of coriander plants treated with salinity and silicon. The EO profile was changed with Cd contamination and Se-NPs spraying. Environmental stresses can change EO biosynthesis and EO profile of medicinal plants (Mirzaie et al. 2020). The changes of main EO profile of summer savory have been reported by Memari-Tabrizi et al. (2021) under Cd stress and Si-NPs. We observed the different trends of main EO profile of coriander leaves under Cd stress as compared to salinity stress addressed by Amiripour et al. (2021). Therefore, we can mention that the type is responsible in changing the EO profile of coriander leaves.

**Conclusions**

Heavy metals mainly cadmium are increasing in the agricultural soils and there are many interests on alleviating cadmium toxicity on plants. According to results of the present study, selenium nanoparticles at 40–60 mg L\(^{-1}\) could modulate the adverse effect of cadmium stress by minimizing its uptake and optimizing water content, photosynthesis pigments, and phenolic content. Therefore, foliar application of selenium nanoparticles at 60 mg L\(^{-1}\) can be recommended for coriander plants cultivated in cadmium-contaminated soils.

**Author contribution** All the authors equally contributed in preparing the article.

**Data availability** Not applicable.

**Declarations**

**Ethical approval** The present study has not been submitted or under reviewed in other journals.

**Consent to participate** All the authors agree to participate in writing and submitting this article in ESPR.

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**Competing interests** The authors declare no competing interests.

**References**

Abbas T, Rizwan M, Ali S, Zia-ur-Rehman M, Qayyum MF, Abbas F, Ok YS (2017) Effect of biochar on cadmium bioavailability and uptake in wheat (Triticum aestivum L.) grown in a soil with aged contamination. Ecotoxicol Environ Saf 140:37–47. https://doi.org/10.1016/j.ecoenv.2017.02.028

Afshari M, Pazoki A, Sadeghipour O (2021) Foliar-applied silicon and its nanoparticles stimulate phyto-chemical changes to improve growth, yield and active constituents of coriander (Coriandrum Sativum L.) essential oil under different irrigation regimes. Silicon 13:4177–4188

Ali-Arab H, Bahadori F, Mirza M, Badi HN, Kalate-Jari S (2022) Variability in essential oil composition and phenolic acid profile of Thymus daenensis Celak. populations from Iran. Ind Crop Prod 178:114345. https://doi.org/10.1016/j.indcrop.2021.114345

Ahmad B, Jaleel H, Sadiq Y, A Khan MM, Shabbir A (2018) Response of exogenous salicylic acid on cadmium induced photosynthetic damage, antioxidant metabolism and essential oil production in peppermint. Plant Growth Regul 86(2): 273–286. https://doi.org/10.1007/s10725-018-0427-z

Amiripour A, Jahromi MG, Soori MK, mohammadi Torkashvand A (2021) Changes in essential oil composition and fatty acid profile of coriander (Coriandrum sativum L.) leaves under salinity and foliar-applied silicon. Ind Crop Prod 168:113599. https://doi.org/10.1016/j.indcrop.2021.113599

Arnon DI (1949) Copper enzymes in isolated chloroplasts. Polyphenoloxidase in Beta vulgaris. Plant Physiol 24:1–15. https://doi.org/10.1104/pp.24.1.1

Ashraf MFFMR, Foolad MR (2007) Roles of glycine betaine and proline in improving plant abiotic stress resistance. Environ Exp Bot 59:206–216. https://doi.org/10.1016/j.envexpbot.2005.12.006

Bates LS, Waldren RP, Teare ID (1973) Rapid determination of free proline for water-stress studies. Plant Soil 39:205–207. https://doi.org/10.1007/BF00018060
Hussain B, Lin Q, Hamid Y, Sanaullah M, Di L, Khan MB, Yang X (2020) Foliage application of selenium and silicon nanoparticles alleviates Cd and Pb toxicity in rice (Oryza sativa L.). Sci Total Environ 712:136497. https://doi.org/10.1016/j.scitotenv.2020.136497

Ikram M, Javed B, Raja NI, Mashwani ZUR (2021) Biomedical potential of plant-based selenium nanoparticles: a comprehensive review on therapeutic and mechanistic aspects. Int J Nanomedicine 16:249. https://doi.org/10.2147/IJN.S295053

Ismael MA, Elyamine AM, Moussa MG, Cai M, Zhao X, Hu C (2019) Cadmium in plants: uptake, toxicity, and its interactions with selenium fertilizers. Metallomics 11(2):255–277. https://doi.org/10.1039/c8m00247a

Khan MIR, Nazir F, Asgher M, Per TS, Khan A (2015) Selenium and sulfur influence ethylene formation and alleviate cadmium-induced oxidative stress by improving proline and glutathione production in wheat. J Plant Physiol 173:9–18. https://doi.org/10.1016/j.jplph.2014.09.011

Khosropour E, Attarod P, Shirvany A, Pypker TG, Bayramzadeh V, Hakimi L, Moeinaddini M (2019) Response of Platanus orientalis leaves to urban pollution by heavy metals. J For Res 30(4):1437–1445. https://doi.org/10.1007/s11676-018-0609-2

Khosropour E, Weisany W, Tahir NAR, Hakimi L (2021) Vermicompost and biochar can alleviate cadmium stress through minimizing its uptake and optimizing biochemical properties in Berberis integerrima ruche. Environ Sci Pollut Res 28(2):1417–1425. https://doi.org/10.1007/s11356-021-17073-6

La VH, Lee BR, Zhang Q, Park SH, Islam M, KimTH (2019) Salicylic acid improves drought stress tolerance by regulating the redox status and proline metabolism in Brassica rapa. Hort Environ Bio Technol 60(1):31–40. https://doi.org/10.1007/s11676-018-0099-7

Li Y, Kong D, Fu Y, Sussman MR, Wu H (2020) The effect of developmental and environmental factors on secondary metabolites in medicinal plants. Plant Physiol Biochem 148:80–89. https://doi.org/10.1016/j.plaphy.2020.01.006

Memari-Tabrizi EF, Yousefpoor-Dokhaniieh A, Babashpour-Asl M (2021) Foliar-applied silicon nanoparticles mitigate cadmium stress through physio-chemical changes to improve growth, antioxidant capacity, and essential oil profile of summer savory (Satureja hortensis L.). Plant Physiol Biochem 165:71–79. https://doi.org/10.1016/j.plaphy.2021.04.040

Merwad ARM, Desok ESM, Rady MM (2018) Response of water deficit-stressed Vigna unguiculata performances to silicon, proline or methionine foliar application. Sci Hortic 228:132–144. https://doi.org/10.1016/j.scienta.2017.10.008

Mirzaie M, Ladannaghmad AR, Hakimi L, Danace E (2020) Water stress modifies essential oil yield and composition, glandular trichomes and stomatal features of lemongrass (Cymbopogon citratus) inoculated with arbuscular mycorrhizal fungi. J Agric Sci Technol 12:27–36

McDonald S, Prenzler PD, Antolovich M, Robards K (2001) Phenolic content and antioxidant activity of olive extracts. Food Chem 73(1):73–84. https://doi.org/10.1016/S0308-8146(00)00288-0

Pérez-de-Laake A (2017) Interaction of nanomaterials with plants: what do we need for real applications in agriculture? Front Environ Sci 5:12. https://doi.org/10.3389/fenvs.2017.00012

Qi WY, Li Q, Chen H, Liu J, Xin SF, Xu M, Wang SG (2021) Selenium nanoparticles ameliorate Brassica napus L. cadmium toxicity by inhibiting the respiratory burst and scavenging reactive oxygen species. J Hazard Mater 417:125900. https://doi.org/10.1016/j.jhazmat.2021.125900

Rady MM, Belal HE, Gadallah FM, Semida WM (2020) Selenium application in two methods promotes drought tolerance in Solanum lycopersicum plant by inducing the antioxidant defense system. Sci Hortic 266:109290. https://doi.org/10.1016/j.scienta.2020.109290
Rastogi A, Tripathi DK, Yadav S, Chauhan DK, Živčák M, Ghorbanpour M, Brestic M (2019) Application of silicon nanoparticles in agriculture. Biotechnology 9:90–98. https://doi.org/10.1007/s13205-019-1626-7

Rizwan M, Ali S, Ali B, Adrees M, Arshad M, Hussain A, Waris AA (2019) Zinc and iron oxide nanoparticles improved the plant growth and reduced the oxidative stress and cadmium concentration in wheat. Chemosphere 214:269–277. https://doi.org/10.1016/j.chemosphere.2018.09.120

Rubio L, Pyrgiotakis G, Beltran-Huacar ZY, Gaurav J, Deloid G, Taylor AF, Rylott EL, Anderson CW, Bruce NC (2014) Investigating the role of nanoparticles in tobacco (Nicotiana szaithi) seedlings. Nanotoxicology. 6:353–360.

Sardo R, Ahmed S, Yasin NA (2021a) Role of exogenously applied putrescine in amelioration of cadmium stress in Coriandrum sativum by modulating antioxidant system. Int J Phytoremed 1-8. https://doi.org/10.1186/s12889-019-0325-1

Sabo-Attwood T, Unrine JM, Stone JW, Murphy CJ, Ghoshroy S, Blom D (2012) Uptake, distribution and toxicity of gold nanoparticles in wheat (Triticum aestivum L.) cadmium transport and accumulation of cadmium, lead, nickel, and strontium in wheat. Chemosphere 214:269–277. https://doi.org/10.1016/j.chemosphere.2019.03.061

Sarker U, Oba S (2018) Drought stress effects on growth, ROS markers, compatible solutes, phenolics, flavonoids, and antioxidant activity in Amaranthus tricolor. Appl Biochem Biotechnol 186(4):999–1016. https://doi.org/10.1007/s12010-018-2784-5

Sefidkon F, Abbasi K, Khaniki, GB (2006) Influence of drying and extraction methods on yield and chemical composition of the essential oil of Satureja hortensis. Food Chem 99(1):19–23

Seregin IV, Kozhevnikova AD (2008) Roles of root and shoot tissues in transport and accumulation of cadmium, lead, nickel, and strontium. Russ J Plant Physiol 55(1):1–22. https://doi.org/10.1134/S1021443708010019

Singh RP, Handa, R, Manchanda G (2021) Nanoparticles in sustainable agriculture: An emerging opportunity. J Control Release 329:1234–1248. https://doi.org/10.1016/j.jconrel.2020.10.051

Sheikhbalipour M, Esmaeipour B, Behnamian M, Gohari G, Giglou MT, Vachova P, Skalkicky M (2021) Chitosan–selenium nanoparticle (Cs–Se NP) foliar spray alleviates stress in bitter melon. Nanomaterial. 11:684–693. https://doi.org/10.3390/nano11030684

Soleymanzadeh R, Iranbaksh A, Habibi G, Ardebili ZO (2020) Selenium nanoparticles protected strawberry against salt stress through modifications in salicylic acid, ion homeostasis, antioxidant machinery, and photosynthesis performance. Acta Biol Cracov Ser Bot. https://doi.org/10.24425/abcrch.2019.127751

Tan LC, Nanchariah, YV, van Hullebusch ED, Lens PN (2016) Selenium: environmental significance, pollution, and biological treatment technologies. Biotechnol Adv 34(5):886–907. https://doi.org/10.1016/j.biotechadv.2016.05.005

Taylor AF, Rylott EL, Anderson CW, Bruce NC (2014) Investigating the toxicity, uptake, nanoparticle formation and genetic response of plants to gold. PLoS One 9:e93793. https://doi.org/10.1371/journal.pone.0093793

Tripathi DK, Singh S, Singh VP, Prasad SM, Chauhan DK, Dubey NK (2016) Silicon nanoparticles more efficiently alleviate arsenate toxicity than silicon in maize cultivar and hybrid differing in arsenate tolerance. Front Environ Sci 4:46. https://doi.org/10.3389/fenvs.2016.00046

Wan Y, Wang K, Liu Z, Yu Y, Wang Q, Li H (2019) Effect of selenium on the subcellular distribution of cadmium and oxidative stress induced by cadmium in rice (Oryza sativa L.). Environ Sci Pollut Res 26(16):16220–16228. https://doi.org/10.1007/s11356-019-04975-9

Wong X, Mao Z, Zhang J, Hemat M, Huang M, Cai J, Jiang D (2019) Osmyotide accumulation plays important roles in the drought priming induced tolerance to post-anthesis drought stress in winter wheat (Triticum aestivum L.). Environ Exp Bot 166:103804. https://doi.org/10.1016/j.envexpbot.2019.103804

Wang F, Zhang X, Zhang S, Zhang S, Sun Y (2020) Interactions of microplastics and cadmium on plant growth and arbuscular mycorrhizal fungal communities in an agricultural soil. Chemosphere 254:126791. https://doi.org/10.1016/j.chemosphere.2020.126791

Wei J, Gao J, Cen K (2019) Levels of eight heavy metals and health risk assessment considering food consumption by China’s residents based on the 5th China total diet study. Sci Total Environ 689:1141–1148. https://doi.org/10.1016/j.scitotenv.2019.06.052

Wu C, Dun Y, Zhang Z, Li M, Wu G (2020) Foliar application of selenium and zinc to alleviate wheat (Triticum aestivum L.) cadmium toxicity and uptake from cadmium-contaminated soil. Ecotoxicol Environ Saf 190(110091). https://doi.org/10.1016/j.ejoes.2019.110091

Yang HM, Wang GX (2001) Leaf stomatal densities and distribution in Triticum aestivum under drought and CO2 enrichment. Chin J Plant Ecol 25:312

Zahedi SM, Abdelrahman M, Hosseini MS, Hoveiez NF, Tran LSP (2019) Alleviation of the effect of salinity on growth and yield of strawberry by foliar spray of selenium-nanoparticles. Environ Pollut 253:246–258. https://doi.org/10.1016/j.envpol.2019.04.078

Zahedi SM, Hosseini MS, Daneshvar Hakimi Meybodi N, Pejnenburg W (2021) Mitigation of the effect of drought on growth and yield of pomegranates by foliar spraying of different sizes of selenium nanoparticles. J Sci Food Agric. https://doi.org/10.1002/jsfa.11167

Zhang H, Xu Z, Guo K, Huo Y, He G, Sun H, Sun G (2020) Toxic effects of heavy metal Cd and Zn on chlorophyll, carotenoid metabolism and photosynthetic function in tobacco leaves revealed by physiological and proteomics analysis. Ecotoxicol Environ Saf 202:110856. https://doi.org/10.1016/j.ecoenv.2020.110856

Zhao Y, Hu C, Wang X, Qiong X, Wang P, Zhang Y, Zhao X (2019) Selenium alleviated chromium stress in Chinese cabbage (Brassica campestris L. ss. Pekinesis) by regulating root morphology and metal element uptake. Ecotoxicol Environ Saf 173:314–321. https://doi.org/10.1016/j.ecoenv.2019.01.090

Zhou J, Zhang C, Du B, Cui H, Fan X, Zhou D, Zhou J (2021) Soil and foliar applications of silicon and selenium effects on cadmium accumulation and plant growth by modulation of antioxidant system and Cd translocation: Comparison of soft vs. durum wheat varieties. J Hazard Mater 402:123546. https://doi.org/10.1016/j.jhazmat.2020.123546

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