

Morphophysiological and phytochemical responses to Arsenic, cadmium and lead stress in Parsley (*Petroselinum crispum*)

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Abstract

Background

This study investigated the effects of varying concentrations of arsenic (As), cadmium (Cd), and lead (Pb) on the morphological, physiological, biochemical traits, essential oil yield and composition, phenolic content, antioxidant activity, and vitamin C content of parsley (*Petroselinum crispum*).

Results

Heavy metals exposure significantly reduced plant height, leaf area, shoot biomass, and relative leaf water content, while petiole length, stem diameter, root length, and root biomass increased. Leaf accumulation of As, Cd, and Pb rose proportionally with treatment levels. Photosynthetic pigments (chlorophyll a, chlorophyll b, and carotenoids) and photosystem II efficiency (Fv/Fm) declined significantly, especially under arsenic and lead stress. Despite growth inhibition, essential oil yield increased, peaking at 0.45% (w/w) under 100 mg/kg arsenic. GC analysis identified eighteen oil constituents, with major compounds including apiol, myristicin, β -pinene, and α -pinene. Heavy metal stress reduced oxygenated compounds and increased hydrocarbons in the oil profile. Total phenol and flavonoid contents increased markedly, with the highest values in the 100 mg/kg arsenic treatment (33 mg GAE/g DW phenols and 29 mg QE/g DW flavonoids). Antioxidant assays (DPPH and FRAP) showed enhanced radical scavenging activity and ferric reducing power, with the strongest effects in the As100 and Cd40 treatments. Additionally, vitamin C content significantly increased under heavy metal stress, reaching up to 170 mg/100g fresh weight in the 100 mg/kg arsenic treatment compared to 128 mg/100g in controls.

Conclusions

These results reveal complex morphological and biochemical adaptations of parsley to heavy metal stress, influencing growth, secondary metabolite production, and antioxidant capacity.

Introduction

A healthy diet and sustainable environment are essential for human well-being, and the consumption of plant-based foods, especially vegetables, is increasing due to their rich content of micronutrients and minerals [1]. Studies suggest that such diets can help prevent heart disease and certain types of cancer, particularly those affecting the digestive system [2]. Soil, water, and air pollution pose serious threats to human health because heavy metals easily accumulate in plants [3, 4]. When these metals enter the food chain, they negatively affect the metabolism and physiology of living organisms. This contamination is often linked to irrigation with urban and industrial wastewater, as many studies have shown the resulting heavy metal buildup in plants and soil [5]. Heavy metals persist in the environment and accumulate in soil, affecting living organisms even at low levels. Over time, they enter the food chain, posing health risks to humans and animals [6]. This risk is especially high for leafy vegetables, which are often eaten fresh [7].

One of these leafy vegetables is parsley (*Petroselinum crispum* (Mill.) belonging to the Apiaceae family, known as a medicinal and food plant, and recognized for its aromatic leaves and roots [8]. Parsley plays an important role in diets worldwide due to its rich nutritional content, including vitamins, minerals, and antioxidants that contribute to

overall health [9, 10]. Parsley is commonly used as a flavoring agent in foods and as a fragrance in cosmetics and perfumery. Its essential oil exhibits antimicrobial, diuretic, and mild antioxidant properties, and myristicin has shown potential as a cancer-protective compound [10]. Non-essential heavy metals like cadmium (Cd), lead (Pb), and arsenic (As) are toxic and serve no biological function, yet often enter the environment through human activities such as mining, industrial processes, and agricultural inputs [11]. While some trace elements support plant metabolism in small amounts, excess levels of these metals pose serious health and environmental risks [12]. Arsenic is a carcinogenic element that enters the human body through water, food, and agricultural products, posing serious health risks [13]. Its toxicity depends on several factors and is linked to epigenetic changes, increasing the risk of diabetes, adverse pregnancy outcomes, and various cancers [14]. Excessive cadmium in plants causes structural and physiological damage, while in humans it disrupts redox balance, impairs organelle function, and damages organs such as the brain, kidneys, bones, and lungs [15]. Its toxicity is linked to oxidative stress and protein binding, leading to severe cellular injury [16]. Lead is a widespread soil contaminant that disrupts plant growth despite having no biological role [17, 18]. In humans, its accumulation can cause chronic health issues such as headaches, fatigue, digestive disorders, and impaired vision [19]. The permissible levels of arsenic, cadmium, and lead in soils designated for leafy vegetable cultivation have been reported to range between 10–20 mg/kg, 1–5 mg/kg, and 6.8–128 mg/kg, respectively [20–22]. According to FAO/WHO, the standard level of As, Cd, and Pb in vegetables is 0.5, 0.2 and 0.3 mg kg [23, 24]. Numerous studies have reported the presence of heavy metal contamination in fruits and vegetables sourced from agricultural production sites in different countries [25]. In East Asia, the average concentrations of heavy metals detected in green leafy vegetables on a dry matter basis ranged from 0.71 to 15.89 mg/kg for Ni, 0.07 to 0.97 mg/kg for Cd, 0.18 to 5.05 mg/kg for Cr, 0.18 to 1.59 mg/kg for Pb, and 7.05 to 18.44 mg/kg for Cu [23]. In India, Cd, Pb, and Zn levels in some leafy herbs exceeded WHO limits, posing greater risk to Parsley leaves than seeds, despite their antioxidant potential [26]. In a greenhouse study, higher soil cadmium increased cadmium and lead accumulation in parsley, while low cadmium levels boosted plant growth. [27]. In parsley, increased cadmium caused higher metal accumulation, reduced chlorophyll, and decreased antioxidant enzyme activity, while non-enzymatic antioxidants slightly increased [28]. In another study, low cadmium concentrations promoted the growth and photosynthesis of *Picris divaricata*, while high concentrations inhibited them and photosynthesis was indirectly affected at higher Cd levels due to reduced stomatal density, despite stable carotenoid and Mn levels [29]. Arsenic suppresses the numbers of leaves, fresh and dry mass of plant, cause curling, lowers photosynthesis and causes necrosis of leaf blades [30]. Heavy metal uptake by plants is largely determined by internal and external factors such as plant genetics, developmental stage, tissue barriers, environmental conditions, and biochemical stressors [31, 32]. In various regions around the world, the use of heavy metal-contaminated soil or water for growing crops like sweet basil, parsley, and other leafy vegetables has raised serious concerns about food safety and environmental health [33]. Also, the effect of contaminated soil under greenhouse conditions was reported by Y Fan, H Li, Z Xue, Q Zhang and F Cheng [34] and B Fattahi, K Arzani, MK Souri and M Barzegar [22]. Heavy metal contamination, particularly by cadmium, lead, and arsenic, in leafy vegetables poses a serious global health concern. This study was conducted under greenhouse conditions using parsley to assess metal accumulation and plant responses. By examining morphological, physiological, and phytochemical changes, the research aims to better understand parsley's tolerance to heavy metals and contribute to safer cultivation practices in contaminated environments.

Materials and methods

Plant material and experimental design

Seeds of Parsley were sourced from local market in the city of Baghdad (Iraq). Prior to sowing, the seeds were sterilized with sodium hypochlorite and sown in pots filled with moderately fertile soil, the properties of which are presented in Table 1. The experiment followed a completely randomized design (CRD) with three replications. Sixty days before sowing, various concentrations of arsenic (As: 0, 25, 50, 75, 100 mg/kg), cadmium (Cd: 0, 10, 20, 30, 40 mg/kg), and lead (Pb: 0, 100, 200, 300, 400 mg/kg) were uniformly mixed into the soil. These metals were first dissolved in distilled water and then applied using a portable sprayer. The treated soil was passed through a 2 mm sieve several times to ensure homogeneous distribution of the metals. Soil moisture was maintained at 55–60% of field capacity, and the soil was incubated at $24 \pm 4^\circ\text{C}$ for two months. After incubation, the soil was transferred into black plastic pots, and seeds were sown at a depth of 1 cm. Following germination, 20 uniform seedlings were retained per pot. The plants were irrigated with distilled water every two days from planting until harvest (approximately 75 days).

Morphological Characteristics

To study the morphological characteristics among different samples, traits such as plant height (cm), petiole length (mm), stem diameter (mm), umbel diameter (mm), root length (cm), and root diameter (mm) were measured. All morphological traits were evaluated under identical conditions using a caliper, ruler, and digital balance. The average of three replicates per treatment was recorded separately.

Physiological Characteristics

Biomass Evaluation of Leaf Area and Biomass Components

The leaf area of all plant leaves in each treatment was measured using a leaf area meter (Delta-T Devices Ltd., England). The fresh weight of the aerial parts and roots was recorded using a digital balance. Subsequently, the samples were dried in an oven at 60°C until reaching a constant weight, and the dry weight was then measured.

Relative water content (% RWC)

The relative water content (RWC) of *Petroselinum crispum* leaves was determined based on the method described by M Browne, NT Yardimci, C Scoffoni, M Jarrahi and L Sack [35]. To measure the saturated weight, leaf samples were submerged in distilled water for 24 hours. Afterward, the dry weight was obtained by placing the leaves in a ventilated oven set at 65°C until a constant weight was achieved. The RWC (%) was calculated using the formula below:

$$\text{RWC (\%)} = [(\text{FW} - \text{DW}) / (\text{SW} - \text{DW})] \times 100 \quad (1)$$

Where: FW = fresh weight of the leaf (g), SW = saturated weight of the leaf (g), DW = dry weight of the leaf (g)

Quantification of Heavy Metals

Heavy metal analysis was performed by drying leaf samples at 60°C for 72 hours, followed by grinding into a fine powder. Around 0.5g of the sample was digested with 25 mL of 65% nitric acid and heated at 250°C for 24 hours in open containers. After partial evaporation, 5 mL of 30% hydrogen peroxide was added to complete the digestion. Concentrations of As, Cd, and Pb were then measured using flow injection atomic absorption spectrometry (Perkin–Elmer 700), based on the method by K Sekabira, H Oryem–Origa, G Mutumba and T Basamba [36].

Assessment of Photosynthetic Parameters

Characterization of Photosynthetic Pigments

The photosynthetic pigments were recorded using 0.2 g of leaves powder was homogenized by adding 7 ml of acetone (80 %). The mixture was centrifuged at 3400 g for 20 minutes at 4 °C (Tabletop model, IEC 215, USA). The resulting supernatant was used to determine the absorbance at 664, 647, and 470 nm using the spectrophotometer (Shimadzu Mini-1240 UV–Vis, USA). The leaves chlorophyll and carotenoids concentration was determined according to A Adelusi, O Akamo and A Makinde [37].

$$\text{Chlorophyll a} = 13.19 A_{664} - 2.57 A_{647} \quad (2)$$

$$\text{Chlorophyll b} = 22.1 A_{647} - 5.26 A_{664} \quad (3)$$

$$\text{Carotenoids} = 100 (A_{470}) - 3.27 (\text{mg chl a}) - 104 (\text{mg chl b}) / 227 \quad (4)$$

Where: A_{664} , A_{647} and A_{470} are the absorbance at 664, 647 and 470 nm, respectively.

Chlorophyll fluorescence parameters and greenness index

Chlorophyll fluorescence parameters were assessed using a portable fluorometer (MINI-PAM, Walz, Germany). Minimal fluorescence (F_0) was recorded after 30 minutes of dark adaptation, and maximal fluorescence (F_m) was measured under light-adapted conditions. From these, variable fluorescence ($F_v = F_m - F_0$) and the maximum quantum yield of PSII (F_v/F_m) were calculated, following the method described by K Maxwell and GN Johnson [38]. Additionally, to estimate chlorophyll content non-destructively, a SPAD-502 meter (Konica Minolta, Japan) was used to measure the greenness index of 20–25 leaves, complementing biochemical determinations of chlorophyll a and b.

Photosynthetic characteristics

Photosynthetic rate (P_n), transpiration rate (E), and intercellular CO_2 concentration (C_i) were measured on the top four leaves of each plant using a portable photosynthesis system (LI-6400, Li-Cor Inc., Lincoln, NE, USA). Measurements were conducted under controlled chamber conditions: leaf temperature at 25 °C, reference CO_2 at $480 \mu\text{mol mol}^{-1}$, water vapor at 1 mmol mol^{-1} , and a photosynthetically active radiation (PAR) of $250 \mu\text{mol m}^{-2} \text{ s}^{-1}$.

Analysis of Phytochemical Parameters

Isolation and Characterization of Essential Oils

Essential oils (EOs) were extracted from 50 g of air-dried aerial parts of parsley by hydro-distillation using a Clevenger-type apparatus for 4 hours [39]. Yields were calculated based on dry weight. GC analysis was performed using an Agilent 7890B system with a flame ionization detector and an HP-5 fused silica column (30 m × 0.32 mm, 0.25 μm film thickness), with helium as the carrier gas (1.1 mL/min). For GC–MS, 1 μL of each EO sample was injected into a Thermoquest–Finnigan system with a trace mass spectrometer, using the same column (0.25 mm ID). Ionization was conducted at 70 eV; ion source and interface temperatures were 200 °C and 250 °C, respectively. Compounds were identified by comparing mass spectra with Wiley 7.0 and Adams libraries, and retention indices were matched with those of C8–C24 n-alkane series under identical conditions.

Extraction Methodology

Thirty grams of plant material, previously ground using a laboratory mill were (model: AG 500 g) mixed with 250 mL of 80% ethanol. The mixture was subjected to ultrasonic extraction for 60 minutes using an ultrasonic bath (WUC-A03H, Witeg Labortechnik, Wertheim, Germany). The extract was kept protected from light, filtered through Whatman No. 4 filter paper and concentrated using a vacuum evaporator at a maximum temperature of 40 °C. The resulting thick extract was transferred to Petri dishes and dried in a vacuum desiccator until a constant weight was achieved. Finally, the dried extract was re-dissolved in 80% ethanol for subsequent analyses. Extracts were filtered using filter paper and used for antioxidant capacity, total Phenolics and flavonoids.

Quantification of Total Phenolics and Flavonoids

The total phenolic content of the extract was measured by a Folin-Ciocalteu assay by partial modifications [40] and expressed as mg of Gallic acid equivalents per gram of dry weight of extract (mg GAE/g DW ext). The total flavonoid content was determined by the aluminium chloride colorimetric method [41] and expressed as mg of quercetin equivalents dry per gram dried weight of extract (mg QE/g DW Ext).

Antioxidant capacity

DPPH method

The antioxidant activity of the ethanolic extracts was assessed using the DPPH radical scavenging assay [42]. Absorbance was measured at 517 nm using a microplate reader (Epoch, BioTek). Radical scavenging capacity (RSC) was calculated using the formula:

$$\text{Inhibition (\%)} = [(A_b - A_s) / A_b] \times 100 \quad (5)$$

Where A_b is the absorbance of the blank and A_s is that of the sample. BHT was used as a positive control. The IC_{50} value, representing the concentration required to inhibit 50% of DPPH radicals, was determined from the dose-response curve.

FRAP method

The antioxidant capacity of the extracts was measured using the FRAP method [43]. A mixture of 40 μ L extract and 2.5 mL FRAP reagent was incubated at 37 °C for 30 minutes in the dark. Absorbance was read at 593 nm using a microplate reader (Epoch, BioTek). Results were expressed as mg Fe^{2+} /g dry weight based on a standard curve of $FeSO_4$.

Total tannin measurement

The tannin content of the ethanolic extracts was determined according to the method described by Z Luthar and I Kreft [44]. Briefly, 400 μ L of the extract solution was mixed with 3 mL of vanillin reagent (4% vanillin in methanol) and 1.5 mL of concentrated hydrochloric acid. The mixture was incubated at 28 °C for 30 minutes. Absorbance was measured at 520 nm using a spectrophotometer. Tannic acid was used to construct the standard calibration curve. The total tannin content (TTC) of the whole plant was expressed as milligrams of tannic acid equivalents per gram of dry weight (mg TA/g DW).

Vitamin C measurement

The concentration of ascorbic acid in *Petroselinum crispum* leaves was determined using a spectrophotometric method based on the procedure described by M Atanassova, S Georgieva and K Ivancheva [45], with some modifications. In this method, a calibration curve was constructed using pure ascorbic acid as the standard to quantify its content in the plant extract. The amount of ascorbic acid equivalents (mg AAE per gram of extract) was calculated according to the formula reported by S Gouveia and PC Castilho [46].

$$V = C \times V/M \quad (6)$$

V=AA content (mg.AAE/g), C=Ascorbic acid Concentration extracted from standard curve (mg/ml), V=Volume of leaves extract (ml) and M= leaves extract weight (g).

Statistical analysis

Data were analyzed using analysis of variance (ANOVA) based on a completely randomized design (CRD) with three replications. SAS software (version 9.0) and SPSS (version 20) were used for statistical analyses. Normality of residuals and ANOVA assumptions were verified using the PROC UNIVARIATE procedure in SAS. Mean comparisons were performed using Duncan's multiple range test at a significance level of $P \leq 0.05$.

Results

Effects of As, Cd and Pb on morphological traits

The effects of different concentrations of As, Cd and Pb on morphological traits of Parsley have been presented in Table 1. The control plants reached a height of 240 cm, which was significantly higher than the plants treated with different concentrations of arsenic, cadmium, and lead. The longest petiole (5.7 cm) was in As 100 mg/kg and the shortest petiole (3.7 cm) was in control plants. Interestingly, with increasing concentrations of arsenic, cadmium, and lead, a progressive increase in petiole length was observed (Table 1). Stem diameter in the control treatment was the lowest (0.91 cm), indicating higher leaf quality. However, this trait increased with the application of heavy metals, and the highest value (1.1 cm) was observed in the 75 and 100 mg/kg As (Table 1). The smallest flower umbel diameter was recorded in the control treatment (14.0 mm), while the largest (15.4 mm) was observed in the 400 mg/kg lead treatment, showing a similar trend to stem diameter. The maximum root length (88.3 cm) was observed in the 400 mg/kg lead treatment, whereas the minimum root length was recorded in the control group, with an average of 64 cm. Although no statistically significant differences were observed in root diameter among the four concentrations of arsenic and cadmium, all treatments showed at least a 10% increase compared to the control. Among the evaluated traits, root diameter was the only one that exhibited no statistically significant differences across the various concentrations of arsenic, cadmium, and lead.

Effects of As, Cd and Pb on physiological traits

Leaf area and leaf fresh and dry weights

Increasing concentrations of arsenic, cadmium, and lead significantly reduced leaf area. The maximum leaf area was recorded in the control treatment (345.0 cm²), whereas the most pronounced reductions were observed in the cadmium 40 mg/kg treatment (300 cm²), and in the arsenic 100 and lead 400 mg/kg treatments (304 cm²) (Table 2). The control treatment exhibited the highest fresh shoot weight (40.9 g), while the lowest was found in the 200 mg/kg lead treatment (30.0 g). A similar pattern was observed for dry weight, with the control producing

12.5 g and the 200 mg/kg lead treatment resulting in the lowest value of 7.8 g (Table 2). According to the results, root fresh and dry weights significantly increased in response to arsenic, cadmium, and lead treatments. The control group exhibited the lowest fresh (6.4 g) and dry (2.1 g) root weights, while the maximum fresh (8.6 g) and dry (4.6 g) root weights were recorded in the 100 mg/kg arsenic treatment (Table 2).

Leaf relative water content (RWC)

The results showed that relative leaf water content in control plants was 92.0%, while it decreased to 80% in certain arsenic and cadmium treatments, indicating approximately a 13% reduction (Table 2).

Leaf concentration of heavy metals

Elevated levels of the heavy metals arsenic, cadmium, and lead led to a significant increase in their accumulation in plant leaves. For arsenic, leaf concentrations rose progressively with increasing treatment levels, reaching 0.61, 0.88, 1.04, 1.19, and 1.34 mg/kg under 0 (control), 25, 75, 100, and 125 mg/kg treatments, respectively. Cadmium showed a similar trend, with concentrations of 0.70, 0.79, 0.94, 1.12, and 1.21 mg/kg corresponding to 0, 10, 20, 30, and 40 mg/kg treatments. Lead accumulation also increased markedly, with leaf concentrations measured at 0.80, 1.20, 1.90, 2.78, and 3.74 mg/kg under 0, 100, 200, 300, and 400 mg/kg treatment levels (Table 2).

Effects of As, Cd and Pb on photosynthetic parameters

SPAD value

The results related to SPAD values indicated that increasing concentrations of heavy metals led to a reduction in chlorophyll content in parsley compared to the control. The lowest SPAD readings were observed in the treatments with 100 mg/kg arsenic, 40 mg/kg cadmium, and 400 mg/kg lead, with values of 14 and 17, respectively. In contrast, the control plants exhibited the highest SPAD value of 24 (Table 3).

Photosynthetic parameters

In this study, three key photosynthetic parameters—net photosynthetic rate (P_n), transpiration rate (E), and intercellular CO_2 concentration (C_i)—were evaluated (Table 3). The highest values of P_n , E , and C_i were recorded in the control treatment, with measurements of $5.41 \mu\text{mol } CO_2 \text{ m}^{-2}\text{s}^{-1}$, $3.99 \mu\text{mol H}_2\text{O } CO_2 \text{ m}^{-2}\text{s}^{-1}$, and $279 \mu\text{mol } CO_2/\text{mol air}$, respectively. As the concentrations of the applied heavy metal treatments increased, a gradual decline was observed in all three parameters. However, this reduction was less pronounced in the cadmium treatments compared to arsenic and lead (Table 3).

Photosynthetic pigments

Exposure to increasing concentrations of arsenic, cadmium, and lead resulted in a significant decline in the concentrations of chlorophyll a, chlorophyll b, and carotenoids. In control plants, chlorophyll a content was 1.1 mg/g fresh weight (FW), which markedly decreased to 0.54 mg/g FW under 100 mg/kg As and to 0.6 mg/g FW under 400 mg/kg Pb. Similarly, chlorophyll b concentration in the control was 0.66 mg/g FW, but it declined to the lowest value of 0.40 mg/g FW under both 100 mg/kg As and 40 mg/kg Cd treatments (Table 3). Carotenoid content also followed the same declining trend, with the highest value observed in the control (0.42 mg/g FW).

Among the cadmium treatments, only the 10 mg/kg level showed a significant difference from the control, while the other three concentrations did not differ significantly from each other.

Effect of As, Cd and Pb on chlorophyll fluorescence and yield of photosystem II (Fv/Fm)

The results of Fv/Fm analysis demonstrated that photosystem II efficiency was significantly affected by arsenic, cadmium, and lead treatments (Table 3). Increasing concentrations of these heavy metals caused a notable decline in Fv/Fm values, indicating stress-induced impairment of the photosynthetic apparatus. Among the treatments, the reduction was more pronounced in arsenic and lead compared to cadmium, suggesting a relatively lower toxicity of cadmium on photosystem II function. The highest Fv/Fm value (0.71) was observed in the control plants, reflecting optimal photosynthetic performance in the absence of heavy metal stress.

Effects of As, Cd and Pb on phytochemical traits

Content of essential oil

The hydrodistillation of Parsley yellow oil gave in 0.25-.45 w/w (relative to dry weight of plant) yield for aerial parts, usually the oil in the Parsley vegetative part is a very low amount. However, the highest essential oil yield of parsley was obtained in plants treated with the highest concentrations of heavy metals (Fig. 1A). Among the treatments, 100 mg/kg arsenic resulted in the greatest oil yield, reaching 0.45% (w/w).

Essential oil composition

Table 5 presents the essential oil (EO) composition of parsley, analyzed using GC-MS and GC-FID, and identified based on the Adams Library and Kováts retention index. A total of eighteen compounds were detected in the oil samples from the aerial parts of parsley, accounting for 92.4–98.5% of the total oil content. Four major compounds apiol, myristicin, β -pinene, and α -pinene were identified in parsley essential oil, representing the highest concentrations among all detected constituents. The highest levels of apiol (23.0%) and myristicin (24.3%) were observed in the control treatment, whereas the highest contents of α -pinene (20.0%) and β -pinene (12.9%) were detected in the arsenic 100 and arsenic 75 treatments, respectively. On the other hand, the lowest levels of apiol (11.9%) and myristicin (17.1%) were identified in the lead 400 treatment. According to Figs. 3B, 3C, and 3D, two groups of compounds were identified in the different samples: hydrocarbon compounds and oxygenated compounds. The highest amount of oxygenated compounds was observed in the control treatment (52%), while the lowest level was detected at higher concentrations of heavy metals, particularly in the arsenic 100 treatment (32%). In contrast, hydrocarbon compounds followed an opposite trend, with the highest content recorded under heavy metal stress, specifically in the arsenic 100 treatment (64.2%).

Content of total phenolics and flavonoids

The total phenol content in parsley leaves of control plants was 12 mg GAE/g DW, and the application of arsenic, cadmium, and lead significantly increased this trait compared to the control (Fig. 2A). Specifically, the total phenol content in the arsenic 100 treatment was nearly three times higher than in the control, increasing from 12 to 33 mg GAE/g DW. Cadmium 400 treatment showed the second highest total phenol content (30 mg GAE/g DW), following the arsenic 100 treatment. With increasing heavy metal concentrations in the soil, the total flavonoid content in the

leaves increased (Fig. 2B). The highest amount was observed in the arsenic 100 treatment (29 mg QE/g DW) compared to the control (16 mg QE/g DW). Additionally, the arsenic 75, cadmium 400, and lead 400 treatments showed similar flavonoid contents of approximately 27 mg QE/g DW. Moreover, the arsenic 25 and lead 100 treatments did not show a significant difference compared to the control.

Leaf antioxidant activity

In the present work, the antioxidant activity of the samples appeared using the DPPH and FRAP methods. The results of the antioxidant activity comparison (DPPH assay) are shown in Fig. 2C. The highest radical scavenging activity (i.e., the lowest IC_{50} values) was observed in the As100 and Cd40 samples, with IC_{50} values of 31.8 μ g/ml and 39.7 μ g/ml, respectively, compared to 26.5 μ g/ml for BHT, a synthetic industrial antioxidant. The lowest radical scavenging activity (IC_{50} = 109.2 μ g/ml) was observed in the control sample. However, in the FRAP assay, the As100 sample exhibited the highest antioxidant activity compared to all other samples, especially the control. The antioxidant activity values ranged from 31.0 to 65.0 mg Fe^{2+} /g dry weight (Fig. 2D).

Total tannin content (TTC)

Samples As100, Cd40, and Pb400 showed the highest total tannin levels, reaching 1.3 and 1.28 mg TA/g DW (Fig. 5), while the Cd10 sample had the lowest content at 0.7 mg TA/g DW (Fig. 3A). The total tannin content in the control treatment was 0.8 mg TA/g DW, which did not show a significant difference compared to Cd10.

Vitamin C

Exposure to varying concentrations of heavy metals (arsenic, cadmium, and lead) led to a significant increase in leaf vitamin C content (Fig. 3B). The control plants exhibited the lowest vitamin C level (128 mg/100g FW), whereas the highest concentrations were found in plants treated with 100 and 75 mg/kg of arsenic, reaching 170 and 167 mg/100g FW, respectively.

Discussion

According to the analysis of morphological traits, the presence of heavy metals adversely affected the quality and yield of parsley. Previous studies have also demonstrated that heavy metals negatively impact plant growth and morphology, resulting in reduced productivity and inhibition of enzymatic activities [47]. The findings of the present study are in agreement with these reports. Heavy metals can disrupt the balance of plant hormones such as auxins and cytokinins, leading to increased cell division and elongation in root tissues, which ultimately results in longer and thicker roots [48]. Also, root elongation and thickening under heavy metal stress may serve as an adaptive strategy to improve resource uptake and reduce exposure to toxicity [49]. Abnormal root morphology, such as radial thickening, endodermal cell wall thickening, and cortical lignification, has been observed in pea plants exposed to high lead levels [50].

Lead has been shown to significantly reduce leaf expansion and surface area in various plant species, including *Allium* spp., barley, and *Raphanus sativus*, by inhibiting cell division and elongation in leaf tissues [50]. The application of heavy metals reduced fresh and dry shoot weights, which represent the economic yield. In one study on parsley, fresh biomass significantly increased at Cd concentrations of 5 and 10 mg kg^{-1} compared to the

control; however, higher Cd levels caused a non-significant decrease in fresh weight, which contrasts with our findings [27]. Previous studies have shown that heavy metals negatively affect plant growth. For example, SA-PR Moghaddam and AKSD-A Fotovat [51] reported that 600 mg/kg soil lead significantly reduced shoot dry weight in sage plants. Similarly, S Amirmoradi, P Moghaddam, A Koocheki, S Danesh and A Fotovat [52] found that cadmium and lead treatments caused a significant decrease in leaf area and shoot dry weight in mint plants. Previous studies have reported a significant reduction in rice grain biomass under cadmium exposure, and a decrease in root and shoot dry weight in plants grown in metal-contaminated soils [53]. These biomass reductions are partly attributed to increased hydrogen peroxide (H₂O₂) accumulation caused by heavy metal-induced oxidative stress [54].

Similarly, leaf relative water content (RWC) in coriander (*Coriandrum sativum* L.) was significantly reduced under increasing concentrations of Cd (to 90%) and Pb (to 88%) compared to control plants, which had an RWC of 94.1% [22]. This pattern was similarly observed in *Fagopyrum kashmirianum*, where reductions in leaf RWC occurred under heavy metal stress [55]. Heavy metals reduce RWC by inducing oxidative stress and generating free radicals, which damage thylakoid membranes and impair water retention. This stress also disrupts chlorophyll synthesis, further weakening the plant's physiological balance [56].

Our findings are consistent with those of B Fattahi, K Arzani, MK Souri and M Barzegar [22], who reported similar results in coriander (*Coriandrum sativum*). According to the results, even at the lowest treatment levels, the concentrations of heavy metals in parsley exceeded the permissible standard limits [20]. This indicates that the plant was able to effectively absorb and accumulate these metals from contaminated soil, although it is clearly unsuitable for dietary consumption. Therefore, based on the results of the present study, soils contaminated with less than 25 mg/kg of As, 10 mg/kg of Cd, and 100 mg/kg of Pb may be considered suitable for cultivating parsley as a leafy vegetable for fresh consumption. Moreover, the concentrations of heavy metals used in this study fall within a range appropriate for phytoremediation purposes, indicating parsley's potential to absorb and accumulate these elements from contaminated soils [57].

A significant reduction in SPAD values in coriander [22], rocket [56], duckweed [58], and tomato [59] was also observed with increasing application rates of cadmium, lead, chromium, and other heavy metals. Consistent with our results, previous studies reported that cadmium reduces SPAD values by inhibiting chlorophyll biosynthesis, breakdown of chlorophyll due to an increase of chlorophyllase enzyme and limiting Mg and Fe uptake. This leads to chlorosis and reduced photosynthetic activity in crops like barley, beans, and wheat [60, 61]. Inhibition of ALAD enzyme activity is another key factor limiting chlorophyll accumulation in leaves [62].

It has been reported that increasing cadmium concentration in the soil either from 0 to 1.25 mM or up to 20 µg/kg and lead up to 400 mg/kg significantly reduces the transpiration and photosynthesis rates in *Brassica juncea* and *Coriandrum sativum* plants [22, 63]. Z Hu, C Zhao, Q Li, Y Feng, X Zhang, Y Lu, R Ying, A Yin and W Ji [29] showed that the photosynthesis of *Phlox divaricata* was inhibited as the Cd concentration increased. Heavy metals affect photosynthesis both directly by damaging chloroplast structure and enzymes, and indirectly by altering water status and stomatal behavior [64]. Increasing levels of As, Cd, and Pb lead to elevated internal CO₂ concentration in stomatal cells, causing stomatal closure and a reduction in leaf photosynthetic rates [65].

Z Hu, C Zhao, Q Li, Y Feng, X Zhang, Y Lu, R Ying, A Yin and W Ji [29] reported that increasing Cd levels led to a decrease in chlorophyll a, chlorophyll b, and carotenoid contents in the leaves of *Phlox divaricata*. Similarly, B Fattahi, K Arzani, MK Souri and M Barzegar [22] found that Pb and Cd stress reduced chlorophyll and carotenoid concentrations in coriander leaves. Also, in *Hydrilla verticillata*, an arsenic concentration of 96 µM caused a

significant reduction in photosynthetic pigment contents [66]. These results suggest that heavy metal stress, particularly from higher levels of arsenic and cadmium, negatively affects pigment content, possibly through disruption of pigment biosynthesis or enhanced degradation [67].

Heavy metals such as lead, cadmium, and arsenic significantly impair photosynthesis by disrupting chlorophyll and carotenoid synthesis, inhibiting Calvin cycle and electron transport chain activities, and reducing enzymatic functions [30]. Lead decreases chloroplast efficiency by affecting respiration and enzyme activity, while cadmium induces stomatal closure and nutrient uptake inhibition, leading to senescence and reduced pigment content [68]. Arsenic lowers photosynthetic rates by affecting phosphate uptake due to its chemical similarity to phosphorus, disrupting energy transfer and leaf development [30].

According to EE Aziz, RM Sabry and SS Ahmed [69], the oil content of parsley ranges between 0.11% and 0.21%. In line with our results, arsenic treatment caused a significant increase in essential oil (EO) yield in basil plants, where the EO yield of control plants was 0.20% (w/w), and at arsenic concentrations of 10 and 50 mg/kg, the yield increased by 3.5 to 4 times, reaching 0.77% and 0.8%, respectively [70]. Our results contradict those of FAE-M Hashem and AF Sahab [71], who reported that the essential oil yield of parsley decreases under stress conditions such as heavy metal exposure. This is because, in our results, treatment with 100 arsenic increased the essential oil yield from 25–45%, representing an 80% increase compared to the control treatment. Exposure to heavy metal stress has been shown to increase essential oil production in plants by activating defense mechanisms that enhance the synthesis of secondary metabolites [72]. The absence of As, Cd, and Pb residues in parsley essential oil suggests that EO extraction excludes heavy metals, likely due to oil's low density preventing metal accumulation [73]. This finding supports the potential cultivation of parsley and other EO-yielding medicinal plants in metal-contaminated soils without compromising oil quality [70]. These results align with previous studies, indicating that many EO-producing species tolerate heavy metal stress without significant phytotoxic effects or reduction in oil yield [70].

Similar chemical profiles were reported by I Marín, E Sayas-Barberá, M Viuda-Martos, C Navarro and E Sendra [74] with major components including myristicin (36.15%), apiol (20.97%), β -pinene (15.47%), and α -pinene (10.43%). Likewise, H Zhang, F Chen, X Wang and H-Y Yao [75] identified myristicin (32.75%), apiol (17.54%), β -pinene (16.64%), and α -pinene (11.54%) as the predominant constituents. In contrast, LMS dos Santos Franciscato, SS Mendes, C Frederico, JE Goncalves, MGI Faria, ZC Gazim and SP Ruiz [76] found apiol (61.94%) and myristicin (9.33%) to be the major constituents in parsley samples from Brazil. These differences in essential oil composition are likely influenced not only by genetic factors but also by environmental conditions particularly soil composition and the availability of mineral elements. Variations in nutrients such as nitrogen, phosphorus, potassium, and trace elements can significantly affect the biosynthesis of secondary metabolites, including essential oil components [77]. In comparison with our results, parsley samples from Egypt showed a similar trend: locations with higher heavy metal content, such as Benisuef, had increased hydrocarbon compounds (up to 60.16%), especially β -myrcene. In contrast, samples from cleaner areas like Bahariya Oasis had higher levels of oxygenated compounds (up to 46.84%) [78]. These findings align with our observation that heavy metal contamination may favor hydrocarbon over oxygenated compound production in parsley essential oil. Abiotic stress conditions particularly heavy metal accumulation, salinity, drought, and nutrient deficiencies can significantly alter essential oil composition and reduce nutrient uptake, often increasing hydrocarbon levels at the expense of oxygenated compounds [79].

In comparison with our findings on phenolic and flavonoid contents in parsley, AA Ibrahim, AA Mosa and LY Mohammed [80] reported that the ethanolic extract contained 75.9 mg·g⁻¹ total phenolics (TA equivalents) and 15.61 mg·g⁻¹ total flavonoids, indicating a notable presence of these compounds in their extract. In a similar study, I Nawaz, A Mehboob, AHA Khan, TA Naqvi, N Bangash, S Aziz, W Khan, I Shahzadi, R Barros and K Ullah [81] reported that increasing cadmium concentration from 10 to 80 µM significantly enhanced phenol content. However, unlike our findings, the flavonoid content decreased under these conditions. A study by B Fattahi, K Arzani, MK Souri and M Barzegar [22] similarly demonstrated that in coriander plants, exposure to Cd and Pb resulted in increased total phenolic content (250–280 µg·kg⁻¹) and total flavonoids (142–167 µg·kg⁻¹ oil) compared to control plants, indicating that heavy metal stress promotes the accumulation of these compounds. These findings suggest that the increase in phenolic and flavonoid contents observed in parsley under heavy metal stress may play a protective role by chelating or neutralizing toxic metals [82]. This biochemical response could potentially contribute to the reduction of heavy metal accumulation within the plant tissues, serving as a natural defense mechanism against soil contamination.

A LEAHU, C DAMIAN, M OROIAN, V MICLESCU and S ROPCIUC [83] reported IC₅₀ values (%) for DPPH radical-scavenging activity, with dried parsley showing a value of 14.45%. In comparison, AA Ibrahim, AA Mosa and LY Mohammed [80] reported FRAP antioxidant activity ranging from 37–65%, indicating notable antioxidant potential in parsley extracts. In line with our study, Y Ulusu, L Öztürk and M Elmastaş [84] demonstrated that antioxidant activity and antioxidant enzyme activities increased with cadmium concentrations ranging from 75 to 300 µM in *Petroselinum hortense* L. This supports the role of enhanced antioxidative defense mechanisms in response to heavy metal stress in parsley. Phenolic compounds contribute significantly to antioxidant activity by scavenging free radicals and chelating metals [85]. Under heavy metal stress, both phenolic content and antioxidant activity increase as part of the plant's defense response to oxidative damage [86]. This correlation highlights the important role of phenolics in enhancing antioxidative protection in contaminated conditions.

Previously, L Zhang, M Xu, Q Guan, J Jiang, K Sun and E Manirafasha [87] reported tannin contents of 0.69% and 0.55% in vegetables such as red pepper and chili pepper, respectively. However, to the best of our knowledge, no data have been reported so far on tannin content in parsley, making this the first study to present such findings. Tannins can chelate transition metals through their ortho-dihydroxyphenolic groups, playing a key role in reducing heavy metal uptake in plants [88]. In leafy vegetables like parsley, this property may help mitigate the effects of soil contamination and contribute to safer crop production [89]. This could explain the increase in tannin content observed in our study with rising heavy metal concentrations.

In comparison, AA Ibrahim, AA Mosa and LY Mohammed [80] reported that the vitamin C content in *Petroselinum crispum* was 4.01 mg·g⁻¹, based on their analysis. Vitamin C is widely recognized as a vital metabolite and a major non-enzymatic antioxidant defense in plant tissues, contributing significantly to the quality and nutritional value of leafy vegetables especially parsley [90]. In fact, parsley is considered one of the richest sources of vitamin C among vegetables with fresh leaves containing between 96.88 and 312.7 mg of vitamin C per 100 g [91].

Conclusion

The present study demonstrated that exposure to varying concentrations of arsenic, cadmium, and lead significantly affects the growth, physiology, and biochemical characteristics of parsley (*Petroselinum crispum*). Heavy metal stress led to a marked reduction in plant height, leaf area, shoot biomass, photosynthetic pigment content, and photosystem II efficiency, indicating impaired growth and photosynthetic performance. Conversely,

root growth parameters and petiole length increased, suggesting adaptive morphological changes to cope with metal toxicity. Importantly, heavy metal accumulation in leaves increased proportionally with external concentrations, confirming parsley's potential for metal uptake. Despite overall growth inhibition, the essential oil yield and antioxidant-related metabolites such as total phenols, flavonoids, and vitamin C significantly increased under heavy metal treatments, particularly in plants treated with arsenic at 100 mg/kg. Changes in essential oil composition, including increased hydrocarbons and decreased oxygenated compounds, reflect the biochemical adjustments in response to metal stress. Enhanced antioxidant activities measured by DPPH and FRAP assays further highlight the activation of defense mechanisms against oxidative stress. These findings reveal the complex interplay between growth suppression and secondary metabolite enhancement in parsley exposed to heavy metals. The results provide valuable insights into parsley's physiological and biochemical responses to environmental contamination, which could have implications for its cultivation in polluted soils and potential use in phytoremediation strategies. Further research is recommended to elucidate the molecular mechanisms underlying these adaptive responses and to assess the safety of parsley consumption from contaminated environments.

Abbreviations

As Arsenic

Cd Cadmium

Pb Lead

GC Gas chromatography

GC-MS Gas chromatography–mass/mass spectrometry

GAE Gallic Acid Equivalent

QE Quercetin Equivalent

DW Dry weight

FW Fresh weight

DPPH 2,2-diphenyl-1-picrylhydrazyl

FRAP Ferric Reducing Antioxidant Power

CRD Completely randomized design

RWC Relative water content

F0 Minimal fluorescence

Fm Maximal fluorescence

Fv Variable fluorescence

Pn Photosynthetic rate

E Transpiration rate
Ci CO₂ concentration
Eos Essential oils
RSC Radical scavenging capacity
BHT Butylated hydroxytoluene
TTC The total tannin content
ANOVA Analysis of Variance
CRD Completely randomized design
TPC Total Phenol Content
TFC Total flavonoid content
HC Hydrocarbon compounds
OC Oxygenated compounds

Declarations

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Author's contribution statement

S.I.M.: Experimentation, Conceptualization Data analysis. A.K.K.: Writing- Original

draft preparation. H.A.: Project administration, Conceptualization, Formal analysis, Data curation. A.V.: Formal analysis, Investigation. R.M.M.: Writing- Original draft preparation, Methodology. S.G.: Formal analysis, Investigation. I.B.S.: Conceptualization, Writing- Reviewing and Editing. R.S.: Conceptualization, Visualization, Reviewing and Editing. F.F.S.: Conceptualization Data analysis. Y.F.M.: Reviewing and Editing.

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References

1. Sarker U, Oba S. Drought stress enhances nutritional and bioactive compounds, phenolic acids and antioxidant capacity of Amaranthus leafy vegetable. BMC Plant Biol. 2018; 18(1):258.
2. Alissa EM, Ferns GA. Dietary fruits and vegetables and cardiovascular diseases risk. Crit Rev Food Sci Nutr. 2017; 57(9):1950-1962.
3. Mishra S, Bharagava RN, More N, Yadav A, Zainith S, Mani S, Chowdhary P. Heavy metal contamination: an alarming threat to environment and human health. In: Environmental biotechnology: For sustainable future. Springer. 2018; 103-125.
4. Sajid A, Ahmad K, Khan ZI, Khalofah A, Ahmad I. Assessing the impact of industrial pollution stress on the physiological defense, proximate composition and morphological traits of riparian vegetation. BMC Plant Biol. 2025; 25(1):992.
5. Tiwari K, Singh N, Patel M, Tiwari M, Rai U. Metal contamination of soil and translocation in vegetables growing under industrial wastewater irrigated agricultural field of Vadodara, Gujarat, India. Ecotoxicol Environ Saf. 2011; 74(6):1670-1677.
6. Nkwunonwo UC, Odika PO, Onyia NI. A review of the health implications of heavy metals in food chain in Nigeria. The Scientific World Journal. 2020; 2020(1):6594109.
7. Sultana R, Tanvir RU, Hussain KA, Chamon AS, Mondol MN. Heavy metals in commonly consumed root and leafy vegetables in Dhaka city, Bangladesh, and assessment of associated public health risks. Environmental Systems Research. 2022; 11(1):15.
8. Marthe F. *Petroselinum crispum* (Mill.) Nyman (Parsley). Medicinal, Aromatic and Stimulant Plants. 2020;435-466.
9. Ajmera P, Kalani S, Sharma L. Parsley-benefits & side effects on health. International Journal of Physiology, Nutrition and Physical Education. 2019;4(1):1236-1242.
10. Alobaidi S. Renal health benefits and therapeutic effects of parsley (*Petroselinum crispum*): a review. Frontiers in Medicine. 2024; 11:1494740.
11. Bibi M, Samiullah FB, Saba Afzal S. Essential and non-essential heavy metals sources and impacts on human health and plants. Pure and Applied Biology (PAB). 2023; 12(2):835-847.

12. Kaur H, Kaur H, Kaur H, Srivastava S. The beneficial roles of trace and ultratrace elements in plants. *J Plant Growth Regul.* 2023; 100(2):219-236.
13. Singh S, Yadav R, Sharma S, Singh AN. Arsenic contamination in the food chain: a threat to food security and human health. *J Appl Biol Biotechnol.* 2023; 11:24-33.
14. Ozturk M, Metin M, Altay V, Bhat RA, Ejaz M, Gul A, Unal BT, Hasanuzzaman M, Nibir L, Nahar K. Arsenic and human health: genotoxicity, epigenomic effects, and cancer signaling. *Biol Trace Elem Res.* 2022;1-14.
15. Hussan MU, Mahmood U, Zarbakhsh S, Hussain S, Hafeez MB, Zahra N, Ahmed M, Wang Q, Yan M. Mitigating Cd stress in alfalfa: the role of melatonin and nano-calcium oxide in enhancing photosynthesis and antioxidant defense. *BMC Plant Biol.* 2025; 25(1):1-17.
16. Nemmiche S. Oxidative signaling response to cadmium exposure. *Toxicological Sciences.* 2017; 156(1):4-10.
17. Zulfiqar U, Farooq M, Hussain S, Maqsood M, Hussain M, Ishfaq M, Ahmad M, Anjum MZ. Lead toxicity in plants: Impacts and remediation. *Journal of environmental management.* 2019; 250:109557.
18. Wang L, Zheng B, Yuan Y, Xu Q, Chen P. Transcriptome profiling of *Fagopyrum tataricum* leaves in response to lead stress. *BMC Plant Biol.* 2020; 20(1):54.
19. Mandal GC, Mandal A, Chakraborty A. The toxic effect of lead on human health: A review. *Human biology and public health.* 2022; 3.
20. Nag R, Cummins E. Human health risk assessment of lead (Pb) through the environmental-food pathway. *Sci Total Environ.* 2022; 810:151168.
21. Kayode O, Aizebeokhai A, Odukoya A. Arsenic in agricultural soils and implications for sustainable agriculture. In: *IOP Conference Series: Earth and Environmental Science.* 2021. IOP Publishing: 012081.
22. Fattahi B, Arzani K, Sourì MK, Barzegar M. Morphophysiological and phytochemical responses to cadmium and lead stress in coriander (*Coriandrum sativum* L.). *Ind Crops Prod.* 2021; 171:113979.
23. Kananke T, Wansapala J, Gunaratne A. Heavy metal contamination in green leafy vegetables collected from selected market sites of Piliyandala area, Colombo District, Sri Lanka. *American journal of food science and technology.* 2014; 2(5):139-144.
24. Rahman MM, Asaduzzaman M, Naidu R. Consumption of arsenic and other elements from vegetables and drinking water from an arsenic-contaminated area of Bangladesh. *J Hazard Mater.* 2013; 262:1056-1063.
25. Kooner R, Mahajan B, Dhillon W. Heavy metal contamination in vegetables, fruits, soil and water–A Critical Review. *International Journal of Agriculture, Environment and Biotechnology.* 2014; 7(3):603-612.
26. Wangenstein H, Samuelsen AB, Malterud KE. Antioxidant activity in extracts from coriander. *Food Chem.* 2004; 88(2):293-297.
27. Kavvadias V, Paschalidis C, Vavoulidou E, Petropoulos D, Koriki A. Effects of soil amended with cadmium and lead on growth, yield, and metal accumulation and distribution in parsley. *Commun Soil Sci Plant Anal.* 2012; 43(1-2):161-175.
28. Ulusu Y, Öztürk L, Elmastaş M. Antioxidant capacity and cadmium accumulation in parsley seedlings exposed to cadmium stress. *Russian journal of plant physiology.* 2017; 64:883-888.
29. Hu Z, Zhao C, Li Q, Feng Y, Zhang X, Lu Y, Ying R, Yin A, Ji W. Heavy metals can affect plant morphology and limit plant growth and photosynthesis processes. *Agronomy.* 2023; 13(10):2601.
30. Bharti R, Sharma R. Effect of heavy metals: An overview. *Materials Today: Proceedings.* 2022; 51:880-885.
31. Kaur R, Das S, Bansal S, Singh G, Sardar S, Dhar H, Ram H: Heavy metal stress in rice: Uptake, transport, signaling, and tolerance mechanisms. *Physiol Plant.* 2021; 173(1):430-448.

32. Guala SD, Vega FA, Covelo EF. Heavy metal concentrations in plants and different harvestable parts: a soil–plant equilibrium model. *Environ Pollut.* 2010; 158(8):2659-2663.
33. Manwani S, Devi P, Singh T, Yadav CS, Awasthi KK, Bhoot N, Awasthi G. Heavy metals in vegetables: a review of status, human health concerns, and management options. *Environmental Science and Pollution Research.* 2023; 30(28):71940-71956.
34. Fan Y, Li H, Xue Z, Zhang Q, Cheng F. Accumulation characteristics and potential risk of heavy metals in soil-vegetable system under greenhouse cultivation condition in Northern China. *Ecological Engineering.* 2017; 102:367-373.
35. Browne M, Yardimci NT, Scoffoni C, Jarrahi M, Sack L. Prediction of leaf water potential and relative water content using terahertz radiation spectroscopy. *Plant Direct.* 2020; 4(4):e00197.
36. Sekabira K, Oryem–Origa H, Mutumba G, Basamba T. Heavy metal phytoremediation by *Commelina benghalensis* (L) and *Cynodon dactylon* (L) growing in urban stream sediments. 2011.
37. Adelusi A, Akamo O, Makinde A. Nitrogen fertilizer effects on the chemical composition and photosynthetic apparatus of *Euphorbia heterophylla* L. and *Macrotyloma geocarpa* (Harms) Marechal and Baudet. *Int J Bot.* 2006; 2:56-63.
38. Maxwell K, Johnson GN. Chlorophyll fluorescence—a practical guide. *J Exp Bot.* 2000; 51(345):659-668.
39. Norani M, Ebadi M-T, Ayyari M. Eco-phytochemical Properties of Ten *Dorema ammoniacum* Populations in Different Climates of Iran. *International Journal of Horticultural Science and Technology.* 2025; 12(4):1117-1142.
40. Slinkard K, Singleton VL. Total phenol analysis: automation and comparison with manual methods. *Am J Enol Vitic.* 1977; 28(1):49-55.
41. Ordonez A, Gomez J, Vattuone M. Antioxidant activities of *Sechium edule* (Jacq.) Swartz extracts. *Food Chem.* 2006; 97(3):452-458.
42. Bozin B, Mimica-Dukic N, Samojlik I, Jovin E. Antimicrobial and antioxidant properties of rosemary and sage (*Rosmarinus officinalis* L. and *Salvia officinalis* L., Lamiaceae) essential oils. *J Agric Food Chem.* 2007; 55(19):7879-7885.
43. Tomasina F, Carabio C, Celano L, Thomson L. Analysis of two methods to evaluate antioxidants. *Biochem Mol Biol Educ.* 2012; 40(4):266-270.
44. Luthar Z, Kreft I. Influence of temperature on tannin content in different ripening phases of buckwheat (*Fagopyrum esculentum* Moench) seeds. *Fagopyrum.* 1999; 16:61-65.
45. Atanassova M, Georgieva S, Ivancheva K. Total phenolic and total flavonoid contents, antioxidant capacity and biological contaminants in medicinal herbs. *Journal of the University of Chemical Technology & Metallurgy.* 2011; 46(1).
46. Gouveia S, Castilho PC. Antioxidant potential of *Artemisia argentea* L'Hér alcoholic extract and its relation with the phenolic composition. *Food Res Int.* 2011; 44(6):1620-1631.
47. Chetan A, Ami P. Effects of heavy metals (Cu and Cd) on growth of leafy vegetables—*Spinacia oleracea* and *Amaranthus caudatus*. *International Research Journal of Environment Sciences.* 2015; 4(6):63.
48. Bucker-Neto L, Paiva ALS, Machado RD, Arenhart RA, Margis-Pinheiro M: Interactions between plant hormones and heavy metals responses. *Genetics and molecular biology.* 2017; 40(1 suppl 1):373-386.
49. Chai M, Li R, Shen X, Yu L, Han J. Multiple heavy metals affect root response, iron plaque formation, and metal bioaccumulation of *Kandelia obovata*. *Scientific Reports.* 2022; 12(1):14389.

50. Asati A, Pichhode M, Nikhil K. Effect of heavy metals on plants: an overview. *International Journal of Application or Innovation in Engineering & Management*. 2016; 5(3):56-66.
51. Moghaddam SA-PR, Fotovat AKSD-A. Study of sage (*Salvia officinalis* L.) cultivation in condition of using irrigated water polluted by cadmium and lead. *Journal of Water and Soil*. 2015; 29(5):1360-1375.
52. Amirmoradi S, Moghaddam P, Koocheki A, Danesh S, Fotovat A. Effect of cadmium and lead on quantitative and essential oil traits of peppermint (*Mentha piperita* L.). 2017.
53. Khan A, Khan S, Khan M, Aamir M, Ullah H, Nawab J, Rehman I, Shah J. Heavy metals effects on plant growth and dietary intake of trace metals in vegetables cultivated in contaminated soil. *Int J Environ Sci Technol*. 2019; 16(5):2295-2304.
54. Rafiq MT, Aziz R, Yang X, Xiao W, Rafiq MK, Ali B, Li T. Cadmium phytoavailability to rice (*Oryza sativa* L.) grown in representative Chinese soils. A model to improve soil environmental quality guidelines for food safety. *Ecotoxicol Environ Saf*. 2014; 103:101-107.
55. Hakeem KR, Alharby HF, Rehman R. Antioxidative defense mechanism against lead-induced phytotoxicity in *Fagopyrum kashmirianum*. *Chemosphere*. 2019; 216:595-604.
56. Yildirim E, Ekinici M, Turan M, Agar G, Örs S, Dursun A, Kul R, Balci T. Impact of cadmium and lead heavy metal stress on plant growth and physiology of rocket (*Eruca sativa* L.). *Kahramanmaraş Sütçü İmam Üniversitesi Tarım ve Doğa Dergisi*. 2019; 22(6):843-850.
57. Bibi A, Farooq U, Naz S, Khan A, Khan S, Sarwar R, Mahmood Q, Alam A, Mirza N. Phytoextraction of Hg by parsley (*Petroselinum crispum*) and its growth responses. *Int J Phytoremediation*. 2016; 18(4):354-357.
58. Sallah-Ud-Din R, Farid M, Saeed R, Ali S, Rizwan M, Tauqeer HM, Bukhari SAH. Citric acid enhanced the antioxidant defense system and chromium uptake by *Lemna minor* L. grown in hydroponics under Cr stress. *Environmental Science and Pollution Research*. 2017; 24(21):17669-17678.
59. Opeolu BO, Adenuga O, Ndakidemi PA, Olujimi O. Assessment of phyto-toxicity potential of lead on tomato (*Lycopersicon esculentum* L) planted on contaminated soils. *International Journal of the Physical Sciences*. 2010.
60. Drążkiewicz M, Baszyński T. Growth parameters and photosynthetic pigments in leaf segments of *Zea mays* exposed to cadmium, as related to protection mechanisms. *J Plant Physiol*. 2005; 162(9):1013-1021.
61. Shakoor MB, Ali S, Hameed A, Farid M, Hussain S, Yasmeen T, Najeeb U, Bharwana SA, Abbasi GH. Citric acid improves lead (Pb) phytoextraction in *Brassica napus* L. by mitigating Pb-induced morphological and biochemical damages. *Ecotoxicol Environ Saf*. 2014; 109:38-47.
62. Gupta P, Jain M, Sarangthem J, Gadre R. Inhibition of 5-aminolevulinic acid dehydratase by mercury in excised greening maize leaf segments. *Plant Physiol Biochem*. 2013; 62:63-69.
63. Kaur P, Bali S, Sharma A, Vig AP, Bhardwaj R. Effect of earthworms on growth, photosynthetic efficiency and metal uptake in *Brassica juncea* L. plants grown in cadmium-polluted soils. *Environ Sci Pollut Res Int*. 2017; 24(15):13452-13465.
64. Parmar P, Kumari N, Sharma V. Structural and functional alterations in photosynthetic apparatus of plants under cadmium stress. *Botanical Studies*. 54: 45. Go to original source Go to PubMed. 2013.
65. Hubbard KE, Siegel RS, Valerio G, Brandt B, Schroeder JI. Abscissic acid and CO₂ signalling via calcium sensitivity priming in guard cells, new CDPK mutant phenotypes and a method for improved resolution of stomatal stimulus–response analyses. *Annals of Botany*. 2012; 109(1):5-17.

66. Srivastava S, Srivastava A, Singh B, Suprasanna P, D'souza S. The effect of arsenic on pigment composition and photosynthesis in *Hydrilla verticillata*. *Biologia plantarum*. 2013; 57(2):385-389.
67. Giannakoula A, Therios I, Chatzissavvidis C. Effect of lead and copper on photosynthetic apparatus in citrus (*Citrus aurantium* L.) plants. The role of antioxidants in oxidative damage as a response to heavy metal stress. *Plants*. 2021; 10(1):155.
68. Rani M, Vikas, Kumar R, Lathwal M, Kamboj A. Effect and responses of lead toxicity in plants. In: *Lead toxicity mitigation: sustainable Nexus approaches*. Springer. 2024; 211-241.
69. Aziz EE, Sabry RM, Ahmed SS. Plant growth and essential oil production of sage (*Salvia officinalis* L.) and curly-leafed parsley (*Petroselinum crispum* ssp. *crispum* L.) cultivated under salt stress conditions. *World Appl Sci J*. 2013; 28(6):785-796.
70. Biswas S, Koul M, Bhatnagar A. Effect of arsenic on trichome ultrastructure, essential oil yield and quality of *Ocimum basilicum* L. *J Med Plant Res*. 2015; 5.
71. Hashem FAE-M, Sahab AF. Chemical response of parsley and mentha herbs to certain stress agents. *Food Chem*. 1999; 65(1):29-33.
72. Sulastri YS, Tampubolon K. Aromatic plants: Phytoremediation of cadmium heavy metal and the relationship to essential oil production. *International Journal of Scientific and Technology Research*. 2019; 8(8):1064-1069.
73. Fattahi B, Arzani K, Souri MK, Barzegar M. Effect of cadmium and lead on morpho-physiological traits and Photosynthesis of sweet basil (*Ocimum basilicum* L.). *Iranian Journal of Horticultural Science*. 2020; 50(4).
74. Marín I, Sayas-Barberá E, Viuda-Martos M, Navarro C, Sendra E. Chemical composition, antioxidant and antimicrobial activity of essential oils from organic fennel, parsley, and lavender from Spain. *Foods*. 2016; 5(1):18.
75. Zhang H, Chen F, Wang X, Yao H-Y. Evaluation of antioxidant activity of parsley (*Petroselinum crispum*) essential oil and identification of its antioxidant constituents. *Food Res Int*. 2006; 39(8):833-839.
76. dos Santos Franciscato LMS, Mendes SS, Frederico C, Goncalves JE, Faria MGI, Gazim ZC, Ruiz SP. Parsley (*Petroselinum crispum*): chemical composition and antibacterial activity of essential oil from organic against foodborne pathogens. *Aust J Crop Sci*. 2022; 16(5):605-611.
77. Safaei F, Alirezalu A, Noruzi P, Alirezalu K. Phytochemical and morpho-physiological response of *Melissa officinalis* L. to different NH₄⁺ to NO₃⁻ ratios under hydroponic cultivation. *BMC Plant Biol*. 2024; 24(1):968.
78. Sabry RM, Ahmed SS. Evaluation of Essential Oil Constituents and Heavy Metals Accumulation of Mint, Parsley and Chamomile that are grown at Various Planting Locations of Egypt. *Egypt J Chem*. 2022; 65(131):511-519.
79. Khalid A. Quality and quantity of *Pimpinella anisum* L. essential oil treated with macro and micronutrients under desert conditions. *International Food Research Journal*. 2015; 22(6):2396.
80. Ibrahim AA, Mosa AA, Mohammed LY. Polyphenol Profile, Antioxidant Potential, Vitamin C and Mineral Contents of Crude Parsley Leaves Extract (*Petroselinum crispum*) and Its Isolated Apigenin: A Comparative Study. *Baghdad Science Journal*. 2025; 22(5):1465-1476.
81. Nawaz I, Mehboob A, Khan AHA, Naqvi TA, Bangash N, Aziz S, Khan W, Shahzadi I, Barros R, Ullah K: Higher cadmium and zinc accumulation in parsley (*Petroselinum crispum*) roots activates its antioxidants defense system. *Biometals*. 2024; 37(1):87-100.
82. Gheshlaghpour J, Asghari B, Khademian R, Sedaghati B. Silicon alleviates cadmium stress in basil (*Ocimum basilicum* L.) through alteration of phytochemical and physiological characteristics. *Ind Crops Prod*. 2021; 163:113338.

83. LEAHU A, DAMIAN C, OROIAN M, MICLESCU V, ROPCIUC S. Variation in content of antioxidant and free radical scavenging activity of basil (*Ocimum basilicum*), dill (*Anethum graveolens*) and parsley (*Petroselinum sativum*). Food and Environment Safety Journal. 2016; 12(4).
84. Ulusu Y, Öztürk L, Elmastaş M. Antioxidant capacity and cadmium accumulation in parsley seedlings exposed to cadmium stress. Russ J Plant Physiol. 2017; 64(6):883-888.
85. Gulcin İ, Alwasel SH. Metal ions, metal chelators and metal chelating assay as antioxidant method. Processes. 2022; 10(1):132.
86. Goncharuk EA, Zagorskina NV. Heavy metals, their phytotoxicity, and the role of phenolic antioxidants in plant stress responses with focus on cadmium. Molecules. 2023; 28(9):3921.
87. Zhang L, Xu M, Guan Q, Jiang J, Sun K, Manirafasha E. Determination of vegetable tannins from plants in China. Biofuels, Bioproducts and Biorefining. 2023; 17(3):592-601.
88. Rice-Evans CA, Miller NJ, Paganga G: Structure–Antioxidant Activity Relationships of Flavonoids and Phenolic Acids. Free Radical Biology and Medicine. 2005; 39(10):1266.
89. Zhang L, Guan Q, Zhang H, Tang L. Effect of metal ions on the interaction of condensed tannins with protein. Foods. 2023; 12(4):829.
90. Orabi SA, Abou-Hussein S. Antioxidant defense mechanisms enhance oxidative stress tolerance in plants. A review. Curr Sci Int. 2019; 8(3):565-576.
91. Valšíková M, Mezeyová I, Rehuš M, Šlosár M. Changes of vitamin C content in celery and parsley herb after processing. Potravinárstvo. vol. 10, no. 1. In.; 2016.

Tables

Table 1 Physico-chemical properties of soil used in pots.

Soil	Clay	Silt	Sand	N	P	K	C	As	Cd	Pb	pH	EC
Silty loam	24%	45%	31%	0.062 g/kg	6.7 mg/kg	1.79 mg/kg	0.64%	0.78 mg/kg	0.54 mg/kg	0.9 mg/kg	7.5	3.14 ds/ m

Table 2 Mean comparison of morphological characteristics in *Petroselinum crispum* under different soil concentrations of arsenic, cadmium, and lead.

		Plant height (mm)	Petiole length (mm)	Stem diameter (mm)	Flower umbrella diameter (mm)	Root length (mm)	Root diameter (mm)
As	Control	240 ^a	3.7 ^d	0.91 ^c	14.0 ^c	64.0 ^c	0.5 ^b
	As25	233 ^b	4.4 ^c	0.94 ^{bc}	14.1 ^c	73.0 ^b	0.61 ^a
	As50	230 ^b	4.3 ^c	1.02 ^b	14.2 ^c	77.0 ^b	0.64 ^a
	As75	223 ^c	4.9 ^b	1.1 ^a	14.8 ^b	78.2 ^b	0.6 ^a
	As100	215 ^c	5.7 ^a	1.1 ^a	15.1 ^a	85.1 ^a	0.6 ^a
Cd	Control	240 ^a	3.7 ^c	0.91 ^b	14.0 ^b	64.0 ^c	0.5 ^b
	Cd10	237 ^{ab}	4.2 ^b	0.95 ^a	14.5 ^{ab}	73.5 ^b	0.61 ^a
	Cd20	233 ^b	4.1 ^b	0.94 ^a	14.9 ^a	76.3 ^b	0.66 ^a
	Cd30	235 ^{ab}	5.0 ^a	0.97 ^a	15.2 ^a	79.8 ^{ab}	0.65 ^a
	Cd40	235 ^{ab}	5.0 ^a	0.96 ^a	15.0 ^a	83.5 ^a	0.62 ^a
Pb	Control	240 ^a	3.7 ^c	0.91 ^b	14.0 ^c	64.0 ^d	0.5 ^c
	Pb100	231 ^b	4.5 ^b	0.97 ^a	14.5 ^{bc}	70.5 ^c	0.59 ^b
	Pb200	231 ^b	4.1 ^b	1.0 ^a	14.9 ^b	77.2 ^b	0.71 ^a
	Pb300	225 ^c	5.4 ^a	1.05 ^a	15.1 ^{ab}	85.1 ^a	0.74 ^a
	Pb400	218 ^c	5.1 ^a	1.0 ^a	15.4 ^a	88.2 ^a	0.7 ^a

As: Arsenic, Cd: Cadmium, Pb: Lead. All data related to As, Cd and Pb were separately analyzed. Mean values are the average of three replications. In each column means with the same letters are not significantly different at 5 % ($P \leq 0.05$) probability level.

Table 3 Mean comparison of physiological characteristics in *Petroselinum crispum* under different soil concentrations of arsenic, cadmium, and lead.

		Stem fresh weight (g)	Stem dry weight (g)	Root fresh weight (g)	Root dry weight (g)	Leaf area (cm ²)	RWC (%)	Leaf heavy metal (mg kg ⁻¹)
As	Control	40.9 ^a	12.5 ^a	6.4 ^b	2.1 ^c	345 ^a	92 ^a	0.61 ^e
	As25	35.1 ^b	9.1 ^b	6.9 ^b	3.5 ^b	321 ^b	88 ^{ab}	0.88 ^d
	As50	32.7 ^{bc}	8.4 ^b	7.1 ^b	3.6 ^b	315 ^c	84 ^b	1.04 ^c
	As75	30.2 ^c	8.1 ^b	8.4 ^a	4.5 ^a	310 ^c	80 ^{bc}	1.19 ^b
	As100	30.9 ^c	8.3 ^b	8.6 ^a	4.6 ^a	304 ^d	80 ^{bc}	1.34 ^a
Cd	Control	40.9 ^a	12.5 ^a	6.4 ^c	2.1 ^d	345 ^a	92 ^a	0.7 ^e
	Cd10	37.1 ^b	10.3 ^b	7.5 ^b	3.3 ^c	333 ^b	85 ^b	0.79 ^d
	Cd20	34.2 ^c	8.9 ^c	7.9 ^a	3.8 ^b	319 ^c	83 ^b	0.94 ^c
	Cd30	31.5 ^d	7.9 ^c	8.1 ^a	4.5 ^a	309 ^d	80 ^{bc}	1.12 ^b
	Cd40	32.8 ^d	8.3 ^c	8.0 ^a	4.2 ^{ab}	300 ^e	80 ^{bc}	1.21 ^a
Pb	Control	40.8 ^a	12.5 ^a	6.4 ^c	2.1 ^c	345 ^a	92 ^a	0.8 ^d
	Pb100	31.4 ^b	8.0 ^b	6.9 ^b	2.6 ^b	328 ^b	87 ^b	1.2 ^{cd}
	Pb200	30.0 ^b	7.8 ^b	7.4 ^a	3.1 ^a	318 ^c	84 ^{bc}	1.9 ^c
	Pb300	32.2 ^b	8.0 ^b	7.4 ^a	3.1 ^a	307 ^d	85 ^c	2.78 ^b
	Pb400	32.9 ^b	8.2 ^b	7.4 ^a	3.0 ^a	304 ^d	84 ^c	3.74 ^a

As: Arsenic, Cd: Cadmium, Pb: Lead. All data related to As, Cd and Pb were separately analyzed. Mean values are the average of three replications. In each column means with the same letters are not significantly different at 5 % ($P \leq 0.05$) probability level.

Table 4 The photosynthetic rate, gas exchange, and some of the leaf biochemical and physiological traits mean comparison of *Petroselinum crispum* under different soil concentrations of arsenic, cadmium, and lead.

		Pn $\mu\text{mol CO}_2$ $\text{m}^{-2}\text{s}^{-1}$	E $\mu\text{mol H}_2\text{O CO}_2$ $\text{m}^{-2}\text{s}^{-1}$	Ci $\mu\text{mol CO}_2/\text{mol air}$	Fv/Fm	Chlorophyll a mg/g FW	Chlorophyll b mg/g FW	Carotenoid mg/g FW	Leaf greenness SPAD
As	Control	5.41 ^a	3.99 ^a	279 ^a	0.71 ^a	1.1 ^a	0.66 ^a	0.42 ^a	24 ^a
	As25	5.0 ^b	3.7 ^b	275 ^{ab}	0.62 ^b	0.9 ^{ab}	0.59 ^b	0.32 ^b	19 ^b
	As50	4.5 ^c	3.48 ^c	278 ^a	0.54 ^c	0.82 ^c	0.5 ^c	0.29 ^b	17 ^b
	As75	4.1 ^d	3.2 ^d	269 ^b	0.41 ^d	0.7 ^c	0.45 ^{cd}	0.27 ^b	14 ^c
	As100	3.5 ^e	2.9 ^e	265 ^b	0.32 ^e	0.54 ^d	0.4 ^d	0.27 ^b	14 ^c
Cd	Control	5.41 ^a	3.99 ^a	279 ^a	0.71 ^a	1.1 ^a	0.66 ^a	0.42 ^a	24 ^a
	Cd10	4.9 ^b	3.2 ^b	271 ^b	0.64 ^b	0.94 ^{ab}	0.6 ^b	0.34 ^b	20 ^b
	Cd20	4.8 ^b	3.1 ^b	265 ^c	0.6 ^b	0.85 ^b	0.54 ^c	0.28 ^c	18 ^b
	Cd30	4.2 ^c	3.1 ^b	261 ^d	0.54 ^c	0.81 ^{bc}	0.42 ^d	0.28 ^c	17 ^b
	Cd40	4.0 ^c	3.0 ^b	260 ^d	0.5 ^c	0.74 ^c	0.4 ^d	0.28 ^c	14 ^c
Pb	Control	5.41 ^a	3.99 ^a	279 ^a	0.71 ^a	1.1 ^a	0.66 ^a	0.42 ^a	24 ^a
	Pb100	4.9 ^b	3.5 ^b	264 ^b	0.61 ^b	0.88 ^b	0.54 ^b	0.29 ^b	22 ^a
	Pb200	4.33 ^c	3.57 ^b	264 ^b	0.5 ^c	0.76 ^{bc}	0.48 ^c	0.27 ^b	18 ^b
	Pb300	3.9 ^d	3.4 ^{bc}	260 ^c	0.38 ^d	0.7 ^c	0.46 ^c	0.28 ^b	17 ^b
	Pb400	3.5 ^e	3.1 ^c	254 ^d	0.29 ^e	0.6 ^d	0.42 ^d	0.27 ^b	17 ^b

As: Arsenic, Cd: Cadmium, Pb: Lead. All data related to As, Cd and Pb were separately analyzed. Mean values are the average of three replications. In each column means with the same letters are not significantly different at 5 % ($P \leq 0.05$) probability level.

Table 5 Chemical composition of essential oils extracted from *Petroselinum crispum* aerial parts grown under different soil concentrations of arsenic, cadmium, and lead.

No	RI ⁺	Compounds	Contro l%	As25 %	As50 %	As75 %	As10 0%	Cd10 %	Cd20 %	Cd30 %	Cd40 %	Pb10 0%	Pb20 0%	Pb30 0%	Pb40 0%
1	920	α -Thujene	1.1	1.4	0.9	0.9	1.5	0.9	0.9	0.9	0.9	1.5	1.5	1.5	1.5
2	927	α -Pinene	14.0	17.9	18.2	17.9	20.0	14.8	14.9	16.5	16.8	15.1	15.4	17.1	18.1
3	966	Sabinene	0.2	0.5	1.0	1.1	0.9	1.2	1.5	1.5	1.7	2.2	2.1	2.0	2.1
4	980	b-Pinene	8.0	9.9	11.5	12.9	12.0	7.4	7.8	8.8	9.2	7.4	7.8	9.7	11.0
5	985	β -Myrcene	1.5	1.8	1.7	2.4	2.4	2.5	2.9	3.9	3.4	2.1	2.1	2.4	2.7
6	997	α -Phellandrene	3.5	3.7	2.9	3.2	3.5	3.7	3.8	3.8	3.7	1.8	1.7	2.1	1.9
7	1014	β -Phellandrene	6.1	6.9	7.1	7.1	8.0	6.8	7.9	7.9	7.3	5.1	5.1	5.9	6.8
8	1018	α -Terpinene	1.9	1.5	1.4	1.6	1.9	0.9	1.7	1.7	1.9	2.1	2	2.3	2.1
9	1026	p-Cymene	0.2	0.9	0.7	0.7	1.0	0.7	0.8	0.8	1.0	0.6	0.5	0.4	0.8
10	1036	Limonene	1.6	1.7	2.7	2.9	2.5	2.1	1.9	1.9	1.9	1.3	1.4	1.9	2.1
11	1118	1,3,8-p-Menthatriene	4.1	5.5	5.6	5.4	6.1	4.9	5.2	5.2	4.8	5.3	5.6	5.9	7.4
12	1428	β -Caryophyllene	2.0	2.3	1.4	1.8	2.4	3.5	3.7	3.7	3.4	1.5	1.6	2.0	2.1
13	1433	α -farnesene	1.1	0.6	0.6	0.8	0.9	0.2	0.3	0.3	0.2	1.1	1.3	1.4	1.1
14	1480	Germacrene D	1.2	0.9	1.4	1.3	1.1	0.6	0.5	0.5	0.8	1.2	1.1	1.2	1.3
15	1528	Myristicin	24.3	22.1	20.9	19.4	17.2	22.3	20.9	19.7	20.4	24.2	23.4	19.7	17.1
16	1550	Elemicin	2.4	2.0	1.6	1.7	1.4	1.6	1.7	0.9	1.1	1.9	1.7	1.2	0.9
17	1578	Caryophyllene oxide	2.3	1.7.0	1.1	1.2	1.4	2.1	2.1	1.7	2.4	3.0	3.1	2.3	3.8
18	1684	Apiol	23.0	17.0	15.9	14.5	12.0	20.2	18.2	12.7	13.1	18.6	17.0	13.9	11.9
Total			98.5	98.0	96.6	96.8	96.2	96.4	96.7	92.4	94.0	96.0	94.4	92.9	94.7

* RI: retention indices according to the normal alkanes between C8-C24. As: Arsenic, Cd: Cadmium, Pb: Lead.

Figures

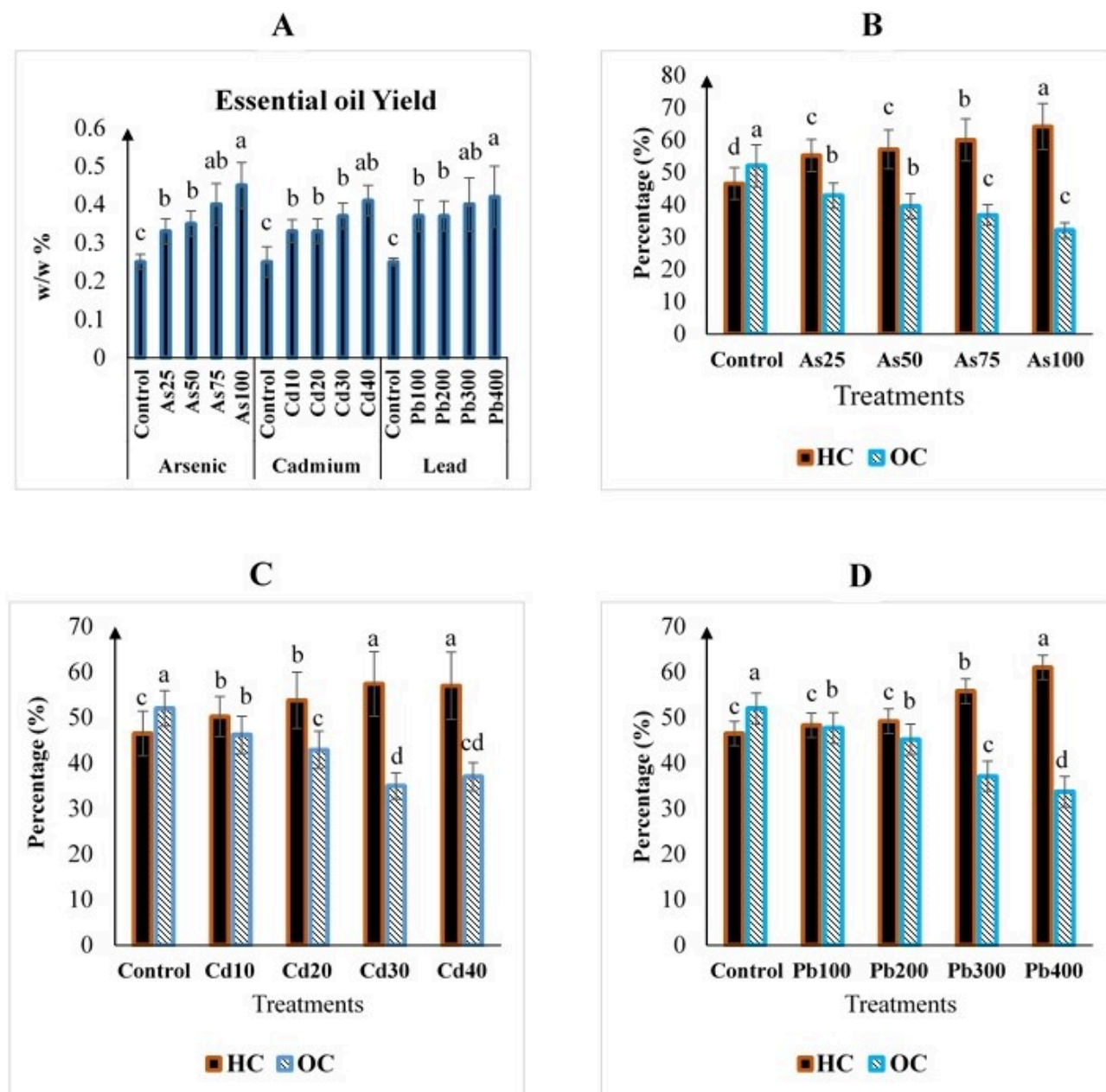


Figure 1

Effect of different soil concentrations of arsenic, cadmium, and lead on Yield (%w/w), Hydrocarbon compounds (HC), and Oxygenated compounds (OC) of *petroselinum crispum* aerial parts essential oil.

As: Arsenic, Cd: Cadmium, Pb: Lead. Significant differences at $P < 0.05$ have been indicated with different letters.

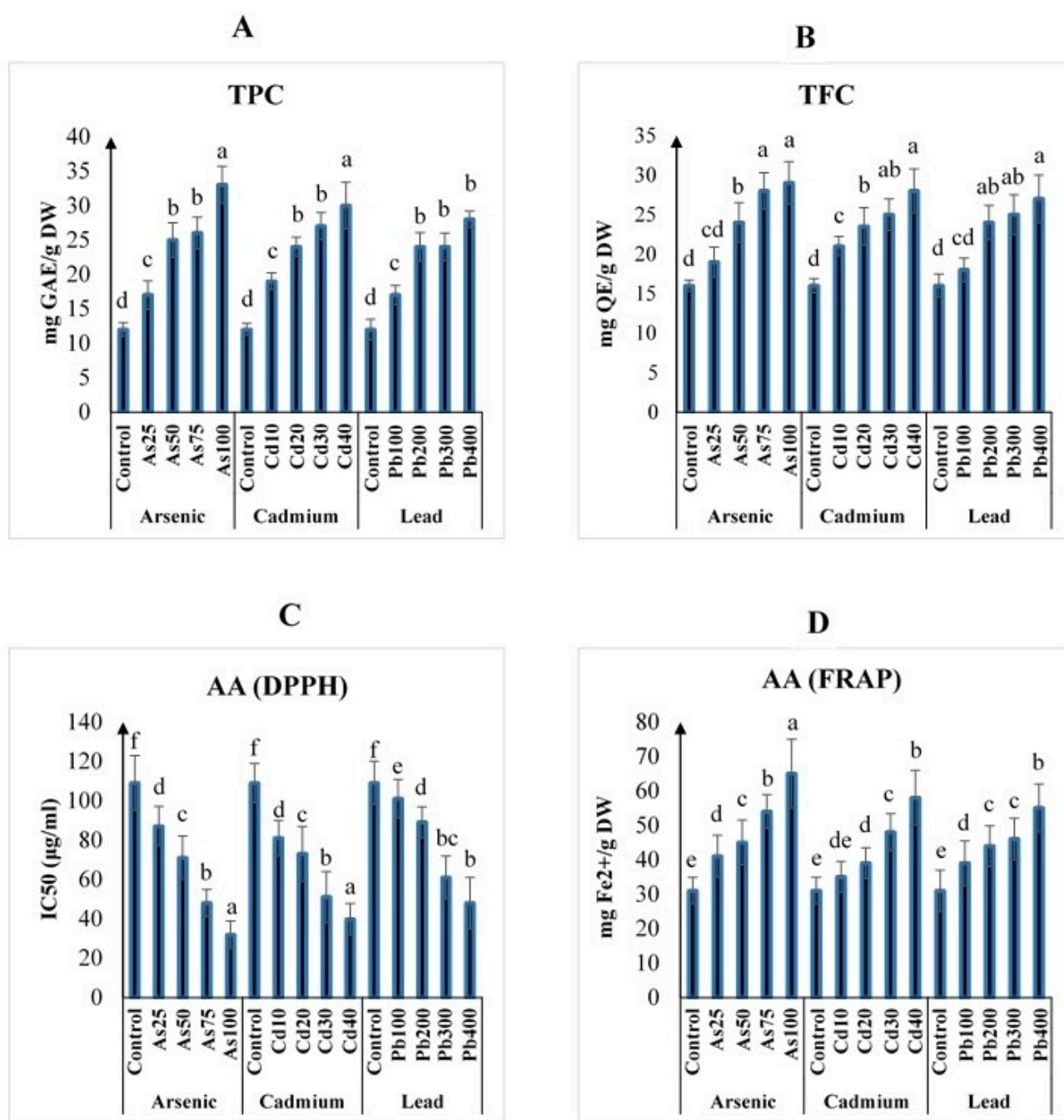


Figure 2

Effect of different soil concentrations of arsenic, cadmium, and lead on Total Phenol Content (A), Total Flavonoid Content (B) and Antioxidant Activity (C: DPPH, D: FRAP) of *petroselinum crispum*.

As: Arsenic, Cd: Cadmium, Pb: Lead. Significant differences at $P < 0.05$ have been indicated with different letters.

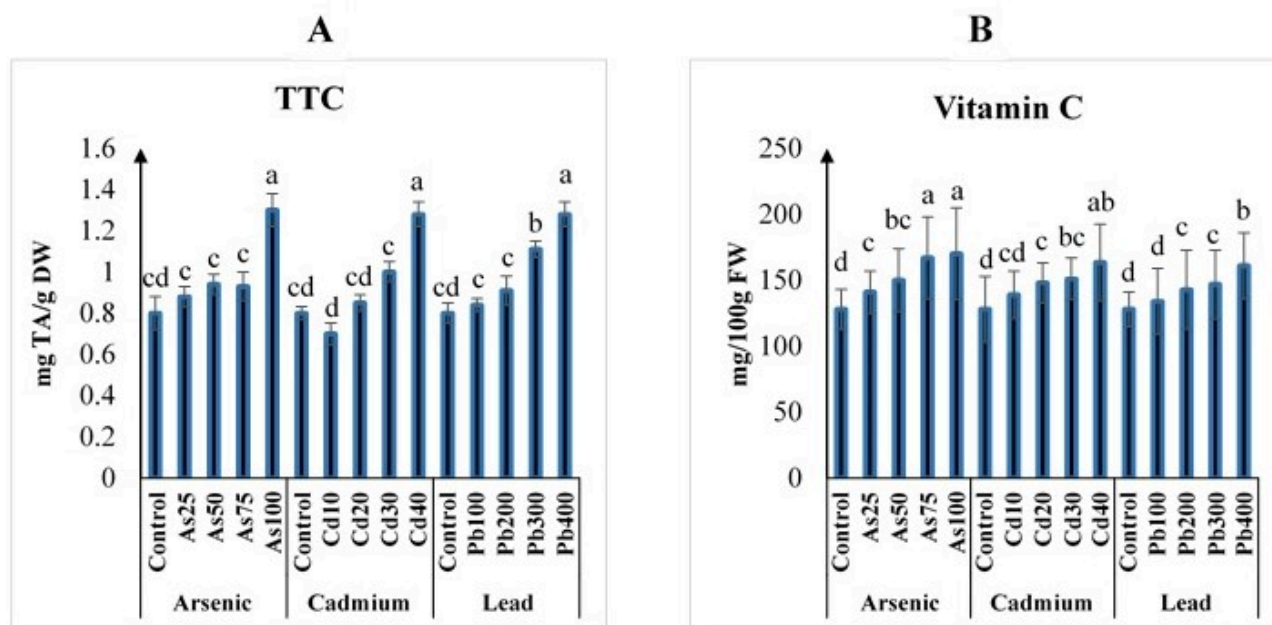


Figure 3

Effect of different soil concentrations of arsenic, cadmium, and lead on Total Tannin Content (A) and Vitamin C concentration (B) of *petroselinum crispum*.

As: Arsenic, Cd: Cadmium, Pb: Lead. Significant differences at $P < 0.05$ have been indicated with different letters.