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Effects of Zeolite and Poultry Manure in PTE Accumulation in *Crithmum maritimum* Grown in Contaminated Soil

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Abstract Soil contamination by potentially toxic elements (PTEs) is a crucial abiotic stress factor, which negatively affects crop growth and yield. Sea fennel (*Crithmum maritimum*) has demonstrated notable tolerance to adverse conditions, making it a potential tolerant candidate for cultivation in contaminated soils. The present study investigated the impact of zeolite and poultry manure (PM) application on plant growth and bioaccumulation of PTEs (Cd, Cu, Pb, and Zn) in a highly contaminated soil. Although the amendments did not lead to significant variations in biomass, the plant thrived in contaminated soil, suggesting high resistance to abiotic stress. Poultry manure reduced Pb availability in soil by 28% but did not inhibit hazardous accumulation in plant tissues. In contrast, zeolite application resulted in elevated Cd concentrations (up to 2.05 mg kg^{-1}) in aboveground biomass. Meanwhile, the addition of PM increased Cu concentrations in plant tissues (up to 3.88 mg kg^{-1}). However, Cd and Pb concentrations exceeded in the aerial biomass the European limits for consumption, posing health risks regarding its use as edible from contaminated soils. The findings highlight the complex effect of soil amendments on PTE mobility and phytoavailability and suggest the potential of *C. maritimum* as a resistant crop in highly polluted soils.

Keywords Soil amendments · Soil health · Remediation · Abiotic stress · Phytoaccumulation · Sea fennel

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1 Introduction

Soil contamination by potentially toxic elements (PTEs) such as lead (Pb), cadmium (Cd), zinc (Zn), and copper (Cu) is a major environmental challenge that has garnered increasing attention due to its detrimental effects on ecosystems, agriculture and human health (Ye et al., 2025; Zheng et al., 2024). Industrial activities, mining, wastewater irrigation, and the excessive use of conventional fertilizers and pesticides contribute to the widespread presence of PTEs in both agricultural and natural soils (Angon et al., 2024). Unlike organic pollutants, PTEs are non-degradable over time, leading to long-term contamination that can negatively affect plant growth, soil microbial activity and health, and groundwater quality (Naz et al., 2022; Thalassinos et al., 2023a, 2023b).

Under specific environmental conditions, such as increased precipitation or variations in soil pH, PTEs may be released from contaminated soils and transported downward through leaching processes (Xu et al., 2024; Zhang et al., 2023a). In highly permeable environments, including karst systems, structural features such as cracks and pores can significantly enhance transport of these elements into groundwater. Their transport and retention are also regulated by physicochemical interactions of soil, including adsorption–desorption dynamics, which affect their mobility. Consequently, contaminated soils can act as long-term sources of groundwater pollution, promoting the accumulation of PTEs in aquifers and posing risk to water quality (Zhang et al., 2023b).

Excessive accumulation of toxic metals disrupts plant metabolism, and basic physiological functions, such as photosynthesis. Consequently, plants growing in contaminated areas often exhibit stunted growth, chlorosis, and reduced productivity (Hafeez et al., 2023). Furthermore, PTEs can enter the food chain through plant uptake, posing risks to human and animal health (Ali & Khan, 2019). Therefore, effective strategies to attenuate contamination and reduce plant abiotic stress are urgently needed to mitigate their harmful effects and restore soil health (Khan et al., 2025). Existing soil remediation strategies include physical, chemical, microbial and combined approaches, each with advantages and limitations. Physical methods, such as soil thermal desorption and soil replacement, can be effective and relatively fast, but are often costly and less suitable for large areas (Gong et al., 2018). Chemical methods, including leaching and stabilization, can treat severely contaminated soils, yet may not completely remove contaminants, and may cause secondary pollution (Song et al., 2022; Xu et al., 2021). Combined methods improve efficiency and treatment time; however, they can be complex, or require high energy input (Song et al., 2022). These gaps highlight the need for alternative approaches thar are sustainable and restoring soil health, such as phytoremediation.

Phytoremediation is a promising, environmentally friendly, and cost-effective approach to addressing soil pollution (Grammenou et al., 2023). This technique utilizes plants to extract, stabilize or transform pollutants, thereby reducing their bioavailability and toxicity. Certain plant species, particularly those with a known tolerance to other environmental stressors, have demonstrated the ability to accumulate or immobilize PTEs, making such plants a valuable tool in soil remediation efforts (Kikis et al., 2024). *Crithmum maritimum,* commonly known as sea fennel, is one such plant that has attracted attention for its potential use in alleviating soil abiotic stresses (Giannakoula et al., 2025; Martins-Noguerol et al., 2024).

C. maritimum is an edible facultative halophyte native to Mediterranean and Atlantic coasts and thrives in high salinity, nutrient-poor soils (Colak Esetlili et al., 2024; Correia et al., 2024). Due to its ability to withstand adverse conditions, *C. maritimum* has been considered a promising candidate for the restoration of degraded and polluted soils. Halophytic species such as *C. maritimum* contribute to phytoremediation due to their resistance to elevated concentrations of PTEs in the rhizosphere (Panda et al., 2025). These plants exhibit a potential for phytoremediation as they can absorb and accumulate PTEs in their aerial parts (phytoextraction) or immobilize them within the root zone (phytostabilization), thereby reducing them (the former concerning total concentrations, the latter concerning available) in the soil and limiting further environmental contamination (Caparrós et al., 2022).

In the natural environment, the plant's capacity to resist or tolerate the PTEs is significantly influenced by the physico-chemical properties of soil, such as pH, organic matter content, and the availability of essential nutrients (Kikis et al., 2025). In many cases, the application of soil amendments can enhance the efficiency of the process by improving soil structure, stimulating microbial activity, and altering the bioavailability of contaminants (Ndour et al., 2025). Bioavailability refers to the fractions of PTEs in the soil that are accessible to plants roots and available for absorption (Mensah & Amoakwah, 2024; Zhakypbek et al., 2024). Among the most commonly used soil amendments are zeolite and manure, both of which have been shown to induce all above mentioned soil-related benefits through various mechanisms.

Zeolite is a natural tectosilicate mineral with highly porous structure and a high cation exchange capacity due to the extensive isomorphic substitution of Si with Al in its crystalline structure. It stands out among adsorbents due to its large surface area and significant adsorption capacity (Motlagh et al., 2025; Thalassinos et al., 2023a, 2023b). Zeolite has been extensively studied for its ability to adsorb and

immobilize PTEs such as Pb, Cd, Co and Mn, demonstrating varying degrees of effectiveness depending on the specific metal and experimental conditions (Pratti et al., 2019). Incorporating zeolite into contaminated soils can improve physical and chemical properties, such as aeration and water retention, while reducing the leaching of PTEs into groundwater. Moreover, its high cation exchange capacity improves nutrient retention, thereby promoting healthier plant growth in degraded environments (Viana et al., 2025).

Poultry manure (PM) is an organic amendment rich in primary nutrients such as nitrogen (N), phosphorus (P), potassium (K), and organic matter, which enhances soil health and fertility and supports plant growth (Jiang et al., 2024). Organic amendments can stabilize PTEs through various retention mechanisms and complex formation with metal ions, thereby reducing their uptake by plants and limiting excessive accumulation in edible plant parts (Wan et al., 2020). However, manure contains dissolved organic matter (DOM), the composition of which changes during composting process and can affect the behavior of soil PTEs (Wu et al., 2023). Additionally, PM itself may contains PTEs such as Cd, Pb, arsenic (As) and chromium (Cr), which may accumulate in soil with repeated application and thus potentially enter the food chain (Wan et al., 2020). Therefore, its application should be carefully managed and monitored to balance soil improvement with environmental and human health protection.

Despite the promising potential of *C. maritimum*, limited research has been conducted to the best of our knowledge on its interaction with soil amendments in degraded and contaminated areas. Although the effects of zeolite and PM on plant growth and PTEs uptake have been extensively studied, their individual effects could provide a clearer distinction of their specific roles in the reduction of plant stresses. The combination of zeolite and PM for soil remediation has only been assessed once by Ortega et al., 2020, who reported sufficient plant development under harsh conditions cause by both inorganic and organic contaminants across a wide range of Mediterranean plants (*C. maritimum* was not included). In addition, there is no direct study evaluating C. *maritimum*'s capacity for contaminant uptake or immobilization. This is a major primary gap. For other halophytes, research exists regarding growth in contaminated soils but there are no comparable metal uptake studies, despite being a salt tolerant species. Interestingly, there are findings indicating high antioxidant content in *C. maritimum* plant extracts as reported by Ashim et al., 2025. Such trait may indicate also tolerance against PTEs, a desired aspect which led to the selection of the specific species in this work. Furthermore, numerous studies have shown effective PTE immobilization by zeolite (El Rasafi et al., 2024; Hudcová et al., 2021; Mensah et al., 2025). Poultry manure has shown improvement of nutrient status coupled with pollutant reduction (Pandey et al., 2020; Saleh & Al Bahrani, 2023). These amendments have not been studied in *C. maritimum* in regards to phytoremediation of PTEs. While previous studies have explored this topic, our study contributes to the existing knowledge by evaluating the effect of zeolite and PM on the growth performance, stress tolerance, and phytoremediation capacity of *C. maritimum* under PTE stress (Cd, Cu, Pb and Zn).

This research aimed to investigate the application of zeolite and PM; specifically whether (i) they enhance plant establishment, growth rate, and biomass production in contaminated soil, (ii) they influence the bioavailability of PTEs in soil, and (iii) they affect the uptake and accumulation of the studied PTEs within the aerial plant tissues. The novelty of the present study lies in the use of naturally contaminated source from a mining site, providing a more realistic view regarding environmental conditions. In addition, it evaluates the performance of a resilient halophytic plant under multi-metal stress. Assessing the individual effects of zeolite and PM in the current pot experiment, this research underscores their distinct roles and potential efficacy withing large-scale phytoremediation strategies.

This study aimed to contribute to a deeper understanding of plant-based restoration approaches and the potential of soil amendments to enhance plant tolerance under abiotic stress. The use of edible plants can stabilize contaminant while producing economically valuable biomass, offering both ecological and economic benefits. However, continuous monitoring of PTEs concentrations in edible plant organs is necessary to ensure food safety. The findings could have implications for implementing sustainable soil management practices, particularly in areas affected by pollution from PTEs. Additionally, the use of resilient species, such as the test crop *C. maritimum* may offer an environmentally friendly alternative

to conventional restoration techniques, supporting efforts to boost the soil health in degraded ecosystems and promote agricultural productivity in contaminated soils.

2 Materials and Methods

2.1 Experimental Design

A 155-day experiment was conducted under greenhouse conditions using a highly contaminated soil of light texture (sand 79.6%, silt 11.6%, clay 8.8%) collected from the urban area of Lavrio, Attica (37.719311° N, 24.044154° E), known for the intense mining activities in the past decades. Lavrio has a long history of mineral exploitation dating back to the third millennium BC, primarily for silver. Modern mining activities were revitalized about 170 years ago, focusing on Pb and Zn ores. These activities continued until the 1970s (Antoniadis et al., 2022). The pseudo-total concentrations of the elements were determined as follows: Cd = 39.59, Cu = 166.01, Pb = 7844, and Zn = 6458 (units, mg kg^{-1}), values that exceeded by far the regulation limits established for agricultural soils (set as follows: Cd = 3, Cu = 140, Pb = 300, and Zn = 300; Commission of the European Communities, 2006). The physicochemical properties of the soil are presented in Table 1.

For the experimental procedure, 2-L pots were used. The experiment including 45 *C. maritimum* plants divided in three treatments, each with 15 replicates: 1. Control (C): unamended soil; 2. Zeolite (Z): soil with the addition of 50 g zeolite (2.5% w/w soil). The zeolite used was a commercially available clinoptilolite with a grain size of 0–0.8 mm (Vivolith 85); 3. Poultry manure (PM): soil added with 50 g of PM (2.5% w/w/soil). The PM was raw and mixed with soil on a dry-matter basis, with the following nutrient content: Total N 19.1 g kg^{-1}, total P 23.0 g kg^{-1}, and total K 5.7 g kg^{-1}. For improved plant growth, we added a nutrient solution (200 mg L^{-1} NPK) to all treatments, including the control; the solution was applied every 14 days at a rate of 150 mL per pot. The cumulative nutrient inputs per pot from the nutrient solution over the experiment were 0.33 g N, 0.33 g P, and 0.33 g K.

Zeolite and PM were selected as soil amendments due to their known effectiveness in improving soil quality and immobilizing PTEs. *C. maritimum* was selected as the test plant due to its ability to withstand adverse conditions, as well as its potential for phytoextraction of PTEs, as discussed in the introduction. In zeolite all studied metals except for Cu (which had a concentration of 15.33 mg kg^{-1}) were below the detection limits (which were Cd = 0.3, Pb = 0.6, and Zn = 1.29) (all units in mg kg^{-1}). As for the poultry manure, it contained Pb = 14.70, Zn = 202.96, and Cu = 87.95, while Cd was below the detection limit (all units in mg kg^{-1}).

Table 1 pH, electrical conductivity (EC) and organic carbon (OC) in the amendments and the three treatments: C = control (no amendments), Z = zeolite added to soil, PM = poultry manure added to soil

	pH	EC (μS cm^{-1})	OC%
Zeolite	7.00	–	–
Poultry manure	7.10	1650.00	37.70
C	8.02 ± 0.21	146 ± 95 [a]	1.49 ± 0.25 [a]
Z	7.81 ± 0.15	175 ± 68 [a]	1.37 ± 0.19 [a]
PM	7.89 ± 0.17	228 ± 55 [b]	3.32 ± 0.22 [b]
Sig	$p = 0.105$ (NS)	$p = 0.031$*	$p = 0.005$**

Values are expressed as mean ± SE (n = 5). Treatments sharing the same letter do not differ significantly (One-Way ANOVA with Tukey's post-hoc test). ** Significant at the level of $p < 0.01$. * Significant at the level of $p < 0.05$. NS = Non-significant

2.2 Soil and Plant Analyses

2.2.1 Soil Analyses

Electrical conductivity (EC) and pH were measured in a 1:5 (W/V) soil-to-water ratio. The organic carbon was determined using the Walkley–Black dichromate oxidation method. The pseudo-total concentrations of PTEs were determined following aqua regia digestion (3:1 HCl:HNO_3) in a digestion system at 140 °C for 3 h under controlled conditions. The DTPA (diethylotriaminopentaacetic acid) extraction method was used to determine the bioavailable concentration of PTEs in soil, applied at a 1:2 ratio (soil:solution), as an extraction method introduced by Lindsay and Norvell (1978).

2.2.2 Plant Analyses

At harvest, the fresh weight (g) of the plants was recorded. The samples were then placed in an oven (at 70 °C for 48 h) to dry and the dry weight (g) was measured. Subsequently, plant samples were pulverized and analyzed for PTE content using the dry ash method (1 g of plant sample, heated for 5 h at 500 °C), then extracted with 10 mL 20% HCl. Finally, both plant and soil extracts were analyzed for the determination of Cd, Cu, Pb, and Zn using atomic absorption spectrometry (Perkin Elmer A3300). All procedures followed the standard Rowell (2014) methodology. For chemical analyses, plant and soil samples from three replicates were pooled to form one composite sample, resulting in five composite samples (n = 5) per treatment. Pooling was applied to obtain representative material and reduce analytical effort, while maintaining sufficient replication at the treatment level.

2.2.3 Quality Assurance and Quality Control (QA/QC)

Quality control procedures were applied for both soil and plant analyses. Sample blanks were included in each batch, and analyses were performed in replicates, with relative standard deviation (RSD) values generally below 10%. For plant analyses, method performance was evaluated using spike recovery tests, with recoveries 90–110%. Soil reference materials included an in-house standard and the certified BCR-141R Calcareous Loam Soil (single extraction), with recoveries ranging from 93–108%. Detection limits (LOD) for Cd, Cu, Pb and Zn were as follows: Cd (0.3 mg kg^{-1}), Cu (0.59 mg kg^{-1}), Pb (0.60 mg kg^{-1}), and Zn (1.29 mg kg^{-1}).

2.3 Plant Accumulation of PTEs

Two bioaccumulation indices were calculated to assess the suitability of *C. maritimum* for the remediation of the contaminated soil: (1) a conventional BAF using total concentrations, which allows comparison with the literature, and (2) bioavailability-based (DTPA-extractable soil) index, reflecting metal uptake from the fraction available for plant absorption.

Bioaccumulation factor (BAF):

$$BAF_{total} = \left(\frac{Concentration\ of\ PTEs\ in\ aerial\ biomass\ (mg\ kg^{-1} dry\ weight)}{Total\ concentration\ of\ PTEs\ in\ soil\ (mg\ kg^{-1} dry\ soil)} \right) \quad (1)$$

$$BAF_{DTPA} = \left(\frac{Concentration\ of\ PTEs\ in\ aerial\ biomass\ (mg\ kg^{-1} dry\ weight)}{DTPA - extractable\ concentration\ of\ PTEs\ in\ soil\ (mg\ kg^{-1} dry\ soil)} \right) \quad (2)$$

PTE uptake by the plant was also calculated as follows:

$$PTEUptake\left(\mu g pot^{-1}\right) = PTE\ concentration\ in\ aboveground\ biomass\left(\frac{mg}{kg}\right) Biomass\ yield\ (g) \quad (3)$$

2.4 Statistical Analysis

Primary and secondary data were analyzed using one-way ANOVA to identify statistically significant differences among treatments at the $p < 0.05$ followed by the Tukey's Post-hoc analysis. Statistical analysis was conducted using the IBM SPSS Statistics v.29 software package.

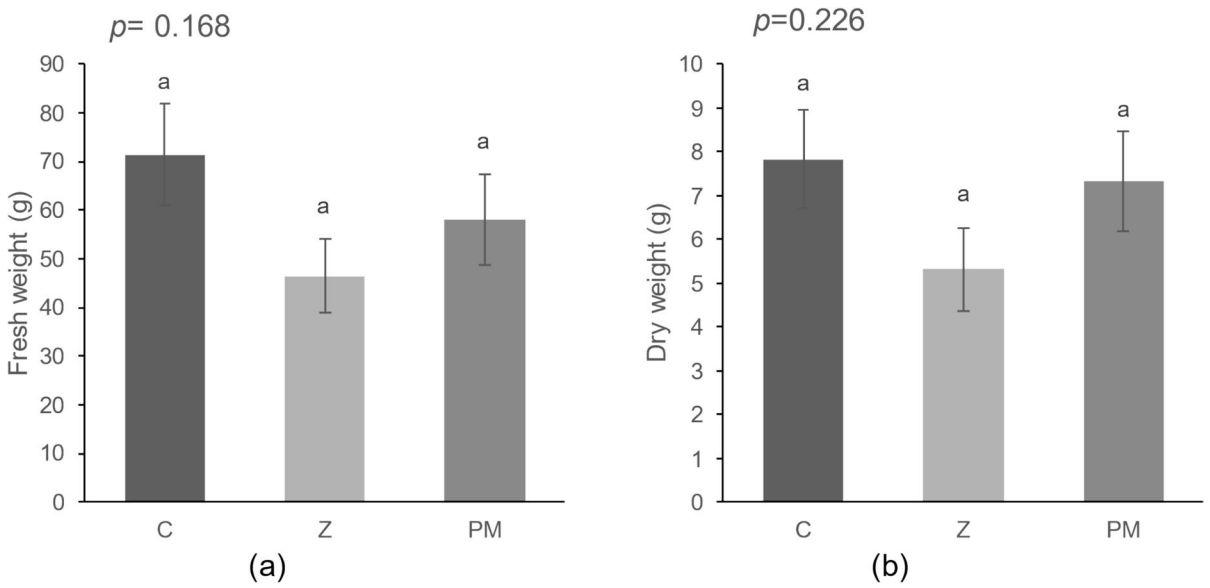


Fig. 1 Impact of soil amendments on (a) fresh and (b) dry weights of *Crithmum maritimum.* Values represent mean ± SE (n = 15). C: unamended control, Z: zeolite-added soil, PM: poultry manure-added soil. Different letters indicate significant differences at $p < 0.05$

3 Results

3.1 Plant Biomass Production

Fresh and dry weight of plants grown on different treatments are shown in Fig. 1. Fresh weight ranged from 46.5 g in the Z treatment to 71.4 g at C, while dry aboveground biomass ranged from 5.3 g (Z) to 7.8 g (C). However, no statistically significant differences were observed among treatments.

The dry over fresh weight percentage (% DW/FW) is commonly used to evaluate the moisture retention capacity of plant, as well as to assess their stability under different treatments. In particular, the C and Z treatments exhibited lower dry weight percentages, 11.2% and 11.4% respectively, indicating greater moisture retention (Fig. 2). In contrast, the PM treatment showed higher water loss, as indicated by the high difference between fresh and dry weight (12.7%). A significant difference was observed for PM compared to the other treatments.

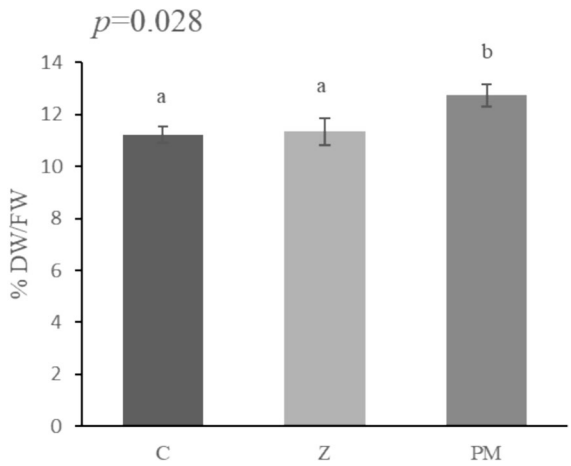


Fig. 2 The percentage of fresh weight relative to dry weight (% DW/FW) of *Crithmum maritimum* under different treatments. Values represent mean ± SE (n = 15). Different letters indicate significant differences among treatments ($p < 0.05$). C: unamended control, Z: zeolite-added soil, PM: poultry manure-added soil

3.2 Soil Properties after the Amendment of Zeolite and Poultry Manure

3.2.1 Availability of PTEs in Soil

The concentrations of PTEs in the soil samples were determined both as pseudo-total (through digestion with aqua regia) and as bioavailable (through extraction with DTPA). The corresponding concentrations are summarized in Table 2.

Table 2 Pseudo-total (aqua regia) and DTPA-extractable concentrations of Cd, Pb, Zn, and Cu in the three treatments: C = control (no amendments), Z = zeolite added to soil, PM = poultry manure added to soil (mg·kg^{-1} dry soil)

	Cd (mg kg^{-1})	Cu (mg kg^{-1})	Pb (mg kg^{-1})	Zn (mg kg^{-1})
Pseudo-total				
C	39.59 ± 1.13	166.01 ± 1.77	7884.00 ± 56.7	6458.00 ± 51.4
Z	38.50 ± 1.02	168.02 ± 1.36	7800.00 ± 32.4	6470.00 ± 15.7
PM	37.20 ± 0.39	165.60 ± 1.04	7890.50 ± 22.0	6445.50 ± 11.8
Sig	$p = 0.186$ (NS)	$p = 0.685$ (NS)	$p = 0.213$ (NS)	$p = 0.727$ (NS)
DTPA				
C	9.55 ± 1.26	1.73 ± 0.22	682.19 ± 63.48 ^{b}	190.61 ± 21.30
Z	10.57 ± 1.21	1.07 ± 0.16	616.42 ± 27.59 ^{ab}	166.34 ± 7.35
PM	8.96 ± 1.14	1.02 ± 0.27	490.23 ± 66.09 ^{a}	191.81 ± 25.08
Sig	$p = 0.235$ (NS)	$p = 0.080$ (NS)	$p = 0.041$*	$p = 0.593$ (NS)

Values are expressed as mean ± SE (n = 5). Treatments sharing the same letter do not differ significantly (One-Way ANOVA with Tukey's post-hoc test). * Significant at the level of $p < 0.05$. NS = Non-significant

The concentrations of DTPA-extractable elements exhibited variation across the treatments, as presented in Fig. 3. Regarding Cd concentrations, although no statistically significant differences were observed, the Z treatment exhibited a higher mean value (10.67 mg kg^{-1}) compared to the C (9.51 mg kg^{-1}), and the PM (8.96 mg kg^{-1}). The concentration of Cu in soil was 1.73 mg kg^{-1} in the C treatment, while the Z and PM treatments showed lower values of 1.07 mg kg^{-1} and 1.02 mg kg^{-1}, respectively. However, these differences were not significantly different. In contrast, statistically significant variations among treatments were observed for Pb ($p = 0.041$). The highest Pb levels were observed at C (682.19 mg kg^{-1}), followed by the Z treatment (614.42 mg kg^{-1}), while the PM treatment exhibited the lowest concentration (490.23 mg kg^{-1}). The Z treatment showed no statistically significant difference from either the control or the PM in this regard. For Zn, the concentrations were 190.61 mg kg^{-1} in the C, 166.34 mg kg^{-1} in the Z treatment, and 191.81 mg kg^{-1} in the PM treatment, but no statistically significant differences were observed among these treatments.

3.3 PTE Concentrations in Plant Aerial Biomass

The Cd concentration in the aboveground biomass of *C. maritimum* showed significant differences among treatments (Fig. 4). The lowest value (0.83 mg kg^{-1}) was observed at C, while higher concentrations were recorded in the Z and PM treatments, reaching 2.05 mg kg^{-1} and 1.46 mg kg^{-1}, respectively. The application of zeolite resulted in an increase in Cd concentration in the aerial parts of the plant by 1.3 units compared to the C ($p < 0.05$). The highest Cu concentration was found in the PM treatment (3.88 mg kg^{-1}), while similar values were recorded for the Z and the C treatments (2.13 and 1.85 mg kg^{-1}, respectively). A significant difference was noted only between the PM treatment and the others. In the case of Pb, although numerical variations were observed, no significant differences among treatments were detected. The recorded concentrations were 30.71 mg kg^{-1} at C, 86.67 mg kg^{-1} at Z, and 46.80 mg kg^{-1} at PM. Similarly, no significant differences were found for Zn, with concentrations ranging from 41.26 mg kg^{-1} in the PM treatment to 49.82 mg kg^{-1} in the C treatment.

3.4 Bioaccumulation Factor (BAF)

The PTE transfer factor from soil to aerial parts of the plant, known as bioaccumulation factor (BAF), is shown in Table 3. For Cd, the BAF_{DTPA} ranged from 0.091 in the C treatment to 0.102 and 0.129 in the Z and PM treatments, respectively. The C treatment exhibited a significantly lower BAF compared to the amended treatments, while the difference between Z and PM treatments was not significant. The corresponding BAF_{total} values were much lower (0.021, 0.053, and 0.039 for C, Z, and PM, respectively). For Cu, significant differences were identified among treatments, with the PM treatment

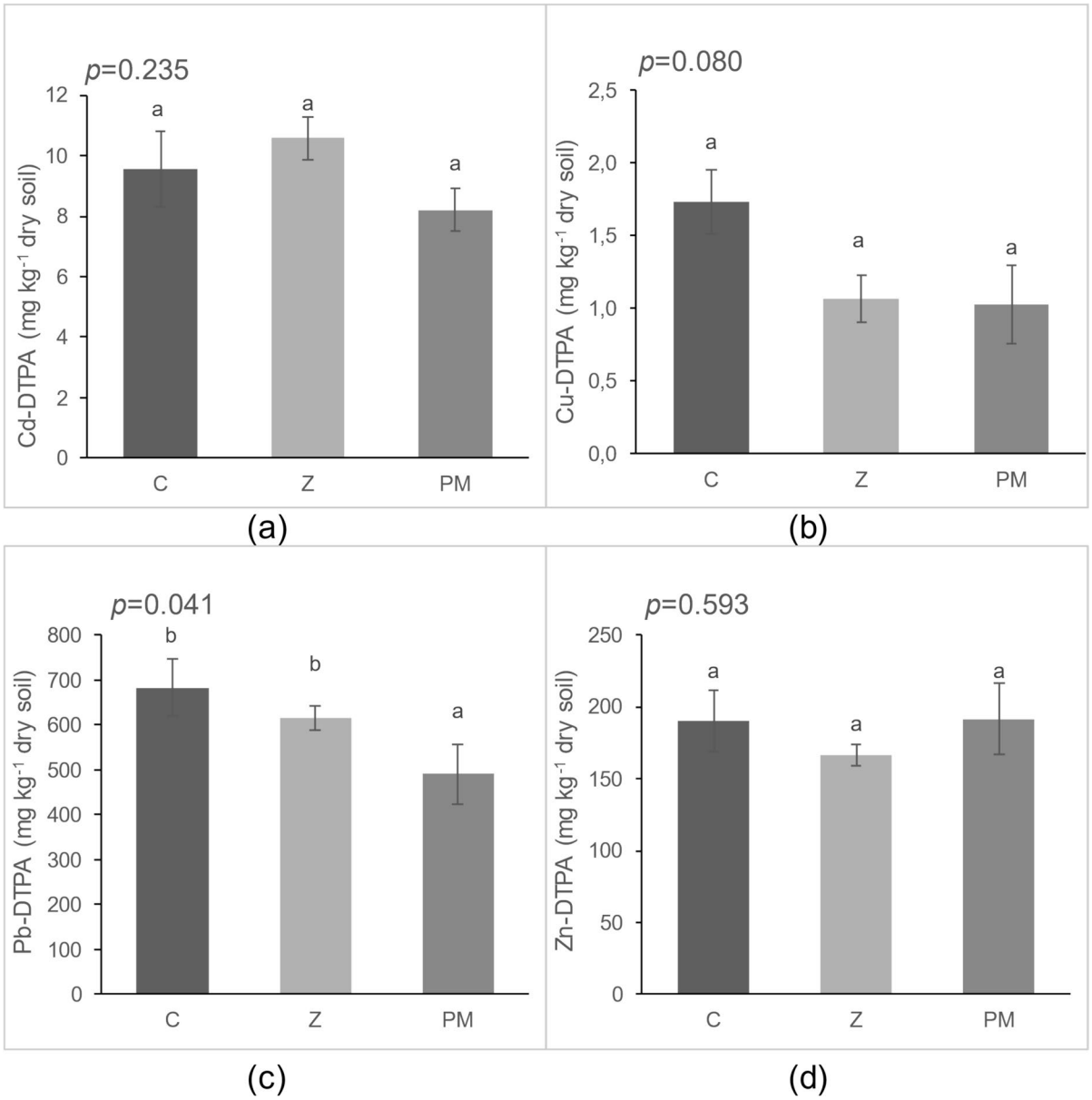


Fig. 3 DTPA-extractable concentrations of **a** Cd, **b** Cu, **c** Pb, and **d** Zn in soil under each treatment. Values represent mean ± SE (n = 5). Different letters indicate significant differences among treatments ($p < 0.05$). C: unamended control, Z: zeolite-added soil, PM: poultry manure-added soil

showing the highest BAF value (5.367), followed by Z (2.298) and C (1.145). Similarly, BAF_{total} values increased from 0.011 at C to 0.013 and 0.024 at PM, confirming the trend. In the case of Pb, the BAF_{DTPA} values were 0.046 (C), 0.139 (Z), and 0.105 (PM); as for BAF_{total} values raged from 0.004 to 0.011, with no significant variations among treatments. Similar results were found for Zn, where BAF_{DTPA} values were 0.257 in the C, 0.295 in the Z treatment, and 0.235 in the PM treatment, and the BAF_{total} values were 0.008, 0.007, and 0.006 for C, Z, and PM, respectively, also without significant differences.

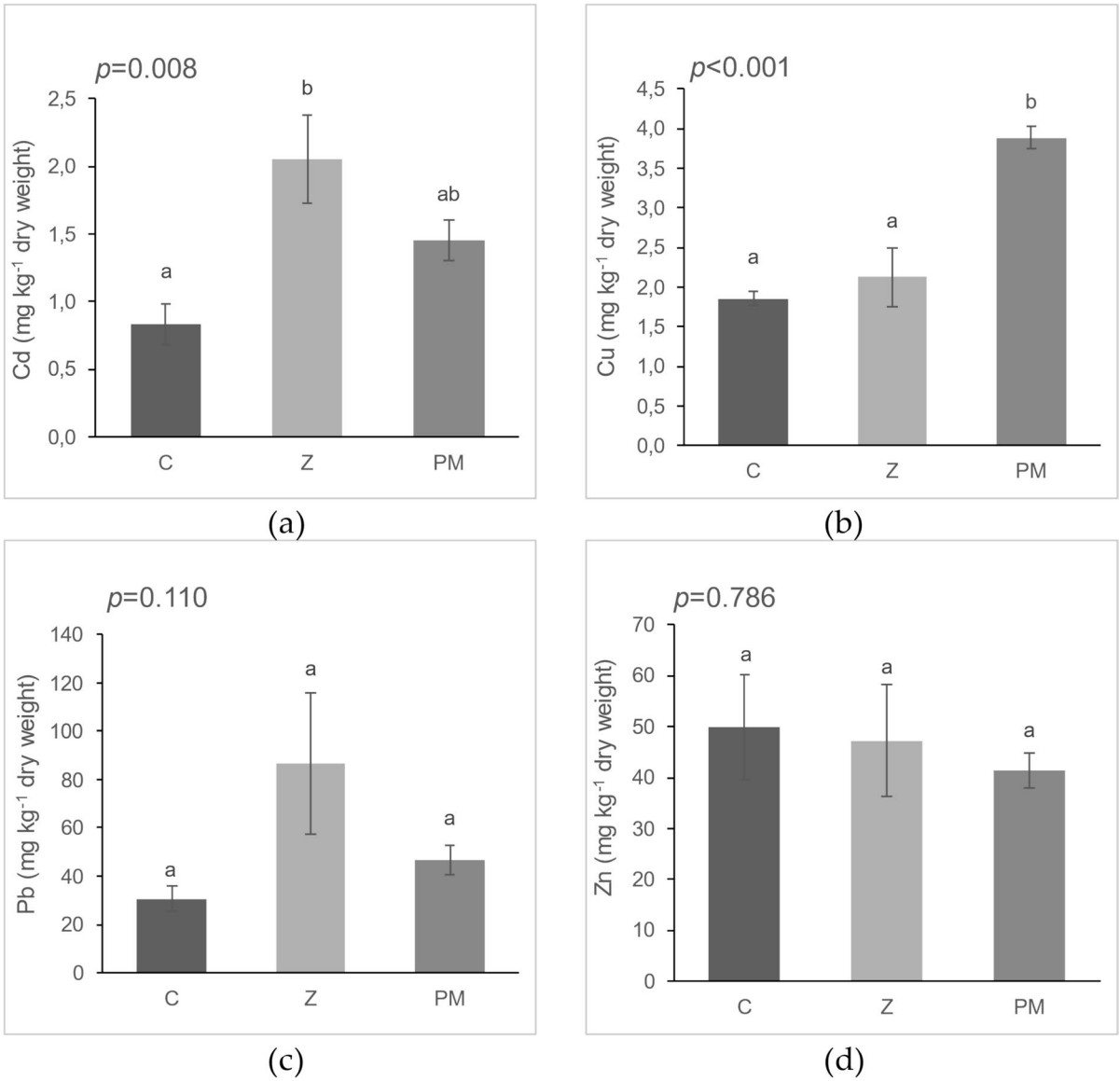


Fig. 4 Concentrations of (**a**) Cd, (**b**) Cu, (**c**) Pb, and (**d**) Zn in the aerial biomass of *Crithmum maritimum* across treatments. Values represent mean ± SE (n = 5). Different letters above the bars indicate significant differences among treatments ($p < 0.05$). C: unamended control, Z: zeolite-added soil, PM: poultry manure-added soil

3.5 Uptake of PTEs in the Aboveground Biomass

The assessment of PTE uptake through aboveground biomass revealed no statistically significant differences among treatments for the elements Cd, Cu, Pb, and Zn (Table 4). These findings suggest that, despite the influence of soil amendments on metal mobility and transport from soil to plant, the final uptake of PTE by the plants, relative to its biomass yield, was not significantly affected.

4 Discussion

Our findings were variable regarding the effect of different soil amendments on both the growth of *C.*

Table 3 Bioaccumulation factor (BAF) of *Crithmum maritimum* across treatments, calculated using total soil concentrations (conventional index, BAF_{total}) and DTPA-extractable soil, bioavailability-based index, BAF_{DTPA}

	Treatment	BAF_{total}	BAF_{DTPA}
Cd	C	0.021 ± 0.004^{a}	0.091 ± 0.019^{a}
	Z	0.053 ± 0.010^{b}	0.102 ± 0.030^{b}
	PM	0.039 ± 0.013^{ab}	0.129 ± 0.029^{b}
Sig		$p = 0.006$**	$p = 0.030$*
Cu	C	0.011 ± 0.001^{a}	1.145 ± 0.147^{a}
	Z	0.013 ± 0.002^{a}	2.298 ± 0.678^{a}
	PM	0.024 ± 0.002^{b}	5.367 ± 1.577^{b}
Sig		$p < 0.001$***	$p = 0.029$*
Pb	C	0.004 ± 0.001^{a}	0.046 ± 0.008^{a}
	Z	0.011 ± 0.004^{a}	0.139 ± 0.045^{a}
	PM	0.006 ± 0.004^{a}	0.105 ± 0.026^{a}
Sig		$p = 0.110$ (NS)	$p = 0.134$ (NS)
Zn	C	0.008 ± 0.002^{a}	0.257 ± 0.029^{a}
	Z	0.007 ± 0.002^{a}	0.295 ± 0.081^{a}
	PM	0.006 ± 0.001^{a}	0.235 ± 0.040^{a}
Sig		$p = 0.793$ (NS)	$p = 0.740$ (NS)

Values represent mean ± SE (n = 5). Different letters indicate significant differences among treatments ($p < 0.05$; one-way ANOVA followed by Tukey's post hoc test). C: unamended control, Z: zeolite-added soil, PM: poultry manure-added soil. *** Significant at the level of $p < 0.001$. ** Significant at the level of < 0.01. * Significant at the level of $p < 0.05$. NS = Non-significant

maritimum and the availability and mobility of PTEs from the soil to the plant. Although no significant differences in fresh and dry weight biomass were observed among treatments, the dry weight percentages exhibited significant differences indicating different moisture retention capacities. Specifically, the lower dry weight percentage values in the control and the treatment with added zeolite indicated increased moisture retention, whereas PM appeared to enhance water loss from the plants. In contrast, El-Samnoudi et al. (2019) reported an increase in relative water content (RWC%) after PM addition to *Sorghum bicolor* L. under drought conditions. This discrepancy highlights the need for further research using more specific physiological indicators. *C. maritimum* is classified as a facultative halophyte, which can grow in both saline and non-saline conditions, as salt is not necessary for optimal growth. Therefore, the cultivation under optimal irrigation with freshwater does not induce major changes in the plant physiology, but is rather associated with the absence of activation signal pathways for osmoregulation (Colak Esetlili et al., 2024; Gómez-Bellot et al., 2021).

Regarding PTEs, the concentration of available forms in the soil varied, with a significant reduction of Pb in the PM treatment. This finding aligns with a previous study, which demonstrated that PM application to soil cultivated with *Oryza sativa* L. significantly reduced the availability of Pb and Cd (Wan et al., 2020). Organic matter contained in PM or SOM, formed during its decomposition, (especially the soluble organic fractions, DOM), includes functional groups (mainly, carboxylic and hydroxyl) capable of binding metal ions, thereby affecting the availability and mobility of metals in soil (Zhu et al., 2023). Although there is a potentially significant role of DOM in the PM treatment, its elution was not directly assessed. However, the fact that SOC was found to have increased significantly over the control (Table 1) strengthens the likelihood of similarly significant increase in the active organic C portion, selectively described as DOC. As for other key soil parameters such as post-harvest pH and EC, their effect is

Table 4 Accumulation of PTEs (μg pot^{-1}) in aboveground biomass across different treatments (C: unamended control, Z: zeolite-added soil, PM: poultry manure-added soil)

Treatments	Cd (μg pot^{-1})	Cu (μg pot^{-1})	Pb (μg pot^{-1})	Zn (μg pot^{-1})
C	6.3 ± 1.1	16.1 ± 3.6	262.8 ± 70.7	435.3 ± 133.8
Z	11.6 ± 1.7	13.4 ± 3.2	507.5 ± 176.9	260.3 ± 42.3
PM	7.2 ± 2.0	18.4 ± 4.3	232.8 ± 61.9	190.9 ± 45.0
Significance	$p = 0.102$ (NS)	$p = 0.646$ (NS)	$p = 0.224$ (NS)	$p = 0.154$ (NS)

*Values represent mean ± SE (n = 5). C: unamended control, Z: zeolite-added soil, PM: poultry manure-added soil. NS = Non-significant

expected to be rather limited in influencing PTE (and particularly, Cd) availability. As for pH, it was found to have not been significantly affected by the addition of the tested materials, while the increase of EC in the PM treatment was slight, albeit significant (Table 1). Although this was the case here, future studies should include direct DOM measurements to better elucidate its potential role in PTE mobility. In contrast, the addition of zeolite did not alter the concentration of PTEs in the soil. Similarly, another study involving a *Portulaca oleraceus* cultivar reported no change in Cd levels following zeolite application. For other metals such as Pb and Zn, the effect of zeolite was limited and only evident at high addition rates of 2% and 4% (Thalassinos et al., 2023a, 2023b). This is likely related to the selectivity of this material for different metal species and the fact that its effectiveness depends on soil conditions (Pratti et al., 2019).

Of particular interest is Cd, as it did not exhibit significant differences in bioavailable concentrations in the soil across treatments; yet it showed increased accumulation in the aboveground plant parts, notably in the zeolite treatment. This elevated Cd concentration in the plant is rather concerning, given that zeolite was expected to reduce the availability of the element. The amendments used (Z and PM) did not contain any Cd and had a neutral pH (≈7); this unexpected increase of Cd in the aboveground organs suggests that other mechanisms may be involved, such as changes in the rhizosphere. Previous studies have demonstrated that the efficacy of zeolite depends on several factors, such as the applied dose and the properties of the metal itself. For instance, Contin et al. (2019) reported a significant reduction in Cd levels only at a 10% zeolite addition, whereas lower application rates had no significant impact. It is thus likely that the improved soil conditions with added zeolite did not negatively affect plant growth, which may have contributed to higher metal accumulation. The use of zeolite has been shown to improve soil water retention capacity and water use efficiency by plants (Al-Busaidi et al., 2011). Improved water availability affects plant physiology by enhancing the transport of nutrients along with PTEs through xylem loading, as observed in the present study (Wegner, 2014). Copper accumulation in the aboveground biomass was increased at PM (3.88 mg kg^{-1}). Similarly, in a study applying compost consisting of a mixture of PM and other animal wastes combined with rice straw, significant elevations in Cu concentration were observed in both aerial and root tissues of *Brassica juncea* (Huang et al., 2020). However, it is notable that the concentration of Cd and Pb in the aerial plant parts across all treatments exceeded the maximum permissible limits established for edible vegetables by EU regulation (EC No 1881/2006), where the thresholds are at 0.05 mg kg^{-1} fresh weight for Cd and 0.3 mg kg^{-1} fresh weight for Pb. As the reported concentrations are expressed on a dry weight basis, conversion to fresh weight was performed using the experimentally determined dry matter content of each treatment. In the zeolite treatment, Cd and Pb concentrations reached 2.05 and 86.67 mg kg^{-1} DW, respectively, with a dry matter content of 11.4%. The corresponding fresh weight concentrations were 0.234 mg kg^{-1} and 9.88 mg kg^{-1} for Cd and Pb, respectively, still exceeding these limits. The fact that Cd and Pb exceeded the regulation limits are particularly important, given the edible nature of the plant; thus, its consumption could pose a risk to public health. Hence, in a scheme where this test plant is to be used in contaminated soil, its use as edible mass should certainly be avoided.

The bioaccumulation factor (BAF) confirmed the above findings, showing that the addition of both soil amendments led to elevated BAF_{DTPA} values for Cd relative to the control. The BAF_{total} values, although much lower, reflected the same trend indicating that Cd accumulation increased in amended soil but remained limited when considered against total soil concentrations. A plant is considered capable of taking up and accumulating toxic substances from soil when it has BAF values greater than unity (Kikis et al., 2024), a criterion that is conventionally applied to total soil-based indices. However, this interpretation is not directly applicable to DTPA-based BAF, which is used here solely as a comparative indicator of uptake from the bioavailable fraction. The BAF index for Cu increased markedly with the addition of PM ($BAF_{DTPA} > 5$), indicating a high uptake of this element by the plant from the bioavailable fraction. Although BAF_{total} values were below 0.03, the pattern confirmed enhanced accumulation in the PM treatment. Notably, even in the control treatment, where the BAF_{DTPA} was at its lowest values, the index was detectable, suggesting a baseline level of uptake of Cu regardless of soil amendment application. Consequently, while the PM amendment significantly

enhanced Cu mobility and subsequent uptake from the bioavailable fraction, the overall accumulation in plant tissues relative to the total soil content remained low. For Pb and Zn, although variations in BAF_{total} and BAF_{DTPA} values were observed, these differences were not significant either in soil and plant biomass or regarding their respective bioaccumulation indices. The limited solubility and mobility of Pb and Zn was not unexpected based on literature reports, and this explains their relative stability in soil and low availability under similar experimental conditions (Natasha et al., 2022; Rahman et al., 2024). Overall, higher BAF_{DTPA} values (e.g., Cu) indicate efficient accumulation from the bioavailable fraction, whereas lower BAF_{total} values (all PTEs), particularly falling below the threshold of 1, suggest a limited accumulation within the aboveground tissues.

It is important to note that, despite the observed effects of soil amendments on the availability of PTEs in the soil and their accumulation in the aboveground biomass, the total quantity of PTEs accumulated by the plant (i.e., total aboveground biomass load) did not differ significantly among treatments. This is likely due to the absence of significant variation in the plant biomass production across treatments. These results should be interpreted as an assessment of PTE accumulation in the aerial plant parts and changes in soil extractability, since root concentrations were not measured and the translocation factor (TF) could not be calculated. Future studies should include PTE concentrations in the roots to better clarify the distribution of metals within plants. Moreover, the observed responses may reflect a combination of soil amendment effects, nutrient inputs from the NPK solution, and rhizosphere-mediated processes rather than solely the immobilization of PTEs.

5 Conclusions

The application of soil amendments such as zeolite and PM modulated the behavior and mobility of PTEs in soil in a complex, element-specific manner. The effectiveness of these treatments was found to be dependent on the intended remediation objective. We found that in certain cases, such as that of Cd, the addition of zeolite may enhance, rather than mitigate, metal uptake by plants. On the contrary, the PM application significantly reduced the Pb availability in soil by 28% relative to the control. Although no improvement in biomass was observed, the plant retained its vigor, indicating an adaptive capacity. However, Cd and Pb concentrations exceeded in the aboveground biomass the European regulation limits for edible plants, limiting thus the use of *C. maritimum* as an edible plant in these environments. These findings highlight the need for further investigation to clarify the mechanisms governing PTE retention by soil and the effect of soil amendments, in order to evaluate the long-term stability in soil and environmental fate of PTEs. While this study focused on isolating the individual effects of zeolite and poultry manure to establish clear performance baselines, the potential synergistic effects of their combined application remain an intriguing path for further exploration. Future research could investigate whether a co-application strategy enhances nutrient use efficiency or PTE removal. Additionally, we recognize that the further examination of key soil parameters is essential to elucidate the factors that promote or limit the availability and mobility of PTEs in the soil–plant interface. A thorough understanding of the mechanisms on how soil amendments influence the fate of PTEs in soil and plants is critical for developing safe and effective management practices for crops cultivated under PTE stress conditions.

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References

Al-Busaidi, A., Yamamoto, T., Tanigawa, T, & Rahman, H. A. (2011). Use of zeolite to alleviate water stress on subsurface drip irrigated barley under hot environments. *Irrigation and Drainage, 60*(4), 473–480. https://doi.org/10.1002/ird.595

Ali, H., & Khan, E. (2019). Trophic transfer, bioaccumulation, and biomagnification of non-essential hazardous heavy metals and metalloids in food chains/webs—Concepts and implications for wildlife and human health. *Human and Ecological Risk Assessment: An International Journal, 25*(6), 1353–1376. https://doi.org/10.1080/10807039.2018.1469398

Angon, P. B., Islam, M. S., Das, A., Anjum, N., Poudel, A., & Suchi, S. A. (2024). Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain. *Heliyon, 10*(7), Article e28357. https://doi.org/10.1016/j.heliyon.2024.e28357

Antoniadis, V., Thalassinos, G., Levizou, E., Wang, J., Wang, S. L., Shaheen, S. M., & Rinklebe, J. (2022). Hazardous enrichment of toxic elements in soils and olives in the urban zone of Lavrio, Greece, a legacy, millennia-old silver/lead mining area and related health risk assessment. *Journal of Hazardous Materials, 434*, Article 128906. https://doi.org/10.1016/j.jhazmat.2022.128906

Ashim, A., Ismaiel, L., Fanesi, B., Nartea, A., Maoloni, A., Orhotohwo, O. L., Darko, H. S. O., Lucci, P., Aquilanti, L., Pacetti, D., Pino, R., Tundis, R., & Loizzo, M. R. (2025). Food-grade polar extracts from sea fennel (*Crithmum maritimum* L.) by-products: Unlocking potential for the food industry. *Foods, 14*(13), Article 2304. https://doi.org/10.3390/foods14132304

Commission of the European Communities. (2006). Commission regulation (EC) No 1881/2006 of 19 December 2006 setting maximum levels for certain contaminants in foodstuffs. *Official Journal of European Union, L364*, 5–24.

Caparrós, P. G., Ozturk, M., Gul, A., Batool, T. S., Pirasteh-Anosheh, H., Unal, B. T., Altay, V., & Toderich, K. N. (2022). Halophytes have potential as heavy metal phytoremediators: A comprehensive review. *Environmental and Experimental Botany, 193*, Article 104666. https://doi.org/10.1016/j.envexpbot.2021.104666

Colak Esetlili, B., Yildiz Aktas, L., Esetlili, M. T., Oztekin, T., Kılıc, C. C., & Kurucu, Y. (2024). Salinity tolerance mechanism of *Crithmum maritimum* L.: Implications for sustainable agriculture in saline soils. *Sustainability, 16*(18), Article 8165. https://doi.org/10.3390/su16188165

Contin, M., Miho, L., Pellegrini, E., Gjoka, F., & Shkurta, E. (2019). Effects of natural zeolites on ryegrass growth and bioavailability of Cd, Ni, Pb, and Zn in an Albanian contaminated soil. *Journal of Soils and Sediments, 19*(12), 4052–4062. https://doi.org/10.1007/s11368-019-02359-7

Correia, I., Antunes, M., Tecelão, C., Neves, M., Pires, C. L., Cruz, P. F., Rodrigues, M., Peralta, C. C., Pereira, C. D., Reboredo, F., & Campos, M. J. (2024). Nutritive value and bioactivities of a halophyte edible plant: *Crithmum maritimum* L. (Sea Fennel). *Plants, 13*(3), Article 427. https://doi.org/10.3390/plants13030427

El Rasafi, T., El Moukhtari, A., Farissi, M., Ziouti, A., Prasad, M. N. V., Oukarroum, A., & Haddioui, A. (2024). Soil amendments as promising strategies for phytomanagement of Cd contaminated soils. *Bio-organic amendments for heavy metal remediation* (pp. 499–513). Elsevier. https://doi.org/10.1016/B978-0-443-21610-7.00041-0

El-Samnoudi, I. M., Ibrahim, A. E. A. M., Abd El Tawwab, A. R., & Abd El-Mageed, T. A. (2019). Combined effect of poultry manure and soil mulching on soil properties, physiological responses, yields and water-use efficiencies of sorghum plants under water stress. *Communications in Soil Science and Plant Analysis, 50*(20), 2626–2639. https://doi.org/10.1080/00103624.2019.1671445

Giannakoula, A. E., Stefanakis, M. K., Papaioannou, C., Tsimpliaraki, S., Kaftantzi, S., Niniraki, A., & Gertsis, A. (2025). Mitigation of oxidative damage caused by salinity in the halophyte *Crithmum maritimum* L. via biostimulant-enhanced antioxidant activity. *Plants, 14*(24), Article 3788. https://doi.org/10.3390/plants14243788

Gómez-Bellot, M. J., Lorente, B., Ortuño, M. F., Medina, S., Gil-Izquierdo, Á., Bañón, S., & Sánchez-Blanco, M. J. (2021). Recycled wastewater and reverse osmosis brine use for halophytes irrigation: Differences in physiological, nutritional and hormonal responses of *Crithmum maritimum* and *Atriplex halimus* plants. *Agronomy, 11*(4), Article 627. https://doi.org/10.3390/agronomy11040627

Gong, Y., Zhao, D., & Wang, Q. (2018). An overview of field-scale studies on remediation of soil contaminated with heavy metals and metalloids: Technical progress over the last decade. *Water Research, 147*, 440–460. https://doi.org/10.1016/j.watres.2018.10.024

Grammenou, A., Petropoulos, S. A., Thalassinos, G., Rinklebe, J., Shaheen, S. M., & Antoniadis, V. (2023). Biostimulants in the soil–plant interface: Agro-environmental implications—A review. *Earth Systems and Environment, 7*(3), 583–600. https://doi.org/10.1007/s41748-023-00349-x

Hafeez, A., Rasheed, R., Ashraf, M. A., Qureshi, F. F., Hussain, I., & Iqbal, M. (2023). Effect of heavy metals on growth, physiological and biochemical responses of plants. *Plants and their interaction to environmental pollution* (pp. 139–159). Elsevier.

Huang, H., Luo, L., Huang, L., Zhang, J., Gikas, P., & Zhou, Y. (2020). Effect of manure compost on distribution of Cu and Zn in rhizosphere soil and heavy metal accumulation by *Brassica juncea*. *Water, Air, & Soil Pollution, 231*(5), 195. https://doi.org/10.1007/s11270-020-04572-4

Hudcová, B., Osacký, M., Vitkova, M., Mitzia, A., & Komárek, M. (2021). Investigation of zinc binding properties onto natural and synthetic zeolites: Implications for soil remediation. *Microporous and Mesoporous Materials, 317*, Article 111022. https://doi.org/10.1016/j.micromeso.2021.111022

Jiang, Y., Yang, W., Zhang, J., Liu, X., Jin, Y., Li, S., Qu, J., & Wang, W. (2024). Comparison of Pb adsorption and transformation behavior induced by chicken manure and its DOM in contaminated soil. *Journal of Environmental Chemical Engineering, 12*(6), Article 114327. https://doi.org/10.1016/j.jece.2024.114327

Khan, M. S. U., Afridi, N., Ritu, S. A., Shipar, S. I., Zaman, S. B., Hasan, N. T., ... & Imran, S. (2025). Enhancing root resilience through sustainable agriculture to mitigate heavy metal pollution and abiotic stresses in a changing climate. *Rhizosphere*, 101251. https://doi.org/10.1016/j.rhisph.2025.101251

Kikis, C., Thalassinos, G., & Antoniadis, V. (2024). Soil phytomining: Recent developments—A review. *Soil Systems, 8*(1), Article 8. https://doi.org/10.3390/soilsystems8010008

Kikis, C., Gannoulis, K. D., Thalassinos, G., Rinklebe, J., Shaheen, S. M., & Antoniadis, V. (2025). From phytoremediation to phytomanagement: The utilization of industrial crops for the restoration of contaminated soils–A review. *Journal of Environmental Chemical Engineering*, 120581. https://doi.org/10.1016/j.jece.2025.120581

Lindsay, W. L., & Norvell, W. (1978). Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Science Society of America Journal, 42*(3), 421–428. https://doi.org/10.2136/sssaj1978.03615995004200030009x

Martins-Noguerol, R., Rico-Jiménez, D., Matias, L., Perez-Ramos, I. M., Moreira, X., Francisco, M., Álvarez, R., Gandullo, J., Pedroche, J., Martínez-Force, E., Moreno-Pérez, A. J., & Cambrolle, J. (2024). Effects of drought and increased temperature on phytochemical traits of the edible halophyte *Crithmum maritimum*: Perspectives for future climatic scenarios. *Environmental and Experimental Botany, 226*, Article 105924. https://doi.org/10.1016/j.envexpbot.2024.105924

Mensah, A. K., Sekyi-Annan, E., & Amoakwah, E. (2025). Availability and mobilisation of potentially harmful elements in contaminated mining sites: A systematic review of using soil amendments and plants for remediation. *Journal of Trace Elements and Minerals, 12*, Article 100234. https://doi.org/10.1016/j.jtemin.2025.100234

Mensah, A. K., & Amoakwah, E. (2024). Soil biogeochemical factors influencing mobilization of toxic. *Perspectives and Insights on Soil Contamination and Effective Remediation Techniques*, *41*. https://doi.org/10.5772/intechopen.1005487

Motlagh, A. H., Hassanlourad, M., Hosseinzadeh, M., & Bakhshy, M. (2025). Dynamic and microstructural analysis of zeolite-stabilized heavy metal contaminated clayey sand. *Environmental Earth Sciences, 84*(6), 155. https://doi.org/10.1007/s12665-025-12178-4

Natasha, N., Shahid, M., Bibi, I., Iqbal, J., Khalid, S., Murtaza, B., Bakhat, H. F., Farooq, A. B. U., Amjad, M., Hammad, H. M., & Arshad, M. (2022). Zinc in soil-plant-human system: A data-analysis review. *Science of the Total Environment, 808*, Article 152024. https://doi.org/10.1016/j.scitotenv.2021.152024

Naz, M., Dai, Z., Hussain, S., Tariq, M., Danish, S., Khan, I. U., Qi, S., & Du, D. (2022). The soil pH and heavy metals revealed their impact on soil microbial community. *Journal of Environmental Management, 321*, Article 115770. https://doi.org/10.1016/j.jenvman.2022.115770

Ndour, P. M. S., Langrand, J., Fontaine, J., & Lounès-Hadj Sahraoui, A. (2025). Exploring the significance of different amendments to improve phytoremediation efficiency: Focus on soil ecosystem services. *Environmental Science and Pollution Research, 32*(2), 485–513. https://doi.org/10.1007/s11356-024-35660-1

Ortega, R., Domene, M. A., Soriano, M., Sánchez-Marañón, M., Asensio, C., & Miralles, I. (2020). Improving the fertility of degraded soils from a limestone quarry with organic and inorganic amendments to support vegetation restoration with semiarid Mediterranean plants. *Soil and Tillage Research, 204*, Article 104718. https://doi.org/10.1016/j.still.2020.104718

Panda, A., Fatnani, D., & Parida, A. K. (2025). Uptake, impact, adaptive mechanisms, and phytoremediation of heavy metals by plants: Role of transporters in heavy metal sequestration. *Plant Physiology and Biochemistry*. https://doi.org/10.1016/j.plaphy.2025.109578

Pandey, V. C., Patel, D., Maiti, D., & Singh, D. P. (2020). Case studies of perennial grasses: Phytoremediation (holistic approach). Phytoremediation potential of perennial Grasses, 337–349

Pratti, L. M., Reis, G. M., dos Santos, F. S., Gonçalves, G. R., Freitas, J. C., & de Pietre, M. K. (2019). Effects of textural and chemical properties of β-zeolites on their performance as adsorbents for heavy metals removal. *Environmental Earth Sciences, 78*(17), Article 553. https://doi.org/10.1007/s12665-019-8568-6

Rahman, S. U., Qin, A., Zain, M., Mushtaq, Z., Mehmood, F., Riaz, L., Naveed, S., Ansari, M. J., Saeed, M., Ahmad, I., et al. (2024). Pb uptake, accumulation, and translocation in plants: Plant physiological, biochemical, and molecular response: A review. *Heliyon, 10*, Article e27724. https://doi.org/10.1016/j.heliyon.2024.e27724

Rowell, D. L. (2014). *Soil science: Methods & applications*. Routledge.

Saleh, Q. O., & Al Bahrani, I. Q. (2023, December). Effect of Zeolite, Poultry Manure and Mineral Fertilizers in Availability of NPK in Calcareous Soil. In *IOP conference series: earth and environmental science* (Vol. 1262, No. 8, p. 082002). IOP Publishing. https://doi.org/10.1088/1755-1315/1262/8/082002

Song, P., Xu, D., Yue, J., Ma, Y., Dong, S., & Feng, J. (2022). Recent advances in soil remediation technology for heavy metal contaminated sites: A critical review. *Science of the Total Environment, 838*, Article 156417. https://doi.org/10.1016/j.scitotenv.2022.156417

Thalassinos, G., Levizou, E., & Antoniadis, V. (2023). Can soil improvers (biochar, compost, insect frass, lime, and zeolite) achieve phytostabilization of potentially toxic elements in heavily contaminated soil with the use of purslane (*Portulacaoleracea*)? *Agronomy, 13*(11), Article 2827. https://doi.org/10.3390/agronomy13112827

Thalassinos, G., Petropoulos, S. A., Grammenou, A., & Antoniadis, V. (2023). Potentially toxic elements: A review on their soil behavior and plant attenuation mechanisms against their toxicity. *Agriculture, 13*(9), 1684. https://doi.org/10.3390/agriculture13091684

Viana, R. D. S. R., Chagas, J. K. M., Paz-Ferreiro, J., & de Figueiredo, C. C. (2025). Enhanced remediation of heavy metal-contaminated soils using biochar and zeolite combinations with additives: A meta-analysis. *Environmental Pollution, 367*, Article 125617. https://doi.org/10.1016/j.envpol.2024.125617

Wan, Y., Huang, Q., Wang, Q., Yu, Y., Su, D., Qiao, Y., & Li, H. (2020). Accumulation and bioavailability of heavy metals in an acid soil and their uptake by paddy rice under continuous application of chicken and swine manure. *Journal of Hazardous Materials, 384*, Article 121293. https://doi.org/10.1016/j.jhazmat.2019.121293

Wegner, L. H. (2014). Interplay of water and nutrient transport: A whole-plant perspective. *Progress in Botany, 76*, 109–141.

Wu, S., Tursenjan, D., & Sun, Y. (2023). Impact of compost methods on humification and heavy metal passivation during chicken manure composting. *Journal of Environmental Management, 325*, Article 116573. https://doi.org/10.1016/j.jenvman.2022.116573

Xu, D. M., Fu, R. B., Wang, J. X., Shi, Y. X., & Guo, X. P. (2021). Chemical stabilization remediation for heavy metals in contaminated soils on the latest decade: Available stabilizing materials and associated evaluation methods-a critical review. *Journal of Cleaner Production, 321*, Article 128730. https://doi.org/10.1016/j.jclepro.2021.128730

Xu, W., Jin, Y., & Zeng, G. (2024). Introduction of heavy metals contamination in the water and soil: A review on source, toxicity and remediation methods. *Green Chemistry Letters and Reviews, 17*(1), Article 2404235. https://doi.org/10.1080/17518253.2024.2404235

Ye, L., Gao, G., Li, F., Sun, Y., Yang, S., Qin, Q., Wang, J., Bai, N., Xue, Y., & Sun, L. (2025). A comprehensive review on biochar-based materials for the safe utilization and remediation of heavy metal-contaminated agricultural soil and associated mechanisms. *Journal of Environmental Chemical Engineering*. https://doi.org/10.1016/j.jece.2025.116179

Zhakypbek, Y., Kossalbayev, B. D., Belkozhayev, A. M., Murat, T., Tursbekov, S., Abdalimov, E., Pashkovskiy, P., Kreslavski, V., Kuznetsov, V., & Allakhverdiev, S. I. (2024). Reducing heavy metal contamination in soil and water using phytoremediation. *Plants, 13*(11), Article 1534. https://doi.org/10.3390/plants13111534

Zhang, P., Yang, M., Lan, J., Huang, Y., Zhang, J., Huang, S., Yang, Y., & Ru, J. (2023a). Water quality degradation due to heavy metal contamination: Health impacts and eco-friendly approaches for heavy metal remediation. *Toxics, 11*(10), 828. https://doi.org/10.3390/toxics11100828

Zhang, W., Xin, C., & Yu, S. (2023b). A review of heavy metal migration and its influencing factors in karst groundwater, Northern and Southern China. *Water, 15*(20), Article 3690. https://doi.org/10.3390/w15203690

Zheng, X., Lin, H., Du, D., Li, G., Alam, O., Cheng, Z., Liu, X., Jiang, S., & Li, J. (2024). Remediation of heavy metals polluted soil environment: A critical review on biological approaches. *Ecotoxicology and Environmental Safety, 284*, Article 116883. https://doi.org/10.1016/j.ecoenv.2024.116883

Zhu, Y., Guan, Q., Kong, L., Yang, R., Wang, W., Jin, Y., Liu, X., & Qu, J. (2023). Overlooked mechanism of Pb immobilization on montmorillonite mediated by dissolved organic matter in manure compost. *Environmental Pollution, 316*, Article 120706. https://doi.org/10.1016/j.envpol.2022.120706

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