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Do Soil Amendments have a Significant Influence on Element Accumulation in Plant Organs? A Meta-analysis

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Abstract

Soil amendments generally impact overall soil health and phytoremediation strategies; however, their effects on element accumulation vary and are inconsistent. This meta-analysis examined data from nine independent studies published between 1975 and 2024 to assess how amendments such as manure, sewage sludge, compost, biochar, peat moss, and lime influence metal accumulation in plants compared to plants grown in unamended soils. Hedges' *g* values were calculated using a random effects model to compare metal accumulation related to amendment use. Additionally, linear regression analysis evaluated how pH and exposure time affect element accumulation. Results showed that amendments significantly reduced overall plant accumulation of As ($p < 0.001$), Cd ($p < 0.001$), Cr ($p = 0.005$), Cu ($p = 0.004$), Pb ($p < 0.001$), and Zn ($p = 0.013$). For the plant-organ comparison, only root arsenic concentrations were significantly lowered by amendments. Exposure time was positively correlated with the accumulation of Cd, Cu, Mn, Ni, Pb, and Zn in whole plants during amendment application. Regarding pH, higher levels increased root arsenic concentrations but decreased levels of Cd, Cr, and Ni in leaves and roots, as well as Cu in leaves, and Mn and Pb in roots. In conclusion, although amendments can reduce overall plant metal accumulation, this effect is influenced by multiple factors; exposure time, soil pH, and other variables such as amendment type and decomposition stage, all affect metal mobility in various ways and account for the high variability observed across studies.

Keywords Phytoremediation · Metal(loid) partitioning · Soil amendments · Bioavailability · Soil pH effect on metal uptake · Meta-regression

Introduction

Soil is an essential resource for the sustaining of life as we know it, as the growth of most plants depends on it. To support plant growth and development, soil must have specific properties, including sufficient nutrient content and availability. Nutrients like nitrogen (N), phosphorus (P), and some metals like copper (Cu) and nickel (Ni) are necessary for an organism's healthy growth and development and cannot be replaced by other components (Brown et al. 2022). Therefore, a deficiency of nutrients in soil will impair the growth of plants and can cause adverse effects like the reduction of root size or overall biomass. Additionally, a nutrient deficiency can also reduce microbial activity in soil, which further affects nutrient cycling and the efficiency of nutrient absorption by plants (Suman et al. 2022; Wang et al. 2024). Essential metals are nutrients that are necessary for an organism's growth and development; however, excess concentration of one or more essential nutrients can also adversely affect plant growth (Otunola et al. 2023). Heavy metals pose particular risks; for instance, Ni presents toxicity even at 20–30 mg kg^{-1} leaf concentrations, or Cu with toxicity at 15–30 mg kg^{-1} concentrations. These micronutrients are needed only in small quantities, and in the concentrations mentioned above, they can reduce yield by more than 10% (Shabbir et al. 2020; Iqbal Khan et al. 2023).It is also important to consider environmental guideline concentrations, like agricultural soil (e.g., CCME

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1999) and drinking water recommendations (World Health Organization 2022); for example Cu in soil and water must not exceed 63 mg kg^{-1} and 2 mg L^{-1} respectively. Regarding nickel, concentrations should not exceed 45 mg kg^{-1} and 0.07 mg L^{-1} for soil and water respectively. Above these levels, these metals can pose risk to plants, animals, and human health.

The presence of other components that are not necessary for organisms is also a key factor in soil quality. This includes heavy metals like cadmium (Cd), lead (Pb), and chromium (Cr), which are some of the most common soil contaminants. These metals can enter the soil from both natural and human sources. Naturally, they are released from igneous and sedimentary rocks through weathering. However, human activities are the main cause of heavy metal pollution, and soils near industries or mines often have higher metal levels. Industrial processes such as burning fossil fuels and coal, waste incineration, battery manufacturing, mining, textile production, and tanning are major emitters of heavy metals. These sources pollute soils either through the deposition of pollutants or from improper wastewater disposal. Additionally, the use of pesticides and fertilizers in agriculture also introduces these pollutants into the soil (Angon et al. 2024).

Some toxic metals may enter soil through the same sources. Lead sources include mining, burning coal, and pesticides (Gul et al. 2020). In the case of cadmium, sources include the PVC industry, phosphate-based fertilizers, electronics manufacturing, and emissions from incineration and industrial processes. For arsenic, its most common sources include industrial dust and waste, smelting, mining, and the use of arsenic-based pesticides and phosphate fertilizers (Angon et al. 2024).

Non-essential metals usually cause toxicity at relatively low concentrations in plant tissues. For example, lead is toxic at tissue concentrations as low as 0.5–28.5 mg kg^{-1}, causing reduced chlorophyll and significant yield losses (Hong et al. 2008; Gul et al. 2020). Cadmium at 3–30 mg kg^{-1} impairs photosynthesis and causes chlorosis (Goncharuk and Zagoskina 2023). For arsenic, critical concentrations vary between 21 and 325 mg kg^{-1}, causing retarded germination and growth, along with chlorosis (Seraj and Rahman 2018). In addition to their toxic effects on plants, it is important to note that metals of both essential (e.g., nickel) and non-essential (e.g., cadmium, chromium, lead) nature are classified as possible human carcinogens by the International Agency for Research on Cancer (Suman et al. 2022). Therefore, regulating metal uptake by plants is crucial, not only to minimize their adverse effects on plant health and crop productivity but also to mitigate potential health risks to humans through the food chain.

Plants exhibit different physiological responses to high metal concentrations in soil. Although many plant species suffer adverse effects from exposure, some can accumulate metals in their tissues without displaying significant toxicity symptoms. This trait and its mechanisms have been recognized for decades, leading to the development of a group of technologies known as phytoremediation (Kafle et al. 2022). Phytoremediation refers to the use of plants and agronomic strategies to remove, immobilize, or transform environmental pollutants. It is an alternative option for addressing the critical issue of soil pollution and degradation, as it supports the cleaning up of soil for further food production or ecological restoration by removing pollutants in a less invasive and more environmentally friendly manner than other conventional methods (e.g., soil washing) (Li et al. 2019).

In the literature, three main techniques of phytoremediation are often highlighted: phytostabilization, phytovolatilization, and phytoextraction. Phytostabilization involves lowering metal mobility in the rhizosphere through mechanisms such as metal precipitation, complexation, or physical adsorption by plant roots. Conversely, phytovolatilization means plants absorb pollutants through their roots, then release them into the atmosphere via transpiration. This technique should only be applied to contaminants that are less harmful in the air than in the soil. Finally, phytoextraction is the most commonly addressed method; it relies on the extraction of pollutants from the environment through their absorption by plant roots, followed by their movement and translocation to aerial tissues without causing significant toxicity symptoms (Wang et al. 2021; Aryal 2024).

Some plants, known as hyperaccumulators, can have highly elevated tissue metal concentrations without showing toxicity symptoms, thereby contributing significantly to the removal of pollutants from the environment. This capacity is measured by the bioaccumulation factor (BAF) values, with a value higher than 1 indicating concentrations higher in individuals than in soils. According to Ali et al. (2022), *Brassica* species, particularly *Brassica juncea*, exhibited BAF ranging from 2 to 5 for Cd, Pb, Cr, and Ni over 60 days. Another well-known hyperaccumulator is *Helianthus annuus* (sunflower). A study by Zhao et al. (2023) demonstrated that sunflowers accumulated high concentrations of cadmium from soil, with a BAF of approximately 2. Individuals were also effective at accumulating zinc, reaching a BAF of around 3. As it was mentioned, the presence of potential polluting sources (e.g., industries, mines) affects the quality of the surrounding soils. However, this is not the only important aspect; some soils may be more prone to the effects of pollution than others, depending on their physico-chemical characteristics. Sandy soils and soils with low organic matter content tend to be more vulnerable due to their low buffering capacity and low sorption, which can allow the leaching and mobility of pollutants. While clay soils with high organic matter content may be more effective at immobilizing metals (Tang et al. 2019; Zhang et al. 2023). This is why it is essential to study the role of organic amendments on metal transport in the soil-plant continuum.

Organic amendments like manure, compost, biochar, and coconut coir are often used in soil to improve its properties and plant yield; this can be done by increasing or decreasing unfavorable soil pH, increasing the organic matter and/or nutrient content, improving soil structure, and supporting water holding capacity in soil (Clemente et al. 2006; Angelova et al. 2017; Li et al. 2023). Chemical or physical amendments like lime, citric acid, or fertilizers offer similar benefits but tend to improve one specific factor, like pH or nutrient content. From a different perspective, amendments can also be used to indirectly enhance soil quality by optimizing phytoremediation (here: phytoextraction), as enriching the pool of nutrients and enhancing their bioavailability for plants also affects metal accumulation patterns. Depending on the type and concentration of the amendment and its interrelation with soil properties, the effects on phytoextraction can be diverse. For instance, amendments like citric acid or EDTA (Gul et al. 2020), make metals more available by decreasing soil pH, which enhances the water solubility of metals; on the other hand, lime amendment immobilizes metals by increasing pH or forming stable insoluble compounds with metals (Clemente et al. 2006; Li et al. 2023).

Organic amendments have diverse roles in metal phytoremediation. For example, biochar from different sources behaves differently: *Miscanthus* straw biochar helps immobilize Cd, Zn, and Pb, while bamboo biochar increases Cd uptake in *Salix psammophila* (Li et al. 2023). Some studies found that biochar can enhance metal uptake due to increased plant biomass from the favorable conditions it provides to the soil (El-Naggar et al. 2024). Similarly, the effects of compost are mixed. For instance, while higher compost content in rapeseed increased metal (Pb, Zn, and Cd) accumulation in pods and reduced it in roots and stems (Angelova et al. 2017), other studies suggest that compost can increase metal uptake through plant biomass increase, as mentioned before with biochar, but also immobilize metals through complexation, precipitation, and sorption (Shrestha et al. 2019). These conflicting results show the complexities of using organic amendments in phytoextraction and indicate the need for further evaluations and complementary assessments.

This paper aims to determine the role of soil amendments in influencing element accumulation in terrestrial plant species' plant organs using the toolbox of meta-analysis. This literature-based evaluation aims to specify (i) how metals and metalloids accumulate in the leaf, stem, and root of species from amended soils compared to unamended conditions, (ii) how exposure time affects the element accumulation schemes in individual element-plant organ relations, and (iii) how soil pH influences the concentration patterns in organs under amendment application.

Materials and Methods

Comprehensive data collection was performed in the Web of Science Core Collection database between 1975 and 2024. This search used the following topic terms and operators: *TOPIC* = (soil amendment) AND *TOPIC* = (heavy metal) AND *TOPIC* = (phytoremediation). A publication (research article or book chapter) satisfied the inclusion criteria of the meta-analysis if it presented metal or metalloid (hereinafter: element) concentrations (given in mg or g kg^{-1}) in one or more plant organs (specified as leaf, stem, root) of any terrestrial plant species growing in soils amended and unamended (control) by soil amendments (manure, sewage sludge, compost, biochar, peat moss, lime). Appropriate papers also had to report names of plant species with amendment type and concentration; however, after the data preparations, these factors could not be involved in the analyses due to low sample sizes for particular element-plant species-amendment comparisons. Besides this limitation of the study, the interpretation and discussion of the results strongly rely on the specific information of the included publications. The documents' references fulfilling the criteria above were also revised as a secondary scan for grey literature. Data was extracted from the text, figures, and tables of publications. The selection process of the appropriate papers is demonstrated in Fig. 1.

During the identification phase, a term and operator-based Web of Science search was conducted, yielding 971 publications. As complementary research, the above term combination was applied as a Google search engine input, yielding 114 studies from various sources (e.g., official publisher websites). During the screening phase, as some items were redundant after merging the above two lists of publications, duplicates were removed, leaving 1033 studies. These were subject to thorough title and abstract evaluation; 97 records were excluded for being out of the targeted topic of this analysis. In the eligibility evaluation, the remaining 936 publications were read by the authors of this paper. This step led to the conclusion that, despite focusing on phytoremediation-related aspects, 481 items lacked addressing one or more cornerstones of this study (e.g., exclusion of soil amendments, undisclosed concentration data, and deficient methodology). In the last phase, the 455 publications yielded were assessed again, and the above-introduced inclusion criteria on data prerequisites were applied. According to the previous, nine papers were selected for the analysis.

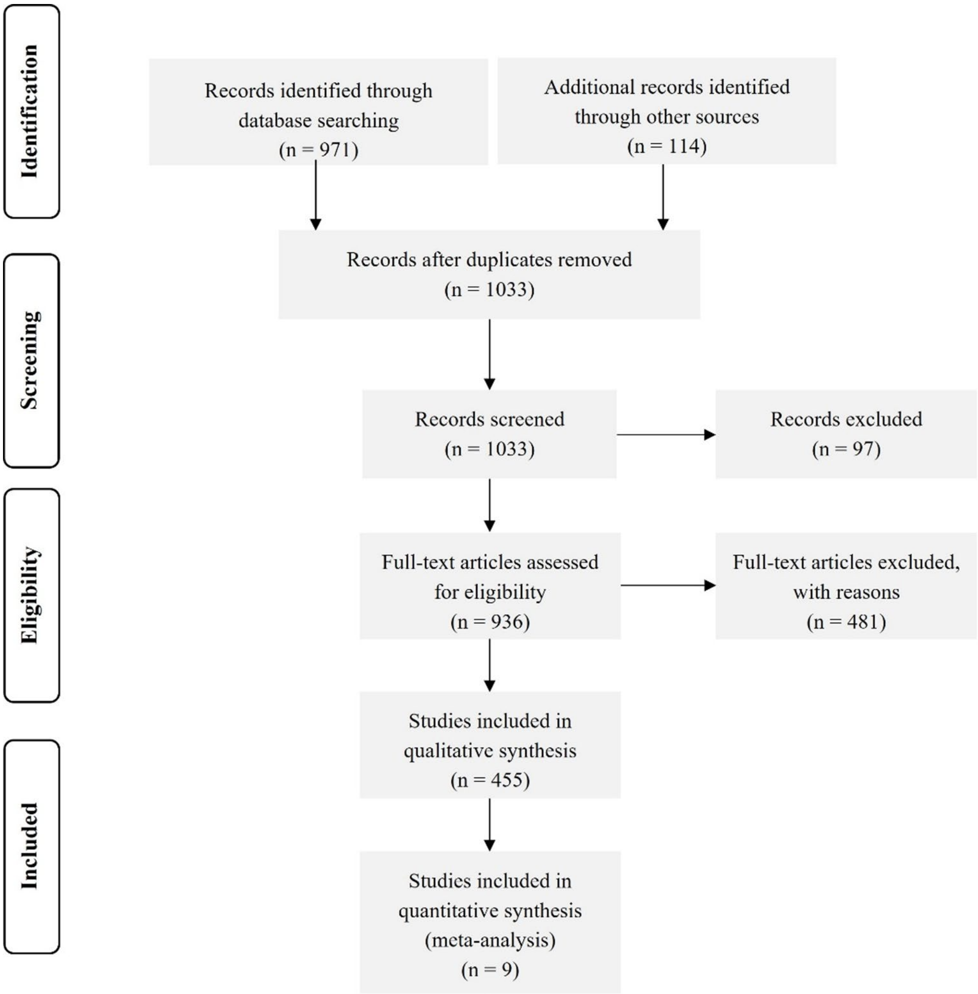


Fig. 1 PRISMA flow diagram of the publication selection procedure

For the meta-analysis, the unbiased, standardized mean difference (Hedges' g) was computed to determine the common effect size of amended and unamended (control) comparisons (Borenstein et al. 2009):

$$g = J\frac{\bar{X}_U - \bar{X}_A}{S_{within}} \tag{1}$$

$$S_{within} = \sqrt{\frac{(n_U - 1)\,S_U^2 + (n_A - 1)\,S_A^2}{n_U + n_A - 2}} \tag{2}$$

and

$$J = 1 - \frac{3}{4\,(n_U + n_A - 2) - 1} \tag{3}$$

$\bar{X}_U$ and $\bar{X}_A$: mean metal concentration (mg kg^{-1}) in plant organs of species collected from unamended (U) and amended (A) soils;

n_U and n_A: sample sizes for plant organs collected from unamended (U) and amended (A) soils;

S_U and S_A: related standard deviation values.

During the interpretation, a negative g value indicates a higher concentration of elements in the plant organs of species growing in amended soils than those from unamended media. A subgroup (leaf-, stem-, and root-based) meta-analysis was conducted to reveal the similarities in accumulation among plant organs collected from amended soils, providing a more detailed overview.

The studies included in this meta-analysis encompass a wide range of contaminated soils and regions, ensuring a comprehensive representation of diverse environmental conditions. Sites include mine-spill areas (e.g., Aznalcóllar, Spain; Clemente et al. 2005), mine tailings (Guangxi Province, China; Gao et al. 2020), industrially polluted soils (Torviscosa, Italy; Marchiol et al. 2007; Islamabad, Pakistan; Khan et al. 2019), agricultural fields (Abha City, Saudi Arabia; Eid et al. 2021), contaminated soils near industries (Chengdu Plain, China; Zhu et al. 2015), as well as experimental farms in North America (Kentucky, USA; Nepal

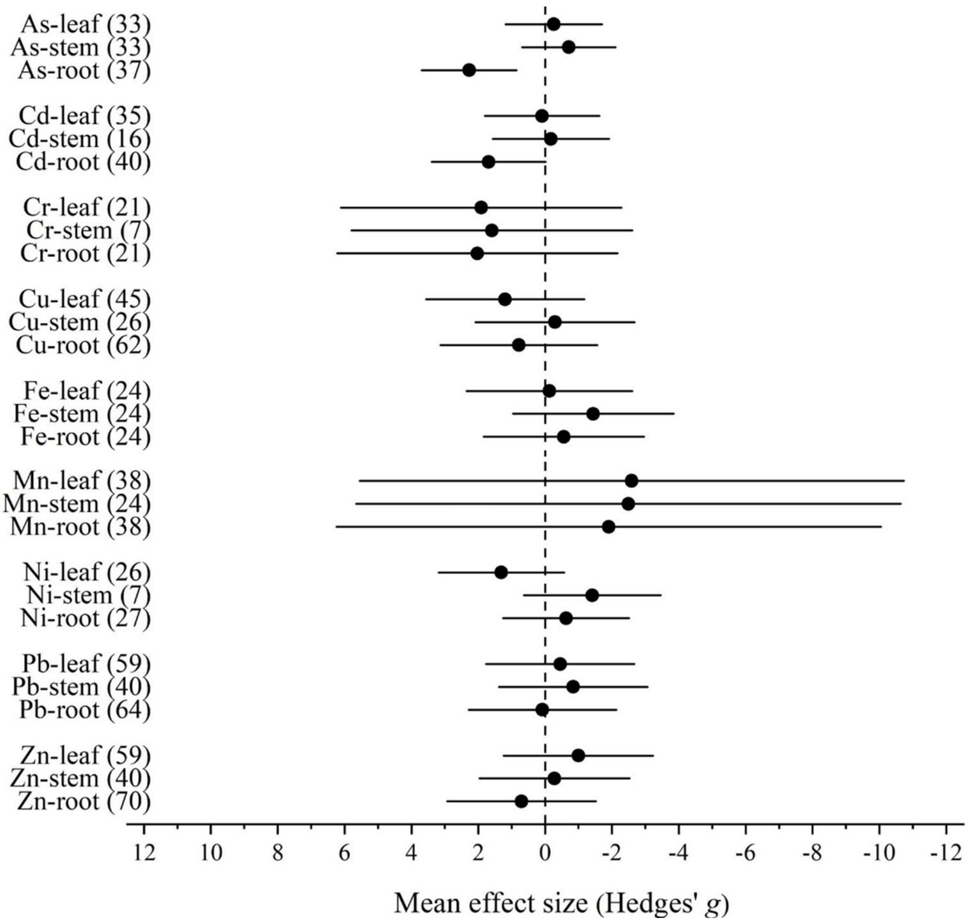


Fig. 2 Accumulation of elements in individual plant organs of species growing in amended soils. Negative Hedges' *g* value means a higher concentration with a 95% CI. Values in parentheses refer to the number of comparisons

et al. 2024; British Columbia, Canada; Padmavathiamma and Li 2010). Other studies considered riverine sediments impacted by mining and industry (Zibo City, China; Zhang et al. 2023). The references for the studies included in the meta-analysis can be found in Supplementary Materials A.

Additionally, the nine research articles included share common attributes; however, their diversity is high in several aspects. Besides fulfilling the selection criteria by publishing information on element accumulation in plants from amended and unamended soils, there are data deficiencies in some parameters (e.g., soil type, weather conditions) and differences by the studied species, organs, elements, and even amendment type (Supplementary Materials A). The data selection procedure indicated that these differences disable the involvement of each variable due to sample size deficiency. Accordingly, the authors of this paper determined that among these highly variable test setup conditions, element-plant organ relations provide sufficient data ($N \geq 5$) for analyzing the nature of moderating effects. Therefore, a random-effects model was employed to determine both the overall effect and the effects of moderators (plant organs). Utilizing the random-effects model allows attributing the distribution of effect sizes to actual differences among studies rather than solely sampling error as the source of variation. The mean effect size was deemed statistically significant if the 95% bootstrap confidence interval (CI; calculated with 999 iterations) did not include zero. Additionally, parameters for effect size heterogeneity (Q, T^2, and I^2) were computed between studies. The total variance (Q_{total}) was assessed using a Q-test, measuring both within-group (Q_{within}) and between-group ($Q_{between}$) variances, with each tested for statistical significance. Moreover, to ascertain the variance explained by covariates, R^2 was calculated (Borenstein et al. 2009). Subgroups with fewer than five cases were excluded from the analysis.

As the final step in the meta-analysis, publication bias, which can result in missing studies and skewed effect sizes, was assessed. To do this, funnel plots and Egger's test were performed (Borenstein et al. 2009). Funnel plot asymmetry was evaluated using weighted regression with multiplicative dispersion and a mixed-effects meta-regression model. When significant asymmetry was detected, the trim and fill method was applied, identifying the number of missing studies, their effect sizes, and standard error values (Duval and Tweedie 2000). Subsequently, missing studies were included in the meta-analysis dataset, and the summary effect size was recalculated, providing an unbiased estimate of the summary effect size (Borenstein et al. 2009).

The relationships between exposure time and plant organ concentration, and soil pH and plant organ concentration were studied by calculating the Pearson correlation coefficient and using linear regression to evaluate potentially significant ($p < 0.05$) influences during element accumulation. Both sub-analyses were conducted in two respects. First, the effects of the factors (exposure time and soil pH) were assessed across the entire plant species (with plant organs pooled). Next, the impact of the factors on element accumulation in individual organs (leaf, stem, root) was also evaluated. Both regression analyses were interpreted and discussed only for those comparisons where at least three publications reported data, leading to a total sample size of $N \geq 15$. Additionally, as an inclusion criterion for these sub-analyses, papers reporting data on the exposure time and pH value were required to present one type or concentration of amendment concerning the specific exposure time or pH value and apply multiple types or concentrations of the selected amendment. With this prerequisite, the authors aimed to exclude biases caused by the uneven number of comparisons among included publications (Supplementary Materials A). During these calculations, R version 4.3.3 (R Core Team 2024) was used.

Results

Based on the inclusion criteria, the following elements could be involved in the analyses (with the chemical symbol and related dry weight-based concentration range for contaminated plants covered by included papers): arsenic (As; 0.01–142 mg kg^{-1}), cadmium (Cd; 0.33–203.28 mg kg^{-1}), chromium (Cr; 4.70–76.28 mg kg^{-1}), copper (Cu; 2.52–706 mg kg^{-1}), iron (Fe; 7.96–6716 mg kg^{-1}), manganese (Mn; 8.57–3187 mg kg^{-1}), nickel (Ni; 0.20–434 mg kg^{-1}), lead (Pb; 0.49–964 mg kg^{-1}), and zinc (Zn; 14.23–2023 mg kg^{-1}), due to their frequent reporting in phytoremediation studies. Additionally, these elements are also relevant for their phytotoxicity effects and human health risks, being classified as priority pollutants by international agencies (e.g., WHO, USEPA) or are essential micronutrients that become toxic at elevated concentrations. Unfortunately, other elements like aluminum that are relevant in acid soils could not be included due to a lack of sufficient data that met the criteria. The results fulfilling the minimum number of comparisons ($N \geq 5$) and the minimum number of papers ($N \geq 3$) reporting data on the specific plant organ-element relation are presented in the following subsections.

Table 1 Hedges' *g* values of the accumulation of elements in plants grown in amended vs. unamended soils (for complementary data, see Supplementary Materials B)

Element	Plant organ	Mean effect size	*p*-value	Concentration change
As	root	2.27	0.002	decrease
As	whole plant	1.66	<0.001	decrease
Cd	whole plant	1.80	<0.001	decrease
Cr	whole plant	6.99	0.005	decrease
Cu	whole plant	1.04	0.004	decrease
Pb	whole plant	0.75	<0.001	decrease
Zn	whole plant	0.67	0.013	decrease

Accumulation of Metals in Response To Amendment Application

The element accumulation was studied in species according to their leaf, stem, and root concentrations. Figure 2 demonstrates the results for each plant part in relation to the nine elements studied. Additionally, significant relations can be found in Table 1.

This sub-analysis, based on 940 amended vs. non-amended comparisons, revealed that the accumulation was significant in only one case: compared to the individuals from unamended soils, the concentration of arsenic significantly decreased in the roots of plants grown in amended soils (Hedges' *g* and 95% CI in the positive range). Similar to the case of As, roots had the lowest concentrations of all plant organs for Cd, Cr, Mn, Pb, and Zn, indicating that soil amendments' applications decreased concentrations generally the most in the underground plant organs. On the other hand, the enrichment of elements was supported the most in the stem for six (As, Cd, Cu, Fe, Ni, Pb) of the nine elements. However, none of the differences were significant or even high. The highest variation in published data was found for Mn, indicating considerably deviating observations across studies. This may come from differences in soil properties, amendment types, plant species, or measurement techniques, all of which can significantly influence manganese mobility and uptake. More than half of all the element-plant organ combinations ($N = 16$) had a higher accumulation of elements in amended soils than in unamended ones (Supplementary Materials B1–B9 and C1–C9).

Correlation between Element Accumulation and Exposure Time

Studying the potential influencing factors on element accumulation besides amendment use, it was observed in this paper that the whole plant concentrations of Cd, Cu, Mn, Ni, Pb, and Zn increased significantly with time. It was also found that the As concentration did not depend significantly on exposure time (Fig. 3 and Supplementary Materials D). For Cr and Fe, the number of reporting papers ($N = 2$) did not satisfy the inclusion criterion presented in the Materials and Methods section. Included publications are presented in Supplementary Materials A. Illustrating the inclusion procedure in the regression analyses, references R1, R3, and R5 shown in Supplementary Materials A each demonstrated information on the As accumulation in plant species from treatments with and without amendment supply ($N \geq 3$ sample size criterion for publications fulfilled), with a total number of 103 comparisons ($N \geq 15$ sample size criterion for comparisons fulfilled).

The evaluation of individual plant organs revealed significantly increased concentration in leaf for Cd, Cu, Mn, Ni, Pb, and Zn, in stem for Pb and Zn, and in root for As, Cd, Cu, Mn, Ni, Pb, and Zn as the exposure to the elements under amendment application got longer (Table 2). The accumulation of Cu in the stem was not significantly influenced by the exposure time. It is also worth noting that leaf As, Cr, and Fe, stem As, Cr, Fe, Mn, and Ni, and root Cr concentration data were insufficient to be included in this analysis based on the low number of involved publications (Supplementary Materials E).

Correlation between Element Accumulation in Plants and Soil pH

Under soil amendment treatment, an increasing soil pH significantly increased the As concentration in whole plant individuals. Unlike the previous, such alteration in soil acidity conditions significantly decreased plant Cd, Cr, Cu, Mn, Ni, and Pb concentrations (Fig. 4). In the case of Zn, plant concentrations were not significantly dependent on soil pH during amendment application schemes. At the same time, for Fe, the number of reporting papers ($N = 2$) was too low to include data in the analysis (Fig. 4 and Supplementary Materials F).

As for the plant organ-based assessment, it was found that an increase in soil pH significantly increased the root arsenic (As) concentration. In contrast, the increase in soil pH significantly decreased the root Cd, Cr, Mn, Ni, and Pb and the leaf concentration of Cd, Cr, and Cu (Table 3). The concentrations of Cu in the stem and root, Mn and Ni in the leaf, Pb in the leaf and stem, and Zn in each plant organ were not significantly dependent on soil pH changes (Supplementary Materials G). Regarding arsenic in leaf and stem, Cd, Cr, Mn, and Ni in the stem, and Fe in each plant organ, the sample size of papers did not fulfill the inclusion criteria.

Discussion

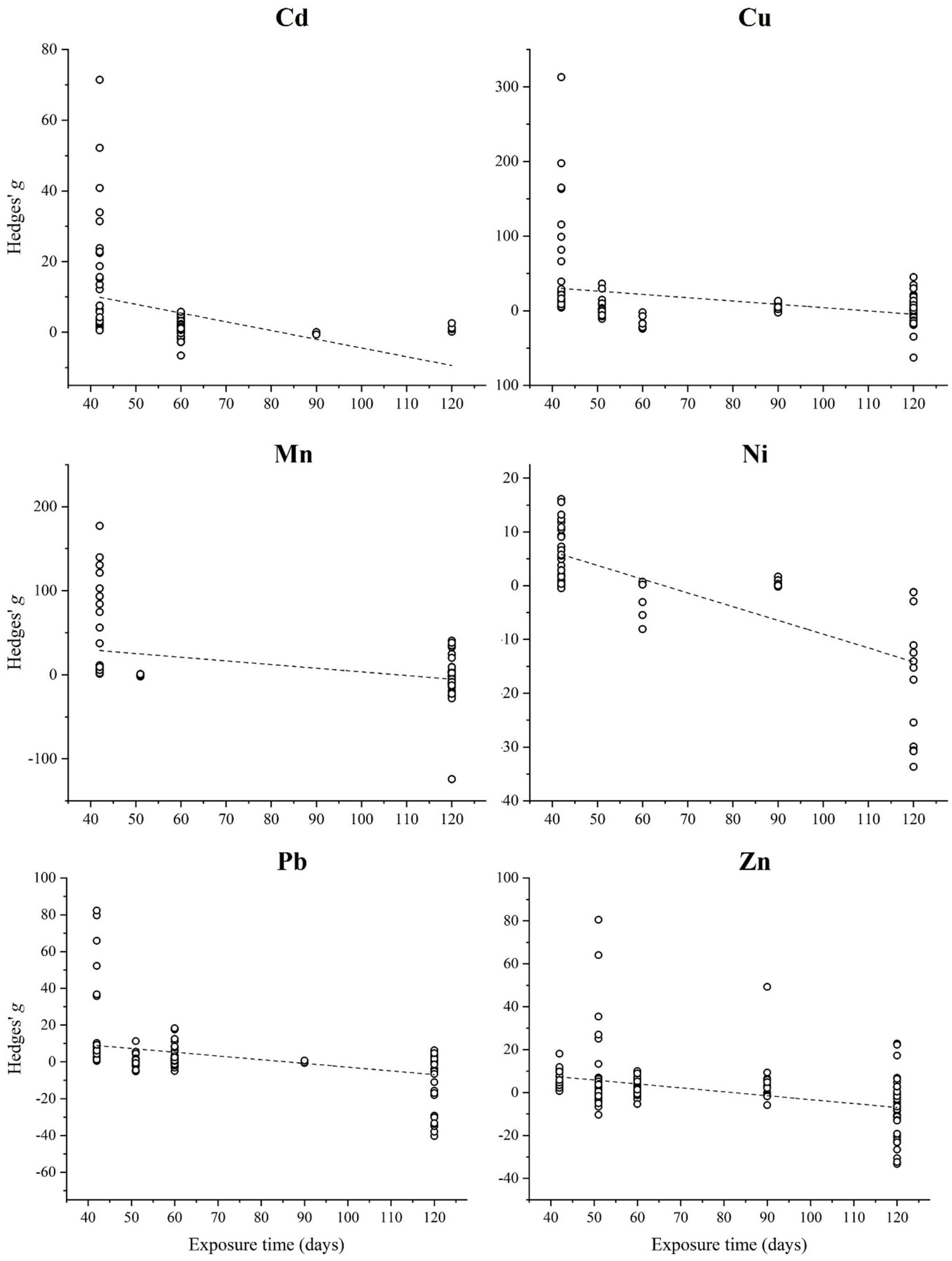
Recently, many papers have been published on the phytoremediation of heavy metals involving soil amendments. This research spans nearly 50 years; however, relevant publications were retrieved only from the last decade. This trend indicates the timeliness and importance of the research approach. Unlike earlier meta-analyses, which often focus on a limited number of elements or plant types, this study provides a multi-element, multi-organ analysis of nine trace elements (As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn) across root, stem, and leaf tissues. It also integrates moderator variables (soil pH, amendment exposure time) to explain heterogeneity in effect sizes, offering mechanistic insights into how amendments influence metal mobility, plant translocation, and organ-specific accumulation. The inclusion of regression models for pH and exposure time, combined with organ-specific analysis, allows this study to identify conditions under which amendments may lead to unintended accumulation in edible or aboveground tissues. These results provide a framework for designing phytoremediation strategies or safer amendment applications in the agricultural field.

Amendment-affected Element Accumulation in Plant Organs

The overall effect sizes across all organs revealed that amendment use significantly reduced the accumulation of several metals, particularly As ($p < 0.001$), Cd ($p < 0.001$), Cr ($p = 0.005$), Cu ($p = 0.004$), Pb ($p < 0.001$), and Zn ($p = 0.013$), as can be seen in Table 1. This overall trend suggests that amendments have the potential to immobilize a great variety of metals in contaminated soils. On the organ-specific level, only the As-root relationship was statistically significant ($p = 0.002$), indicating a decrease in root concentrations of plants grown in amended soils compared to unamended ones.

Organic amendments alter soil physical and chemical properties, which in turn influence metal availability. One of the most common responses to amendment addition is an increase in soil pH due to improved buffering capacity and resistance to acidification. Elevated pH levels typically promote the stabilization of metal cations through interactions with hydroxyl groups (–OH) on soil surfaces. This is most likely the reason why amendments showed an overall tendency to decrease the accumulation of metals in plants. This effect varies with the type of amendment; for example, biochar is particularly effective at raising soil pH due to its high content of alkaline compounds, such as ash (Lwin et al. 2018; Gao et al. 2023).

Additionally, organic amendments tend to increase soil cation exchange capacity (CEC), influencing metal mobility. Amendments like compost and manure introduce negatively charged functional groups like phenolics to soil, providing sorption sites to positively charged metal ions. While amendments like biochar also affect the soil structure by improving aggregation and increasing reactive


Cd
Cu
Mn
Ni
Pb
Zn
Hedges' g
Hedges' g
Hedges' g
Exposure time (days)
Exposure time (days)
80
60
40
20
0
300
200
100
0
100
200
100
0
-100
20
10
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50
60
70
80
90
100
110
120

Fig. 3 Significant correlation (linear regression) between the mean effect size (Hedges' *g*; interpreted as the relative accumulation intensity of elements for individuals from amended soils compared to those from unamended soils) of element accumulation and exposure time (for complementary data, see Supplementary Materials D)

surfaces, which also promotes metal immobilization (Laird et al. 2010; Chiodi et al. 2025). All these mechanisms are involved and are probably the reason for the decrease in the accumulation of metals in plants grown in amended soils.

However, this trend does not always apply to As. An increase in soil pH can enhance the solubility of As, particularly arsenate (As(V), increasing its bioavailability. Despite this, organic amendments may still reduce arsenic mobility by enhancing the soil's CEC and facilitating arsenic immobilization through complexation or surface binding with organic matter (Beesley et al. 2014; Yamaguchi et al. 2011). The effectiveness of an amendment, however, depends on its properties. For instance, biochar binds arsenic more stably than compost due to its lower dissolved organic carbon (DOC) content, which reduces the formation of soluble metal complexes and limits mobility (Beesley et al. 2014). Therefore, the significant reduction in arsenic accumulation and uptake by roots observed with amendment application is more likely due to complexation mechanisms than to pH-induced changes. Furthermore, organic amendments release organic acids during decomposition, which can either promote metal mobility through chelation and competition for sorption sites or reduce it via complexation and immobilization (Lin et al. 2025). For instance, low molecular weight organic acids (LMWOAs) produced at early stages of decomposition contain functional groups (e.g., –COOH) that form soluble compounds with metals. While humic acids formed later in decomposition bind metals more strongly and reduce bioavailability, due to the presence of carboxylic and phenolic groups (Antoniadis et al. 2005; Guo et al. 2019). These dynamics were also demonstrated by O'Dell et al. (2007), who found that compost with high humus content can reduce Cu and Zn availability by more than 90%.

Despite the As-root relationship being the only organ-specific statistically significant result, other determining trends can be identified. Roots had the lowest accumulation of Cd, Cr, Mn, Pb, and Zn among all plant organs in amended soils compared to unamended soils. However, leaves and stems showed increased concentrations of several metals. Specifically, six of the nine elements (As, Cd, Cu, Fe, Ni, Pb) increased stem concentration with the use of amendments. This trend suggests that amendments may influence not only metal mobility in soil but also metal translocation within plants. However, since the differences were not statistically significant, and since there is a trend for amendments to reduce the overall plant accumulation in several metals, definitive conclusions cannot be drawn. Further studies are needed to confirm this effect. Nevertheless, it is still valuable to explore the potential mechanisms that could explain the observed increase in translocation.

Metal-specific translocation pathways may explain a slight increase in metal accumulation in stems following amendment application. Mobile metals such as Cd, Cu, and Ni are efficiently transported via xylem once inside root cells, mediated by transporter proteins like HMA4 and ZIPs. Organic amendments may alter root physiology or pH conditions in a way that promotes transporter activity or the availability of chelating ligands like histidine and organic acids, enhancing root-to-shoot metal mobility. As stems are key vascular conduits with limited detoxification capacity, this can result in temporary metal accumulation before redistribution to metabolically active tissues (Page and Feller 2015; Pasricha et al. 2021).

On another note, the lack of statistically significant results may be attributed to the complex interactions between soil amendments, metal behavior, and plant uptake mechanisms, as existing studies often show inconsistent results. Wang et al. (2020) showed that amendment type and dose differentially influenced metal uptake and translocation, increasing Cu and Fe uptake at high doses of biochar and manure, while reducing Cd, Pb, and Zn with hydroxyapatite. Similarly, Parvin et al. (2022) found that organic matter increases the mobile fractions of Cd to around 55% of the total Cd concentrations. Conversely, a recent study in okra plants cultivated in contaminated soils amended with orange peel-derived biochar (OPDBC) and poultry manure (PM) found that both amendments reduced the accumulation of several metals (Pb, Cd, Cr, Zn, Ni, and Cu). Further, OPDBC was especially effective in lowering Cd uptake in okra plants by up to 37% (Ghani et al. 2024).

Therefore, although this study did not find statistically significant differences in metal accumulation across plant organs, it was still found that amendments tend to reduce the overall metal accumulation. Additionally, observed trends in other studies suggest that, even though responses are variable, amendments do influence metal mobility and translocation. This variability likely results from differences in amendment type, dosage, and decomposition stage, highlighting the need for more standardized protocols that consider these parameters, particularly the decomposition stage, when evaluating the impacts of amendments on metal uptake and mobility..

The Effects of Exposure time on Element Accumulation

The studies included in this meta-analysis varied in their duration, ranging from 40 to 120 days. This heterogeneity

Table 2 Significant correlation (linear regression) between the mean effect size (Hedges' *g*) of plant organ element accumulation and exposure time (for complementary data, see Supplementary Materials D)

Element	Plant organ	F-value	*p*-value	Correlation
As	root	5.561	0.024	positive
Cd	leaf	11.932	0.002	positive
Cd	root	4.832	0.034	positive
Cu	leaf	10.758	0.002	positive
Cu	stem	3.222	0.08	positive
Cu	root	5.004	0.029	positive
Mn	leaf	4.275	0.046	positive
Mn	root	9.413	0.004	positive
Ni	leaf	21.354	< 0.001	positive
Ni	root	125.039	< 0.001	positive
Pb	leaf	13.242	< 0.001	positive
Pb	stem	10.551	0.003	positive
Pb	root	15.203	< 0.001	positive
Zn	leaf	9.326	0.003	positive
Zn	stem	15.183	< 0.001	positive
Zn	root	16.016	< 0.001	positive

in time frames makes it difficult to generalize temporal effects on metal accumulation, as short-term dynamics may not reflect long-term outcomes influenced by plant development, amendment aging, or seasonal changes. Although the regression analysis revealed significant correlations between exposure time and metal accumulation, the results should be interpreted cautiously and should not be applied to longer periods.

The linear regression between exposure time and effect sizes indicates significant correlations for six out of the nine elements (Cd, Cu, Mn, Ni, Pb, and Zn, each with $p < 0.001$) studied for whole plants. In these cases, exposure time was associated with increased plant metal concentrations when amendments were used. Singh and Sinha (2005) found that Cr, Fe, Zn, and Mn concentrations in *Brassica juncea* elevated with exposure time over a 90-day study period in amended tannery soil. Similarly, Li et al. (2023) found that applying rice straw biochar, powdered palygorskite, and powdered hydroxyapatite positively influenced Cd and Zn accumulation in *Quercus* species over time. These amendments improved soil health, promoted the proliferation of soil microorganisms, and stimulated biomass production, ultimately enhancing root tolerance and increasing metal uptake over time.

However, the relationship between time and metal accumulation is complex. Lettens et al. (2011) investigated intra- and inter-annual changes in Cd, Zn, Mn, and Cu concentrations in poplar foliage on contaminated soil. The study indicated that metal concentrations increased at the end of the growing season but declined interannually. This pattern was attributed to higher nutrient uptake during the growing season, followed by a stabilization phase where plant growth slows down, reducing both nutrient and metal uptake. Additionally, over time, biomass accumulation could dilute metal concentrations in plant tissues even if the uptake is high. This aligns with the findings of the present analysis, as the maximum exposure time among the selected studies was 120 days, approximately the length of a typical growing season, which shows that the observed trend of increased metal accumulation over time more likely reflects seasonal uptake patterns than long-term accumulation trends.

As this study was focused on organic amendments, the increase in metal accumulation over time may be linked to the production of low molecular weight organic acids (LMWOAs) as organic amendments decompose in the soil. Since the formation of humus and more stable organic compounds is a long process, it can be assumed that most organic amendments used in these studies were still generating LMWOAs that increase the availability of metals, as mentioned before.

When analyzing individual plant organs, a significant increase in metal concentration over time was observed in leaves for Cd ($p = 0.002$), Cu ($p = 0.002$), Mn ($p = 0.046$), Ni ($p < 0.001$), Pb ($p < 0.001$), and Zn ($p = 0.003$), in stems for Pb ($p = 0.003$) and Zn ($p < 0.001$), and in roots for As ($p = 0.024$), Cd ($p = 0.034$), Cu ($p = 0.029$), Mn ($p = 0.004$), Ni ($p < 0.001$), Pb ($p < 0.001$), and Zn ($p < 0.001$). Exposure time and amendment use generally led to higher metal accumulation in roots and leaves than in stems. Nevertheless, this trend aligns with findings by Lettens et al. (2011), who reported increased foliar concentrations of Cd, Zn, and Cu in poplars by the end of the growing season. Possible explanations for this increased accumulation over time include the reduction of transpiration, particularly during dry seasons like summer, which leads to the concentration of solutes, such as metals, in plant tissues. Conversely, the increase in leaf concentrations over time could be related to plant defense mechanisms to protect themselves from harmful pollutants by accumulating them in their leaves, so their removal can be facilitated through leaf shedding (Lettens et al. 2011; Rascio and Navari-Izzo 2011).

With a similar purpose, the increase in root metal concentrations over time could also be due to common plant defense strategies. These include restricting metal uptake by trapping them with exuded organic acids or binding them to anionic compounds in cell walls. Additionally, metals entering root cells can be sequestered in vacuoles or detoxified through complexation to avoid their translocation (Gunawardana et al. 2010; Rascio and Navari-Izzo 2011). Furthermore, as previously mentioned, stems are vascular conduits; they serve primarily as such and possess limited detoxification and storage capacities. Metals may accumulate temporarily in the stem, but over time, they are translocated to other plant parts, such as leaves or, in some cases,

Fig. 4 Significant correlations (linear regression) between the mean effect size (Hedges' *g*; interpreted as the relative accumulation intensity of elements for individuals from amended soils compared to those from unamended soils) of element accumulation and soil pH (for complementary data, see Supplementary Materials F)

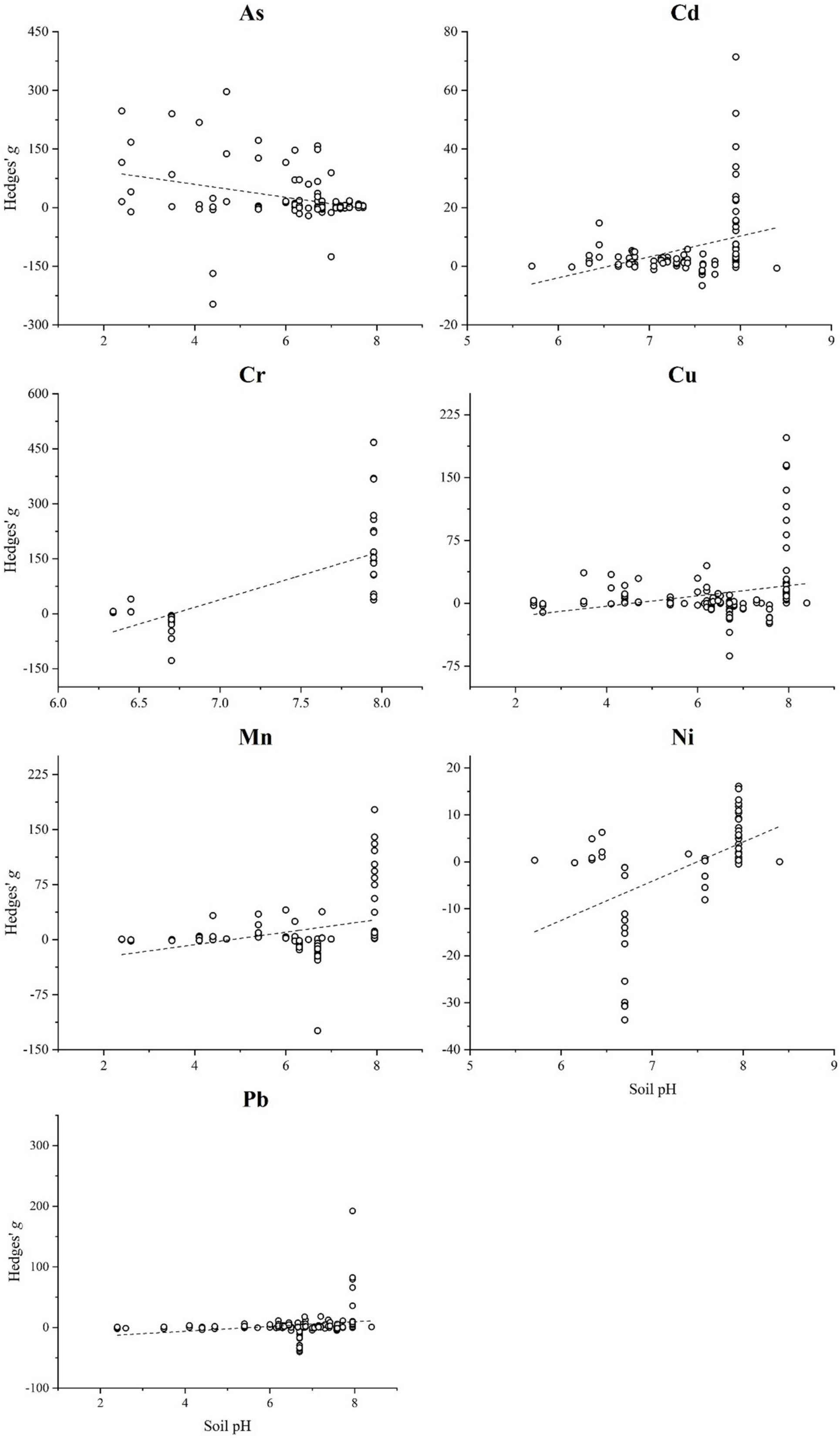

Table 3 Significant correlations (linear regression) between the mean effect size (Hedges' *g*) of plant organ element accumulation and soil pH (for complementary data, see Supplementary Materials F)

Element	Plant organ	F-value	*p*-value	Correlation
As	root	13.107	<0.001	Positive
Cd	leaf	5.806	0.022	Negative
Cd	root	6.845	0.013	Negative
Cr	leaf	16.028	<0.001	Negative
Cr	root	36.521	<0.001	Negative
Cu	leaf	7.791	0.008	Negative
Mn	root	8.162	0.007	Negative
Ni	leaf	4.129	0.05	Negative
Ni	root	26.457	<0.001	Negative
Pb	root	7.479	0.008	Negative

back to the roots. Therefore, with continued metal uptake, long-term accumulation tends to occur primarily in roots or leaves (Page and Feller 2015; Pasricha et al. 2021).

It is also important to note that the variability in study duration may influence the results of the meta-analysis. Longer exposure time may increase metal accumulation and potentiate the effects of amendments. However, since this meta-analysis evaluates the standardized effect sizes (Hedges' *g*) and not directly the mean concentrations between amended and unamended soils, differences in duration are less problematic. Nonetheless, this variation may still contribute to the observed heterogeneity across studies.

The Effects of Soil pH on Element Accumulation

The effect of soil pH on metal availability, mobility, and plant uptake has been extensively studied. Therefore, analyzing the relationship between pH, amendment use, and element accumulation across the selected studies was fundamental. It was found that increasing soil pH positively influenced the whole plant concentration of As ($p < 0.001$) with the use of amendments. In contrast, the contrary was observed for Cd ($p < 0.001$), Cr ($p < 0.001$), Cu ($p = 0.007$), Mn ($p < 0.001$), Ni ($p < 0.001$), and Pb ($p = 0.009$) with increasing pH negatively influencing element accumulation in amended soils, supporting immobilization. For the plant organ-based analysis, similar results are observed: an increase in soil pH significantly increased the root arsenic concentration, whereas it decreased the root Cd ($p = 0.003$), Cr ($p < 0.001$), Mn ($p = 0.007$), Ni ($p < 0.001$), and Pb ($p = 0.008$), and the leaf concentration of Cd ($p = 0.002$), Cr ($p < 0.001$), and Cu ($p = 0.008$). It can be stated that higher soil pH in amended soils does not favor the plant accumulation of most elements, except for As. Willscher et al. (2017) conducted a study analyzing the effects of soil pH and Fe, Mn, Ni, Zn, and Pb on tintense asntial of *Helianthus tuberosus*. It was found that lower pH levels tended to increase heavy metal accumulation in plant tissues, with the highest accumulation occurring at pH 4, more than twice as intensive than at pH 6, and with toxicity effects appearing as heavy metal concentrations increased under low pH. Similarly, Shrestha et al. (2019) assessed the effect of organic amendments, such as compost and coconut coir, on the bioavailability of Zn, Cd, Pb, Co, and Ni and their uptake by switchgrass. It was reported that all amendments significantly increased soil pH to a more neutral level (6.4), reducing metal bioavailability by promoting the formation of metal hydroxides and carbonate complexes.

Soil pH interacts closely with the composition and aging of organic amendments, influencing metal availability over time. Wang and Kuzyakov (2024) found that pH regulates the microbial priming of soil organic matter (SOM), affecting both the rate of amendment decomposition and the types of functional groups available for metal complexation. At lower pH levels, microbial activity mainly mineralizes labile organic matter, releasing LMWOAs that increase metal mobility. Conversely, at higher pH, microbial activity favors humification, increasing the abundance of carboxyl and phenolic groups that support metal immobilization.

In addition to these biological processes, the physicochemical effects of pH on soil are also very important. The relationship between pH and heavy metal availability has been widely evaluated. It is well established that increasing soil pH enhances the adsorption capacity of most metals due to the increased negative charge on soil colloids, clay minerals, organic matter, and hydrous oxides (Ma et al. 2025). A high pH indicates a greater abundance of OH^- ions in soil, promoting the formation of metal hydroxides ($M(OH)^+$), which are readily adsorbed by negatively charged soil colloids. Furthermore, because H^+ concentrations are lower at high pH, there is less competition with metal cations for exchange sites. Moreover, since most metal hydroxides are insoluble, they tend to precipitate, further reducing their bioavailability to plants (Zhu et al. 2023; Wan et al. 2024). Therefore, pH not only influences the chemical environment of soil but also how amendment aging affects metal bioavailability over time.

Unlike other metals, As shows a different behavior, increasing its concentration in plant tissues with an increasing pH. This behavior has been studied before by Yamaguchi et al. (2011). Here, the authors investigated the release of As from soil-to-soil solution, in other words, its mobilization, by calculating the solution-to-soil ratio of As concentration (RL/S) and the factors that influence it. The study found that $R_{L/S}$ increased with pH from zero at pH 5.8 to more than 10 at around pH 7. Additionally, a study by Bandara et al. (2021) assessed the effects of biochar type and pH on As bioavailability, and demonstrated that biochar significantly increased soil pH between 1 and 3 units, consequently increasing the bioavailable As by 49% as pH rose from 4.6 to 7.4.

This behaviour can be explained by understanding the speciation of As in soil. Arsenate (As(V) usually exists as a negatively charged species (e.g., $H_2AsO_4^-$, $HAsO_4^{2-}$) at higher pH values and aerobic environments, while arsenite (As(III) is usually neutral and dominates under reducing or anaerobic conditions (e.g., $H_3AsO_3^0$). Therefore, as most soils are aerobic environments, As tends to be more abundant as As(V) and negatively charged, which causes As (V) to be less easily adsorbed at higher pH levels than at lower pH levels (Yamaguchi et al. 2011; Bandara et al. 2021; Wan et al. 2024) Moreover, at high pH, iron hydroxides that act as ligands for As dissolve due to reductive dissolution, releasing As into solution, especially at pH over 7 (Yamaguchi et al. 2011). This can be further explained by the physiological mechanisms of arsenic uptake in plants. As(V) mimics phosphate (PO_4^{3-}) and is taken up via phosphate transporters, such as members of the PHT1 family, while As(III) is transported through aquaglyceroporins such as nodulin-26-like intrinsic proteins (NIPs) (Li et al. 2016). As soil pH increases, the sorption capacity of both phosphate and As(V) to soil particles declines due to the increased negative surface charge. Consequently, both As(V) and phosphate concentrations in soil solution increase, intensifying the competition between them, which can lead to greater As(V) uptake, especially in phosphate-limited soils. Once As(V) enters the plant cell, it is reduced to As(III) by arsenate reductase. The resulting As(III) is then detoxified by forming complexes with thiol-rich peptides and sequestered in the vacuoles of root cells, which limits its translocation to aboveground organs, thereby increasing root accumulation (Abbas et al. 2018).

However, pH is not the only factor influencing Asuptake by plants. de Souza Costa et al. (2021) studied the phytoremediation of arsenic-contaminated soils using red mud amendments with *Urochloa brizantha*. The authors found that while the amendment increased soil pH, promoting As desorption, this did not necessarily lead to higher As uptake by the plant. Concentrations in the species decreased, likely due to other influencing factors such as organic matter, iron, and aluminum oxide minerals. Therefore, the elevated uptake of arsenic at higher pH is likely due to enhanced arsenate mobility, its structural similarity to phosphate, and its uptake via phosphate transporters rather than a direct physiological response to pH alone.

Limitations and Proposals

Despite the effort to employ robust statistical analyses considering a broad range of variables and performed on reliable scientific data, this study also has some specific shortcomings. As individual studies include highly diverse experimental setups under various conditions, general data heterogeneity is considered high. To mitigate the influence of this limitation, authors of papers focusing on phytoextraction research are encouraged to give a highly detailed description of the methods used and environmental conditions, therefore enabling such complementary evaluations to additional groups of variables with sufficient sample sizes. Further, sample sizes for some plant organ-element relations are low due to the demand for a high-resolution element accumulation assessment within plants. In this case, grouping of elements according to some selected common features may increase sample sizes; however, this would lower the explanatory power of statements for individual elements. Based on the objective of this paper to give an overview of the effects of amendment on element uptake without losing scientific merits, type-based (e.g., organic vs. inorganic) separation of amendments could not be done due to low sample sizes in the target groups. This latter can be overcome if the nature of supplying data is altered; in case, for instance, the demand for SD or SE values is eliminated when scanning studies to be included, the dataset for the statistical analyses would be much broader. However, this would also require the applicable statistical concept (e.g., calculation of RII – relative interaction intensity instead of Hedges' *g*).

On the other hand, the temporal dynamics of amendment effects and application timing are also potential factors to be considered in forthcoming research. According to this analysis, exposure duration was positively correlated with metal accumulation. However, the studies' maximum exposure period was 120 days, the typical time of a growing season. Based on published research, metal uptake tends to increase during the plant growth phase, and the organic amendments' decomposition stage is crucial as early decomposition can increase metal availability. In contrast, later stages aid in metal stabilization. Therefore, for phytoextraction to be more efficient, amendments should ideally be applied during the initial stages of decomposition and in accordance with the growing season. On the other hand, more mature amendments, or earlier application before planting, may help lower the risk of metal mobilization and accumulation in crops when used in agriculture.

Conclusions

This meta-analysis studied the effects of organic soil amendments on metal accumulation and distribution in plant organs. Through a subgroup analysis, it was found that amendments significantly reduced the overall plant accumulation of As, Cd, Cr, Cu, Pb, and Zn, which could be attributed to the tendency of organic amendments to increase pH and promote the formation of metal oxides. Additionally, the arsenic (As) root accumulation decreased significantly following amendment application, as increased pH increases arsenic mobility; this effect is most likely due to organic ligand complexation rather than pH changes. In agricultural projects, this mechanism could help reduce the accumulation of metals in edible crops located in contaminated soils. However, in remediation projects, these amendments may decrease the bioavailability of metals, which could negatively influence their removal in phytoextraction-based strategies, increasing the relevance of techniques such as phytostabilization. For other metals, such as Cd, Cu, Fe, Ni, and Pb, non-significant but consistent enrichment was observed in the stem, suggesting that amendments may promote translocation under certain circumstances. This could be beneficial for optimizing phytoextraction strategies but raises concerns about metal accumulation in edible plant parts in agricultural systems. Still, further studies are required before any sensible suggestions can be made.

Increased pH was associated with reduced availability of most cationic metals, except for arsenic, which showed increased mobility and root concentration at high pH due to its speciation in soil and competition with phosphate. For that reason, in acidic soils, organic amendments with pH buffering capacity can potentially immobilize metals and be helpful in agricultural settings. Still, caution must be exercised in situations with As, where an increase in pH can elevate its solubility. Exposure time was also directly related to increased metal accumulation in most cases, perhaps connected with plant seasonally based uptake patterns and effects of amendment decomposition.

While this research did not directly explore the decomposition stages of amendments, literature evidence suggests that initial decomposition releases low-molecular-weight organic acids (LMWOAs) that enhance metal solubility. In contrast, the later stages allow for humification and stabilization of metals. These processes might have been responsible for the heterogeneity between studies. Regarding practical applications, in agricultural contexts, organic amendments could reduce metal accumulation, especially arsenic, when properly decomposed before planting. For phytoextraction, early-stage decomposition or fresh amendments might enhance metal availability and root uptake, especially during active plant growth.

In conclusion, additional research is needed to identify the effects of specific amendment types on element accumulation in different organs of plant species. In this paper, exposure time and soil pH were identified as core variables; however, including additional variables would provide further evidence for designing effective remediation strategies and their application in agricultural practices.

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Data Availability Data will be made available on request.

Declarations

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