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Evaluation of the phytoremediation potential of ornamental plants in lead (Pb)-contaminated soil

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ABSTRACT

The Pb contamination in soil poses significant environmental and public health risks due to its non-biodegradable and bioaccumulative nature. This study evaluates the phytoremediation potential of six ornamental plant species—*Helianthus annuus*, *Gaillardia grandiflora*, *Brassica juncea*, *Euphorbia tithymaloides*, *Tradescantia pallida*, and *Canna indica*—for remediating Pb-contaminated soils. These species were selected for their short life cycles, adaptability, and tolerance to Pb stress. Pot experiments were conducted with soil spiked at Pb concentrations of 0, 20, 40, 80, and 160 mg kg^{-1}, and plant growth responses, Pb accumulation, and phytoremediation efficiency were assessed over 120 days. Growth parameters, including plant measurements (root and shoot length) and biomass, were recorded, alongside Pb concentrations in plant tissues. Phytoremediation efficiency was evaluated through bio-concentration factor (BCF), translocation factor (TF), and tolerance index (TI). Results showed that *C. indica*, *B. juncea*, *G. grandiflora*, and *H. annuus* exhibited enhanced or stable growth under Pb stress, while *T. pallida* was highly sensitive, showing significant growth reductions. *T. pallida* and *G. grandiflora* demonstrated the highest Pb accumulation, with *G. grandiflora* indicating phytoextraction potential (TF > 1). All species had BCF_{root} values > 1, indicating effective Pb uptake, particularly in roots. These findings suggest that the tested ornamental plants, especially *G. grandiflora* and *C. indica*, are promising candidates for phytoremediation of moderately Pb-contaminated soils, offering both environmental and esthetic benefits.

NOVELTY STATEMENT

This study presents the first comprehensive evaluation of the phytoremediation potential of six understudied ornamental plant species—*H. annuus, G. grandiflora, B. juncea, E. tithymaloides, T. pallida*, and *C. indica*—specifically selected for their short life cycles and Pb tolerance, in moderately contaminated soils under natural outdoor conditions in a semi-arid urban environment. Unlike prior research focused on individual hyperaccumulators or longer-cycle edibles with food chain risks, our work demonstrates the dual esthetic and remedial value of these non-edible ornamentals, highlighting *G. grandiflora*'s novel phytoextraction efficiency and *C. indica*'s superior phytostabilisation *via* high root biomass accumulation, offering a rapid, sustainable strategy for urban Pb remediation that integrates environmental restoration with landscape enhancement.

KEYWORDS

Bioconcentration factor; ornamental plants; Pb-contamination; phytoremediation; translocation factor

Introduction

The Pb-contamination in soil is a serious environmental concern, primarily driven by human activities such as vehicular emissions, mining, smelting, coal combustion, Pb-based paints, and chemical fertilizers (Bouida et al. 2022; Angon et al. 2024). It is recognized by the World Health Organization (WHO) as one of the top 10 chemicals of public health concern (WHO 2021) and ranked as the second most toxic metal for plants and animals after arsenic (ATSDR 2022). The Pb is non-essential for biological processes, and its persistent, non-biodegradable, and bioaccumulative nature leads to severe ecological impacts (Mani et al. 2016). Human exposure to Pb, primarily through ingestion or inhalation, can cause developmental delays in children, kidney damage, hypertension, miscarriages, birth defects, DNA damage, neurological disorders, and encephalopathy in both children and adults (Wu et al. 2016; Ullah et al. 2020). In plants, Pb induces reactive oxygen species, inhibits enzymatic activity, disrupts water balance, impairs membrane permeability, affects mineral nutrition, and hinders morphology, growth, and photosynthesis (Deepika and Haritash 2023b).

In the Delhi National Capital Region (NCR), elevated Pb levels have been reported in both agricultural and urban soils due to dense traffic emissions, industrial discharge, and wastewater irrigation practices. For example, Rani et al. (2021) recorded mean Pb concentrations of approximately 18.45 mg kg^{-1} in 84 agricultural soil samples collected across the Delhi–NCR region. Similarly, Surya et al. (2022) reported mean Pb concentrations of 33.56 ± 9.81 mg kg^{-1} in agricultural soils

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irrigated with water from the Yamuna River. These concentrations indicate the persistent anthropogenic input. This widespread contamination highlights the urgent need for developing plant-based and eco-friendly remediation strategies.

Phytoremediation, an eco-friendly, cost-effective, and sustainable approach, uses plants' natural abilities to absorb, transport, stabilize, or degrade pollutants, including heavy metals, in the rhizosphere (Madhav et al. 2024). This technique encompasses several mechanisms, including phytoextraction, phytostabilisation, phytodegradation, phytovolatilization, and rhizofiltration (Balint-Ponici et al. 2019). Phytoextraction and phytostabilisation are the most widely applied for heavy metal removal. Phytoextraction involves plants absorbing contaminants through roots and translocating them to shoots and leaves (Suman et al. 2018), while phytostabilisation immobilizes pollutants by adsorption onto root surfaces or accumulation within roots (Muthusaravanan et al. 2018). To date, around 721 hyperaccumulators are reported from 52 families (Huang et al. 2020), but the application of phytoremediation is still not popular due to the longer growth cycle, low biomass, risk of entering into the food chain, weak disease resistance, and shallow root systems (Liu et al. 2011; Farooq et al. 2020). Ornamental plants, however, offer a viable alternative due to their rapid growth, high biomass, metal tolerance, and non-edible nature, which minimizes the risk of food chain contamination (Sehrawat et al. 2021). Additionally, these plants enhance the esthetic appeal of contaminated sites and may provide economic benefits (Mahmood-Ul-Hassan et al. 2020). Several ornamental plants have shown promise for Pb phytoremediation. For instance, *Pelargonium hortorum, Mesembryanthemum criniflorum*, and *Godetia grandiflora* are effective for Pb extraction (Manzoor et al. 2018). while *Tagetes erecta* excels in phytostabilisation (Madanan et al. 2021). Other species, including *Tithonia diversifolia, Helianthus annuus* (Adesodun et al. 2010; Al-Jobori and Kadhim 2019), *Melastoma malabathricum* (Selamat et al. 2014), *Cordyline fruticosa* (Herlina et al. 2020), *Panax notoginseng, Chlorophytum comosum, Calendula officinalis* (Shao et al. 2019), *Amaranthus caudatus, and Tagetes patula* (Aghelan et al. 2021), have also demonstrated Pb remediation potential. This study investigates the Pb accumulation and/or hyperaccumulation potential of six ornamental plant species: *Helianthus annuus* (L.), *Gaillardia grandiflora* L. (Asteraceae), *Brassica juncea* L. (Brassicaceae), *Euphorbia tithymaloides* L. (Euphorbiaceae), *Tradescantia pallida* L. (Commelinaceae), and *Canna indica* L. (Cannaceae). These species were selected for their high biomass, short life cycles, low maintenance, adaptability, and tolerance to Pb stress. The research aims to evaluate their growth responses and Pb accumulation characteristics under varying Pb concentrations, contributing to the development of effective phytoremediation strategies for Pb-contaminated soils.

Materials and methods

Chemicals and reagents

All chemicals and reagents used in this study were of analytical grade and obtained from SRL and Merck, India. Ultrapure water was used for the preparation of all the solutions.

Soil characterization

The experiments were conducted outdoors in a natural environment in Delhi NCR, India. Soil samples were collected from a depth of 0–15 cm in the horticultural plots on the campus of Delhi Technological University (DTU). Before air drying, stones and plant residues were carefully removed from the soil. The experimental site, located on the outskirts of Delhi, was confirmed to have Pb contamination below the detection limits (BDL < 0.002 mg-L^{-1}). This was verified by analyzing the soil samples using Atomic Absorption Spectroscopy (AAS). The soil was then passed through a 2 mm stainless steel sieve and stored in plastic bags at room temperature (28–30 °C) until use. The soil samples were analyzed for a range of physicochemical properties. pH, electrical conductivity (EC), and total dissolved solids (TDS) were measured after vigorously mixing the samples with deionized water in a 1:10 ratio for two hours, using digital meters. Soil texture was determined through particle size analysis or the sieve method (ASTM 2007). Organic carbon and phosphorus levels were assessed using standard test methods (Walkley and Black 1934; Bray and Kurtz 1945). Total Kjeldahl's nitrogen (%) was measured following Blake's method (1965), while cations like sodium, potassium, calcium, and lithium were analyzed using a flame photometer (APHA 1992). Table 1 represents the various physicochemical characteristics of soil before the phytoremediation process.

Experimental setup

Pot experiments were conducted to assess the remediation potential of various plant species under Pb stress. To introduce Pb contamination in soil, lead nitrate [Pb $(NO_3)_2$] was used to prepare the stock solution. The sieved soil was filled into plastic grow bags, with each bag containing 9 kg of soil. For each plant species, the soil was spiked with the Pb solution to create four different Pb treatments (Table 2), while one unspiked bag was kept as a control (T0 treatment). The spiked soil was allowed to equilibrate for one month, undergoing four wetting and drying cycles with intermittent mixing during each cycle. After equilibration, saplings of similar size for each plant species were transplanted into the pots, with three saplings per bag. The saplings, all of approximately equal growth, were sourced from the DTU campus. Tap water, with a Pb concentration below detectable limits

Table 1. Soil characteristics before phytoremediation.

Soil characteristics	Value
Soil Texture	Sandy Loam
pH	7.4
EC (µS/cm)	838
TDS (ppm)	418
SOC (%)	0.4
P (g/kg)	0.21
TKN (%)	0.42
Na (g/kg)	6.69
K (g/kg)	0.23
Ca (g/kg)	0.26
Li (g/kg)	0.0004
Pb (mg-L^{-1})	BDL* (<0.002)

(<0.002 mg/l), was used to avoid external Pb contamination during the experiments. Additionally, a reference pot filled with soil spiked at a known concentration of 20 mg-kg^{-1} Pb was maintained without any plants (T0' treatment). At the end of the experimental period, 95% of the Pb was recovered from the reference soil sample, and Pb values for all soil samples were corrected against this recovery rate. The experiment was conducted under natural light conditions without any fertilizer application. Since the study was conducted during the winter season (November 2022 to March 2023), less water (300 ml per bag) was required for plant growth, and watering was done every other day.

Estimation of physical parameters of plants

Once the plants reached stability in their physical growth and completed nearly a full life cycle (120 days), they were harvested for further analysis. To facilitate easy uprooting, the plants were freshly watered to loosen the soil. The plants were manually uprooted, and the root and shoot lengths were measured using a metric ruler. In the lab, the plants were thoroughly washed with tap water to remove any remaining soil from the roots and other parts. The plants were then separated into roots, stems, and leaves, and oven-dried at 80 °C for 72 h to achieve a constant weight. The dry biomass of each part was recorded, and the samples were stored in zip-lock poly bags for future use.

Thermochemical extraction and analysis of Pb

Oven-dried plant tissues were finely ground into a powder. For metal extraction, 1 g of each plant tissue—roots, stems, leaves, and inflorescence—was placed in crucibles. The samples were thermally oxidized in a muffle furnace at 500 °C for two hours. After cooling, the ash was transferred into conical flasks and mixed with 0.43 M nitric acid solution in a 1:25 ratio (Groenenberg et al. 2017). The mixtures were shaken for two hours in an incubator shaker, followed by centrifugation at 5000 rpm for 10 min to obtain clear extracts. These extracts were subsequently analyzed using AAS to determine the Pb concentration.

Measurement of phytoremediation efficiency

The phytoremediation efficiency of plants was estimated using the bio-concentration factor (BCF), translocation factor (TF), and total heavy metal accumulation rate of plants.

Table 2. Experimental Details.

Pb treatment	Experimental setup	Ornamental plant species
T0′	Control soil +20 mg/kg Pb	*B. juncea* (Indian Mustard)
T1	Control soil + 20 mg/kg Pb + Plant sp.	*T. pallida* (Purple plant)
T2	Control soil + 40 mg/kg Pb + Plant sp.	*E. tithymaloides* (Zigzag plant)
T3	Control soil + 80 mg/kg Pb + Plant sp.	*C. indica* (Canna lily)
T4	Control soil + 160 mg/kg Pb + Plant sp.	*G. grandiflora* (Indian blanket)
T0	Control soil + Plant sp.	*H. annuus* (Sunflower)

The Pb tolerance of plant species was evaluated using the tolerance index (TI).

The BCF was described as (Huang et al. 2020)

$$BCF = \frac{metal\ concentration\ in\ the\ plant\left(mg/kg\right)}{metal\ concentration\ in\ the\ soil\left(mg/kg\right)} \quad (1)$$

The TF showed the ability of plants to translocate heavy metals from the roots to the shoots and it was calculated as follows (Khan et al. 2023):

$$TF = \frac{metal\ concentration\ in\ the\ shoot\left(mg/kg\right)}{metal\ concentration\ in\ the\ root\left(mg/kg\right)} \quad (2)$$

The total heavy metal accumulation rate (μg g^{-1} day^{-1} DW) of plant species can be calculated as follows (Deepika and Haritash 2024):

$$Total\ metal\ accumulation\ rate = \frac{DW_s \times C_s + DW_r \times C_r + DW_l \times C_l}{DW_s + DW_r + DW_l \times days\ of\ harvest} \quad (3)$$

Where, DW (g) is dry weight, C (μg/g) is the concentration of Pb and the subscript of DW or C denotes the stem (s), root (r) and leaf (l).

TI of the plants was calculated as (Ullah et al. 2023)

$$TI = \frac{Total\ biomass\ of\ treatment\ plants}{Total\ biomass\ of\ control\ plants} \times 100 \quad (4)$$

Statistical analysis

All experiments were conducted in triplicate. Data were expressed as mean ± standard deviation (SD). Statistical analyses were performed using SPSS software (version 28). Differences among treatments were evaluated by one-way analysis of variance (ANOVA), followed by Duncan's Multiple Range Test (DMRT) for post-hoc comparisons. Statistical significance was considered at $p < 0.05$.

Results and discussion

Physical growth parameters of plants grown in Pb-contaminated soil

The effects of Pb-contamination on the growth of six ornamental plant species were assessed over 120 days across five Pb treatments (T0 to T4, 0 to 160 mg kg^{-1}). The study examined root length, shoot length, and biomass to evaluate species-specific responses to Pb stress and their suitability for phytoremediation in moderately contaminated soils (Figure 1 and 2). Root growth parameters, specifically, root length and biomass responses, varied among species under increasing Pb concentrations (Figure 1). *C. indica* and *B. juncea* showed increased root length and biomass up to the T3 treatment (80 mg kg^{-1}), with a slight, non-significant decline at T4 (160 mg kg^{-1}). *E. tithymaloides* exhibited stable

root growth across all treatments, showing no significant changes. *G. grandiflora* displayed peak root length and biomass at T2 (40 mg kg^{-1}), with no further increases at higher concentrations. *H. annuus* demonstrated significant root growth enhancements, with root length and biomass increasing 48.78% and 252.38%, respectively, at T4 as compared to T0. In contrast, *T. pallida* was highly sensitive, experiencing a 52% reduction in root length and a 62% reduction in biomass at T4 compared to T0.

Shoot growth patterns generally mirrored those of root growth across the studied species (Figure 2). *C. indica* and *B. juncea* maintained stable shoot growth up to T3, with *B. juncea* showing a 38.6% increase in shoot biomass at T3. At T4, *C. indica* exhibited a 13.5% reduction in shoot length and a 20.6% reduction in biomass, while *B. juncea* showed a 32.8% reduction in shoot length but stable biomass. *G. grandiflora* and *H. annuus* displayed significant shoot growth improvements, with *G. grandiflora* recording an 83.3% increase in shoot length and a 176% increase in biomass, and *H. annuus* showing a 38.5% increase in shoot length and a 106% increase in biomass. *E. tithymaloides* showed no significant shoot growth changes across treatments, while *T. pallida* experienced substantial reductions (62.8% in shoot length and 35% in biomass) at T4.

The Pb toxicity typically displays as stunted growth, chlorosis, and leaf shedding (Alkhatib et al. 2019; Chandrasekhar and Ray 2019; Adepoju et al. 2024). However, no visible toxicity symptoms were observed in any species at 160 mg kg^{-1}, likely because severe Pb toxicity occurs at concentrations above 200 mg kg^{-1}, primarily through root growth inhibition (Manzoor et al. 2018; Ramírez et al. 2020; Umer and Hussain 2023). This inhibition disrupts cell division in root apices (Yoon et al. 2006; Nas and Ali 2018). Except for *T. pallida*, all species either maintained or enhanced growth under Pb stress, consistent with prior studies. For example, Ma et al. (2022) reported a 42.25% and 28.87% increase in root length for Hydrangea "Endless Summer" at 100 and 200 mg kg^{-1} Pb, respectively. Similarly, Rapistrum rugosum and Sinapis arvensis showed no biomass reduction at 100–500 mg kg^{-1} Pb (Saghi et al. 2016), and Coronopus didymus exhibited enhanced growth at 500–2900 mg kg^{-1} Pb (Sidhu et al. 2017). The tolerance of *C. indica*, *B. juncea*, *E. tithymaloides*, *G. grandiflora*, and *H. annuus* may be attributed to Pb

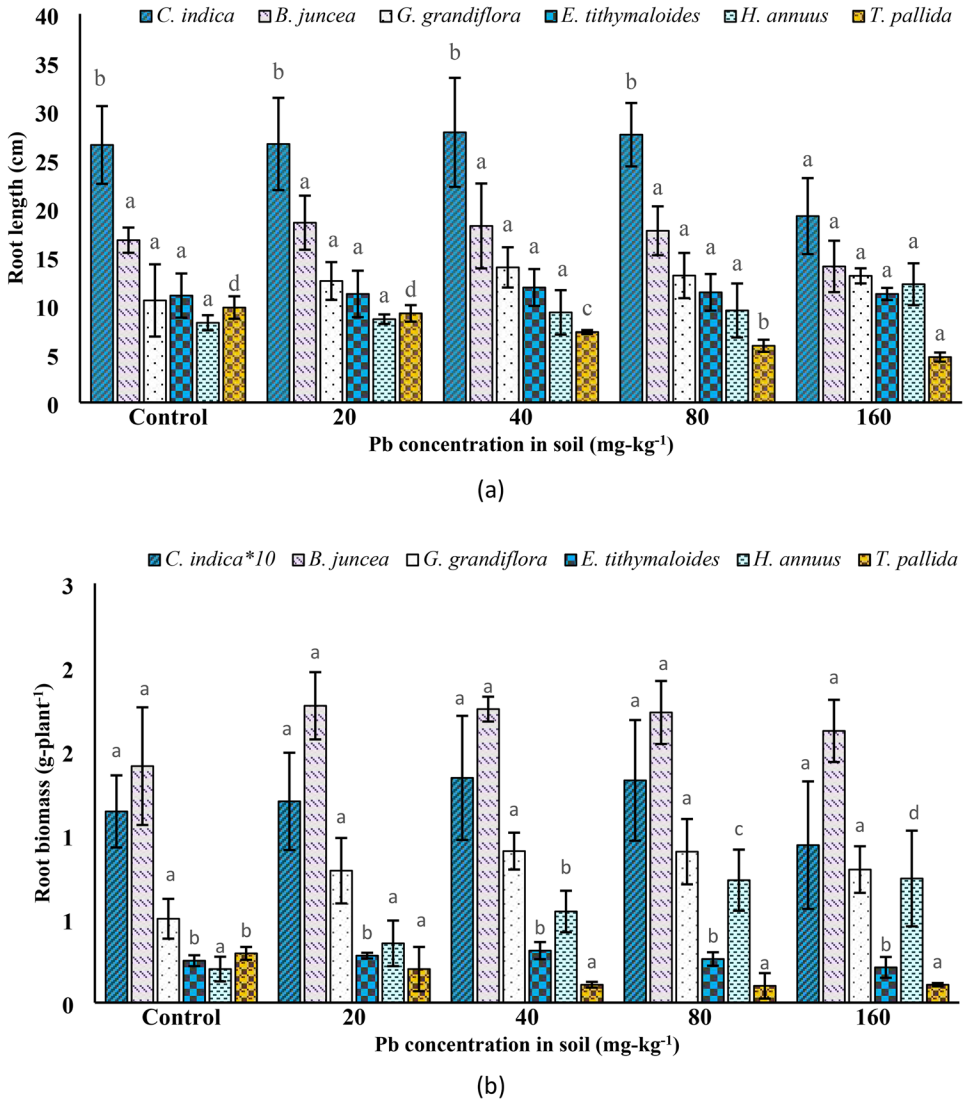


Figure 1. Effect of different Pb treatments on (a) root length, and (b) root biomass. Treatment means ± SD with letter groupings—means sharing the same letter do not differ significantly at $p < 0.05$ by Duncan's multiple range test.

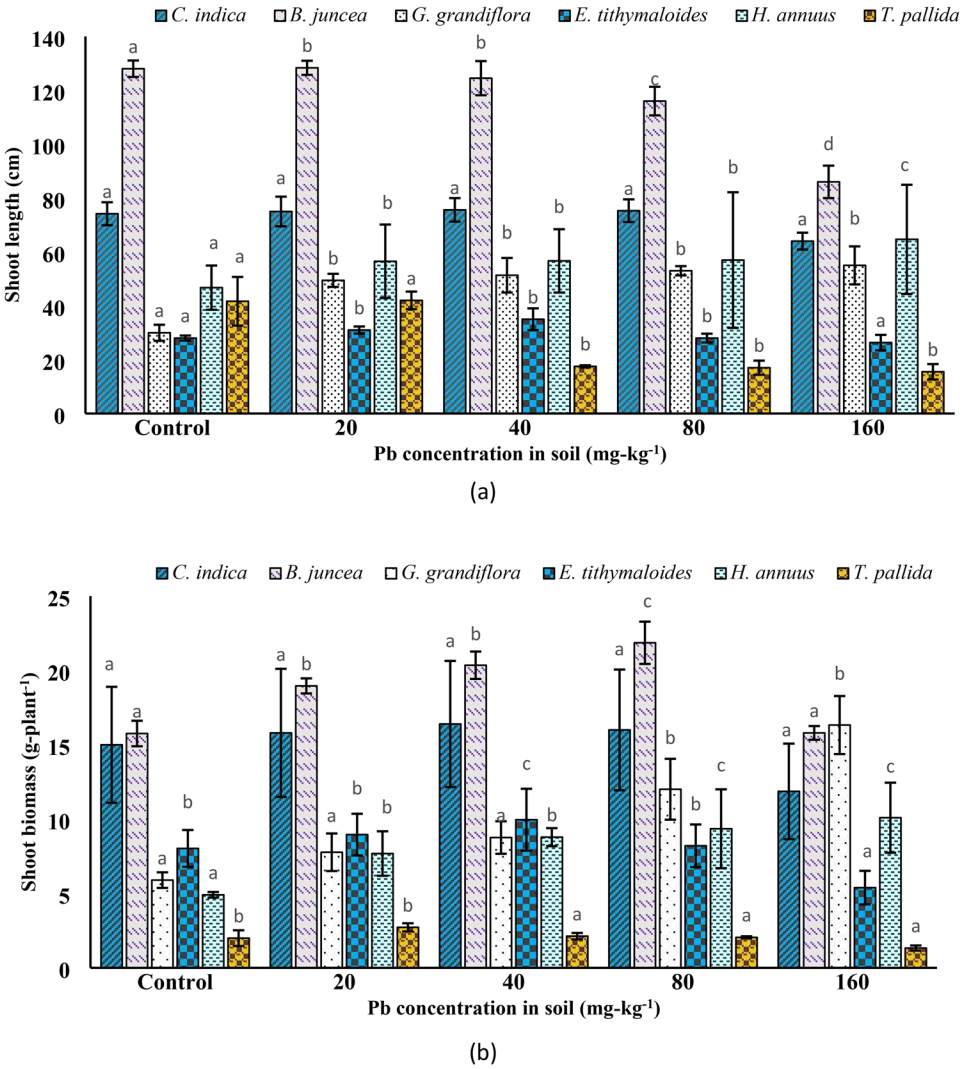


Figure 2. Effect of different Pb treatments on (a) shoot length, and (b) shoot biomass. Treatment means ± SD with letter groupings—means sharing the same letter do not differ significantly at $p < 0.05$ by Duncan's multiple range test.

sequestration in non-metabolic compartments (*e.g.,*cell walls and vacuoles), preventing cellular disruption, and elevated antioxidant enzyme activity (*e.g.,*superoxide dismutase, guaiacol peroxidase, lipoxygenase) to mitigate oxidative stress (Huang et al. 2012). Low Pb concentrations (10 mg kg^{-1}) can also enhance chlorophyll and carotenoid content, improving photosynthetic efficiency in species like *Chrysanthemum indicum* (Mani et al. 2015). However, some ornamental plants, such as *Vinca rosea* and *Tagetes erecta*, show reduced growth at moderate Pb levels (50–80 ppm) (Ehsan et al. 2016; Eid et al. 2018). Therefore, the varied responses across species highlight the influence of factors such as soil properties, Pb concentration, exposure duration, and species-specific traits (Gao et al. 2010). As all plants in this study were grown under identical conditions, the pronounced sensitivity of *T. pallida* likely stems from its unique physiological response to Pb stress, distinguishing it from the more tolerant species.

G. grandiflora and *H. annuus* exhibited the most robust growth enhancements under Pb stress, followed by *B. juncea*, *C. indica*, and *E. tithymaloides*, which showed neutral or positive responses. *T. pallida* was highly sensitive, with significant growth reductions. These results suggest that *C. indica*, *B. juncea*, *E. tithymaloides*, *G. grandiflora*, and *H. annuus* are promising candidates for phytoremediation in moderately Pb-contaminated soils, combining environmental restoration with ornamental value.

Partitioning of Pb and estimation of phytoremediation efficiency

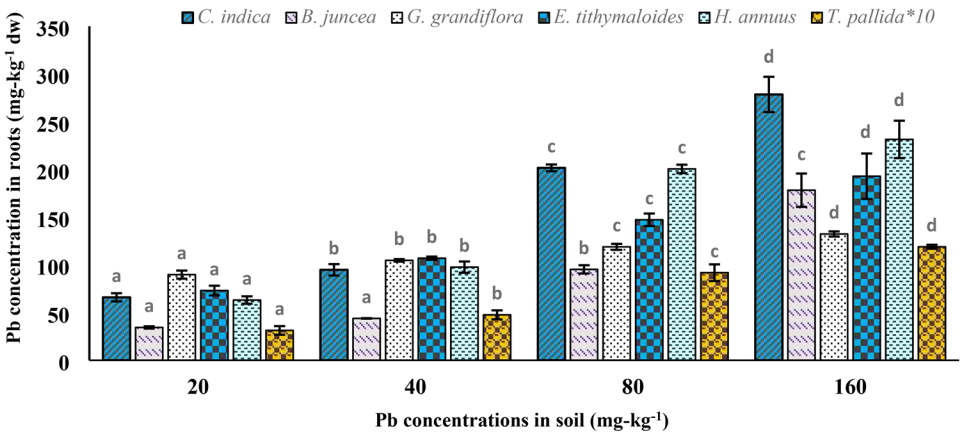
Difference in Pb-concentration and uptake among ornamental plants

After 120 days, Pb concentrations in roots and shoots were analyzed across T1–T4 treatments (Figure 3). The Pb accumulation increased with soil Pb levels, with roots generally showing higher concentrations than shoots, except in *G. grandiflora*. The Pb concentrations in roots ranged as follows: *C. indica* (65.95–278.50 mg kg^{-1}), *B. juncea* (34.40–178.17 mg kg^{-1}), *G. grandiflora* (89.75–132.3 mg kg^{-1}), *E. tithymaloides* (73.06–192.81 mg kg^{-1}), *H. annuus* (63.10–231.37 mg kg^{-1}), and *T. pallida* (313–1189 mg kg^{-1}). *T. pallida* exhibited the highest root Pb concentration at T4 (1189 mg kg^{-1}), indicating strong root accumulation. In shoots, Pb concentrations were generally lower than in roots,

except for *G. grandiflora*, which exhibited higher shoot concentrations than roots across treatments. The shoot concentrations of plant species were as follows: 14.95 mg kg^{-1} to 37.91 mg kg^{-1} in *C. indica*, 28.86 mg kg^{-1} to 87.19 mg kg^{-1} in *B. juncea*, 102 mg kg^{-1} to 210 mg kg^{-1} in *G. grandiflora*, 8.50 mg kg^{-1} to 31.94 mg kg^{-1} in *E. tithymaloides*, 12.95 mg kg^{-1} to 21.62 mg kg^{-1} in *H. annuus*, and 141 mg kg^{-1} to 257 mg kg^{-1} in *T. pallida*. *T. pallida* also showed high shoot Pb at T4 (257 mg kg^{-1}), suggesting greater translocation compared to other species.

Higher root Pb accumulation aligns with prior studies, as roots act as a primary barrier to Pb transport, supporting phytostabilisation (Saghi et al. 2016; Gupta et al. 2017; Shao et al. 2019; Ullah et al. 2019; Testa et al. 2023). *G. grandiflora*'s higher shoot concentrations indicate phytoextraction potential, consistent with findings for *Amaranthus caudatus*, *Ricinus communis*, and *Tagetes patula* (Bosiacki et al. 2013; Aghelan et al. 2021). Low Pb bioavailability in soils, due to precipitation by sulfate and phosphate ions, limits uptake (Romeh et al. 2016), but a positive correlation between soil and plant tissue Pb levels was observed, consistent with the findings of Madanan et al. (2021). Their pot experiments with heavy metals (Zn, Cd, and Pb) ranging from 20 to 160 mg kg^{-1} demonstrated that total metal uptake increased with soil metal concentration. Notably, Zn and Cd uptake were approximately 13 times higher than Pb uptake, underscoring the relatively limited bioavailability of Pb. According to the report, root retention is likely enhanced by physiological adaptations, such as thickened xylem cell walls (Alkhatib et al. 2019). Such adaptations restrict Pb translocation to aerial parts, minimizing toxicity to photosynthetic tissues and enhancing plant tolerance to Pb stress. This mechanism is particularly advantageous for phytostabilisation.

Total Pb accumulation (concentration × biomass) is critical for phytoremediation efficiency (Ullah et al. 2025). A positive correlation was observed between soil Pb levels and total plant Pb uptake (Figure 4). At T4, root Pb accumulation was highest in *C. indica* (2615 µg $plant^{-1}$), followed by *H. annuus* (325.86 µg $plant^{-1}$), *B. juncea* (290.74 µg $plant^{-1}$), *G. grandiflora* (132.06 µg $plant^{-1}$), *T. pallida* (125.53 µg $plant^{-1}$), and *E. tithymaloides* (40.96 µg $plant^{-1}$). Despite *T. pallida*'s high root Pb concentration, its low biomass reduced total accumulation. Shoot Pb accumulation at T4 was highest in *G. grandiflora* (3489 µg $plant^{-1}$), followed by *B. juncea*



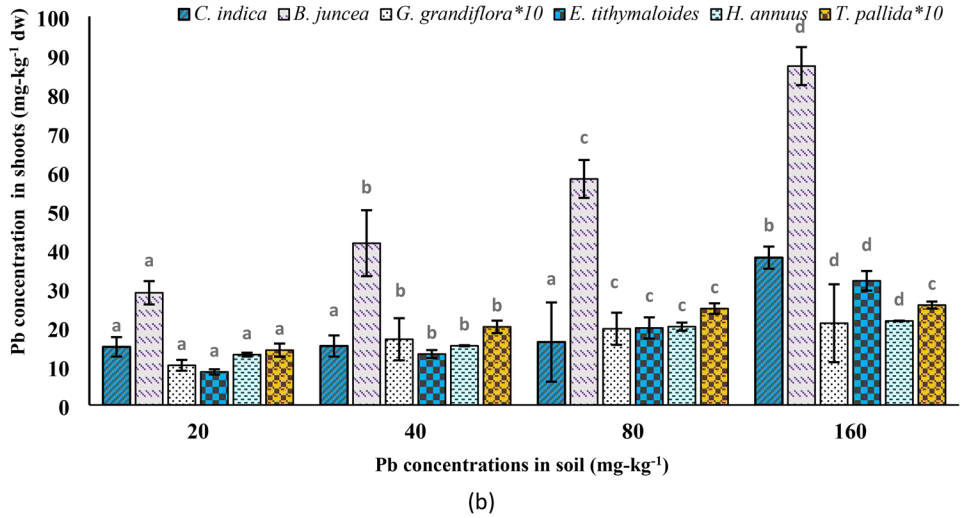


Figure 3. Pb concentration in (a) roots, and (b) shoots of ornamental plants species. Treatment means ± SD with letter groupings—means sharing the same letter do not differ significantly at $p < 0.05$ by Duncan's multiple range test.

(1384 µg plant^{-1}), *C. indica* (449.95 µg plant^{-1}), *T. pallida* (391 µg plant^{-1}), *H. annuus* (340 µg plant^{-1}), and *E. tithymaloides* (171.81 µg plant^{-1}). High shoot accumulation of Pb in *G. grandiflora* suggests hyperaccumulation potential, while high root accumulation in *C. indica* is driven by its large biomass, as larger biomass provides more active absorption or metal binding sites (Jampasri et al. 2021). These results confirm that; besides the Pb concentration and accumulation capacity, the harvestable biomass of a plant is critical for efficient heavy metal extraction (Sarwar et al. 2017).

Difference in phytoremediation efficiency measures among ornamental plants

Identifying plant species tolerant to Pb is crucial for managing HM-contaminated soils. The TI is a key metric for assessing plant tolerance to heavy metals, based on growth response under metal stress (Piotto et al. 2018; Rehman et al. 2019). In this study, six plant species were grouped into three categories based on TI: (1) species with a negative TI-Pb concentration correlation, such as *T. pallida*; (2) species with a positive TI-Pb correlation, including *G. grandiflora* and *H. annuus*, and (3) species where TI increased at lower Pb levels but decreased at higher concentrations, such as *E. tithymaloides*, *C. indica*, and *B. juncea* (Table 3). These reports are in accordance with various previous reports. For example, Hamvumba et al. (2014) reported that TI of H. annuus increased up to Pb concentration of 500 mg kg^{-1} of soil. Similarly, TI of B. juncea increased to 109% at Pb concentration of 136 mg kg^{-1} (Bassegio et al. 2020). TI was set at 100% when Pb had no impact on growth (*e.g.,* T0 treatment). According to Lux et al. (2004), plants are classified as highly tolerant (TI > 60%), moderately tolerant (TI = 35–60%), or sensitive (TI < 35%). All six species exhibited TI values above 60%, indicating high Pb tolerance, even at 160 mg kg^{-1}, with no signs of phytotoxicity.

Two additional indices, the BCF and TF, were used to evaluate phytoremediation potential. BCF measures a plant's ability to accumulate Pb relative to soil concentration, while TF indicates Pb translocation from roots to shoots (Deepika and Haritash 2023a). Plants with BCF and TF > 1 are suitable for phytoextraction, while those with BCF > 1 but TF < 1 are better for phytostabilisation (Mahdavian et al. 2017; Hesami et al. 2018). However, to qualify as a Pb hyperaccumulator, a plant must accumulate >1000 mg kg^{-1} Pb in addition to having BCF and TF > 1 (Ullah et al. 2020b). BCF and TF values were calculated for the six ornamental plants to assess their phytoremediation potential in Pb-contaminated soil (Table 3).

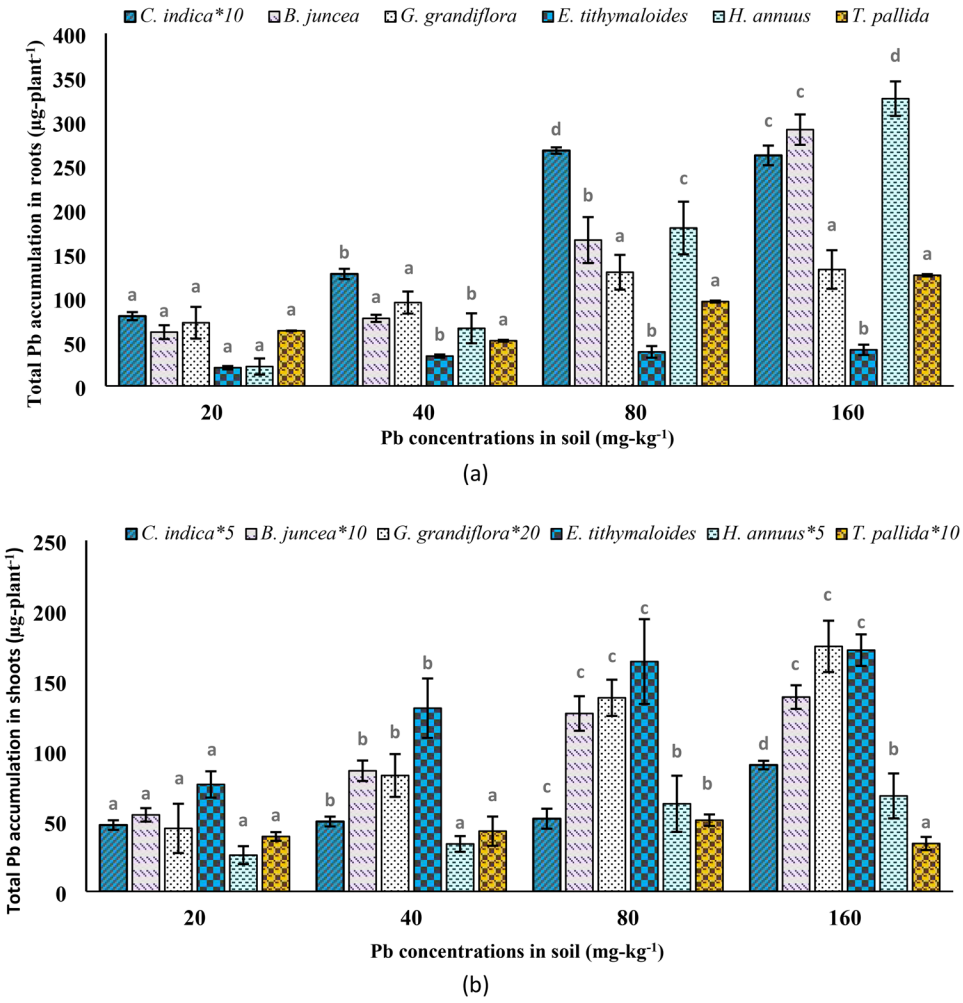


Figure 4. Total Pb accumulation in (a) roots, and (b) shoots of ornamental plants species. Treatment means ± SD with letter groupings—means sharing the same letter do not differ significantly at $p < 0.05$ by Duncan's multiple range test.

Table 3. Phytoremediation efficiency measures ($p < 0.05$).

Plant species	Treatments	BCF (Shoot)	BCF (Root)	TF	Tolerance index	Pb accumulation rate (μg g^{-1} day^{-1} DW)
C. indica	T1	0.75 ± 0.13^{c}	3.30 ± 0.22^{c}	0.23 ± 0.02^{c}	105 ± 4.61^{b}	0.3080 ± 0.05^{a}
	T2	0.38 ± 0.07^{b}	2.37 ± 0.15^{b}	0.16 ± 0.04^{b}	112.87 ± 4.99^{c}	0.4247 ± 0.07^{b}
	T3	0.20 ± 0.13^{a}	2.52 ± 0.04^{b}	0.08 ± 0.05^{a}	110.79 ± 3.83^{b}	0.8346 ± 0.08^{c}
	T4	0.24 ± 0.02^{a}	1.74 ± 0.12^{a}	0.14 ± 0.02^{b}	80.53 ± 3.51^{a}	1.201 ± 0.15^{d}
B. juncea	T1	1.44 ± 0.15^{d}	1.72 ± 0.06^{b}	0.84 ± 0.1^{b}	120.1 ± 8.84^{b}	0.2442 ± 0.02^{a}
	T2	1.04 ± 0.21^{c}	1.09 ± 0.06^{a}	0.94 ± 0.19^{b}	127.99 ± 13.08^{b}	0.3484 ± 0.06^{b}
	T3	0.72 ± 0.06^{b}	1.09 ± 0.05^{a}	0.6 ± 0.02^{a}	136.64 ± 13.5^{b}	0.5073 ± 0.04^{c}
	T4	0.54 ± 0.03^{a}	1.11 ± 0.19^{a}	0.49 ± 0.06^{a}	101.35 ± 3.85^{a}	0.7976 ± 0.02^{d}
G. grandiflora	T1	5.10 ± 0.06^{d}	4.48 ± 0.21^{d}	1.13 ± 0.03^{a}	160 ± 29.01^{a}	0.8420 ± 0.12^{a}
	T2	4.23 ± 0.31^{c}	2.61 ± 0.03^{c}	1.62 ± 0.13^{b}	178.62 ± 26.41^{a}	1.364 ± 0.09^{b}
	T3	2.45 ± 0.05^{b}	1.48 ± 0.04^{b}	1.64 ± 0.1^{b}	252.9 ± 36.95^{b}	1.585 ± 0.05^{c}
	T4	1.31 ± 0.01^{a}	0.82 ± 0.02^{a}	1.58 ± 0.04^{b}	295.55 ± 46.88^{b}	1.712 ± 0.06^{d}
E. tithymaloides	T1	0.43 ± 0.03^{d}	3.65 ± 0.25^{d}	0.58 ± 0.01^{a}	111.66 ± 6.24^{b}	0.087 ± 0.01^{a}
	T2	0.33 ± 0.03^{c}	2.67 ± 0.04^{c}	0.61 ± 0.06^{a}	124 ± 12^{c}	0.1334 ± 0.009^{b}
	T3	0.25 ± 0.03^{b}	1.84 ± 0.08^{b}	0.67 ± 0.06^{a}	102 ± 7.14^{b}	0.1977 ± 0.07^{c}
	T4	0.20 ± 0.02^{a}	1.21 ± 0.15^{a}	0.84 ± 0.17^{b}	67.76 ± 5.6^{a}	0.3168 ± 0.03^{d}
H. annuus	T1	0.64 ± 0.02^{d}	3.10 ± 0.19^{c}	0.2 ± 0.03^{c}	202.34 ± 28.93^{a}	0.1217 ± 0.005^{a}
	T2	0.38 ± 0.03^{c}	2.44 ± 0.14^{b}	0.15 ± 0.01^{b}	230.16 ± 22.91^{a}	0.1655 ± 0.003^{b}
	T3	0.25 ± 0.01^{b}	2.5 ± 0.05^{b}	0.1 ± 0.01^{a}	316.90 ± 37.36^{b}	0.2542 ± 0.02^{c}
	T4	0.13 ± 0.01^{a}	1.44 ± 0.12^{a}	0.09 ± 0.01^{a}	334.91 ± 39.57^{b}	0.3320 ± 0.05^{d}
T. pallida	T1	7.05 ± 0.86^{d}	15.67 ± 2.29^{c}	0.46 ± 0.12^{b}	128.23 ± 23.5^{c}	1.264 ± 0.14^{a}
	T2	5.04 ± 0.42^{c}	11.90 ± 1.19^{b}	0.43 ± 0.08^{b}	97.67 ± 5.7^{b}	1.792 ± 0.09^{b}
	T3	3.10 ± 0.17^{b}	11.49 ± 1.10^{b}	0.27 ± 0.04^{a}	93.81 ± 6.08^{b}	2.335 ± 0.09^{c}
	T4	1.61 ± 0.06^{a}	7.43 ± 0.14^{a}	0.22 ± 0.01^{a}	62.73 ± 4.86^{a}	2.705 ± 0.54^{c}

BCF_{root} values exceeded 1 for all species across treatments, except for *G. grandiflora* under T4, indicating effective Pb accumulation in roots. *T. pallida* showed the highest BCF_{root}, ranging from 15.67 ± 2.29 (T1) to 7.43 ± 0.14 (T4), while *B. juncea* had the lowest, ranging from 1.72 ± 0.06 (T1) to 1.11 ± 0.19 (T4). BCF_{shoot} values were >1 for *T. pallida* and *G. grandiflora* across all treatments, but only up to T2 for *B. juncea*, likely due to reduced metal uptake at higher Pb concentrations (Aransiola et al. 2013). The BCF_{shoot} order was *T. pallida* > *G. grandiflora* > *B. juncea* > *C. indica* > *H. annuus* > *E. tithymaloides*. For TF, only *G. grandiflora* had values >1 across all treatments, suggesting potential as a Pb hyperaccumulator. Other species had TF < 1, possibly due to Pb adsorption on root surfaces, immobilization by cell wall pectins, precipitation of insoluble Pb salts, accumulation in plasma membranes, sequestration in vacuoles, or barriers like the Casparian strip (Sterckeman et al. 2011; Saghi et al. 2016). The highest BCF_{root}, BCF_{shoot}, and TF values occurred under T1, likely due to lower Pb toxicity. These values decreased with increasing soil Pb concentrations, consistent with prior studies (Alaboudi et al. 2018; Shao et al. 2023). For instance, Tagetes erecta showed BCF and TF values of 0.78 and 0.23 at 20 mg kg^{-1} Pb, but these dropped to 0.11 and 0.19 at 160 mg kg^{-1} (Madanan et al. 2021).

C. indica showed the highest root Pb accumulation due to its large biomass, while *T. pallida* had the highest root Pb concentration but limited accumulation due to low biomass. *G. grandiflora* exhibited strong phytoextraction potential with high shoot Pb accumulation and TF > 1. These findings highlight *C. indica*, *B. juncea*, *E. tithymaloides*, *G. grandiflora*, and *H. annuus* as viable candidates for phytoremediation, with *G. grandiflora* particularly suited for phytoextraction and others for phytostabilisation.

Conclusion

This study demonstrates the potential of six ornamental plant species—*H. annuus*, *G. grandiflora*, *B. juncea*, *E. tithymaloides*, *T. pallida*, and *C. indica*—for phytoremediation of Pb-contaminated soils. Most species, except *T. pallida*, exhibited high tolerance to Pb stress, with stable or enhanced growth up to 160 mg kg^{-1} Pb. *G. grandiflora* showed exceptional phytoextraction potential, with high Pb accumulation in shoots and TF values > 1, while *C. Indica* excelled in phytostabilisation due to significant root Pb accumulation and large biomass. *T. pallida*, despite high Pb uptake, was limited by reduced growth, making it less suitable for practical applications. The high BCF_{root} values across all species confirm their ability to accumulate Pb, particularly in roots, supporting their use in phytostabilisation. These ornamental plants offer a sustainable, cost-effective, and esthetically pleasing approach to remediating Pb-contaminated soils. Future research should explore their performance under field conditions and over extended periods to optimize phytoremediation strategies and assess long-term ecological impacts.

Author contributions

All authors contributed to the study conception, design, data collection, and analysis.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

All data used or analyzed during this study are included in this article.

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