***Pak. J. Bot.*, 58(11): November 2026.**

ARTICLE **DOI: http://dx.doi.org/10.30848/PJB2026-11(12)**

ENHANCING THE PHYTOEXTRACTION CAPACITY OF TWO ORNAMENTAL PLANTS BY ORGANIC FERTILIZER IN LEAD AND ALUMINUM CONTAMINATED SOIL

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Abstract

Globally, the risks, environmental and health-wise, posed by soil contamination with heavy metals, particularly lead (Pb) and aluminum (Al), is significant. The use of ornamental plants, in phytoextraction, as a remedy strategy against this contamination is not only aesthetically viable but also a sustainable strategy. Two ornamental species: *Bougainvillea spectabilis* and *Zinnia elegans* were evaluated in this study for their potential to extract Pb and Al from contaminated soil. The study also assessed the role of organic fertilizer (5% farmyard manure) in boosting their phytoextraction efficiency. Under controlled greenhouse conditions, plants were subjected to three concentrations (100, 200, and 300 mg kg⁻¹) each of Pb (as $Pb(NO_3)_2$) and Al (as $AlCl_2$), with or without organic amendment. Morphological, physiological, and biochemical parameters were measured six weeks post-treatment conditions. The results revealed that both Pb and Al significantly ($p \leq 0.05$) led to reduction in the plant height, leaf number, leaf area, and biomass in both species. These adverse effects were, however, ameliorated by the use of organic fertilizer as growth parameters were improved by up to 28%. Physiological parameters like, stomatal conductance, transpiration rate, chlorophyll fluorescence (Fv/Fm), and total chlorophyll content, were also affected negatively by the heavy metal soil contamination. These indicators, nevertheless, were also ameliorated with the of organic amendment. The increase in metal accumulation in shoots and roots was proportional with rising external concentrations. Comparatively, the shoots recorded higher accumulation than roots. The translocation factor (TF) was increased by up to 75% in *B. spectabilis* and 72% in *Z. elegans* as organic fertilizer further improved metal uptake and translocation. Taken together, these results upholds that organic fertilizer greatly promotes the growth, physiology, and metal-accumulating capability of both *B. spectabilis* and *Z. elegans*. Therefore, this investigation lends credence to the adoption of organic-amended ornamental plants as an efficient, sustainable panacea for the phytoextraction of Pb and Al from contaminated soils, while combining remediation with ecological and aesthetic advantage.

Key words: Aluminum (Al); *Bougainvillea spectabilis*; Heavy metal stress; Lead (Pb); Phytoextraction; Soil remediation; *Zinnia elegans*.

Introduction

Heavy metals soil contamination still rank high as part of the environmental challenge faced worldwide. It is largely caused by improper waste disposal and anthropogenic activities like mining, industrial emissions and agricultural practices (Haghighizadeh *et al*., 2024). The challenge heavy metals pose in the environment could be more dire than organic pollutants since heavy metals are non-degradable and can remain in soils for many years, leading to significant risks to human well-being, health, food safety and ecosystem, through bioaccumulation and trophic transfer (Yadav *et al*., 2025). Lead (Pb) and aluminum (Al) are among the most notable metallic pollutants. Even at relatively minute concentrations, both Pb and Al exhibit high toxicity to humans, plants, animals, and humans (Generalova *et al*., 2025; Ofoe *et al*., 2023).

Lead is a highly toxic and prevalent element. According to the Agency for Toxic Substances and Disease Registry (ATSDR), it ranks second on the priority list of hazardous substances. Coupled with natural processes such as volcanic activity and weathering, anthropogenic sources contribute to Pb release and accounts for its pervasiveness and widespread. These activities include effluents from industries, leaded gasoline, paints and batteries (Raj & Das, 2023). Pb toxicity, in plants, disturbs the uptake of nutrients, activity of enzyme, triggers oxidative stress, and impairs photosynthesis, leading to reduction in growth and yield decline (Ur Rahman *et al*., 2024). According to the World Health Organization (WHO), the maximum allowable lead (Pb) concentration is 2 mg kg⁻¹ in plants and 50–300 mg kg⁻¹ in agricultural soils. Exceeding these limits can result in severe morphological and physiological damage.

Despite its abundance in the Earth's crust, Aluminum becomes phytotoxic especially in acidic soils ($pH < 5.5$), where it solubilizes into the mobile Al^{3+} form. The negative consequences of Al toxicity, leading to enormous reductions in plant productivity, emanates from its root elongation inhibition, membrane integrity disruption, and cellular division disturbance and nutrient acquisition interference (Ofoe *et al*., 2023). Unlike other plants that exclude Al from their root uptake, hyperaccumulators are

Received: 23-02-2026 Revised: 08-05-2026 Accepted: 19-05-2026 Online: 11-06-2026

plants that can take up Al and translocate it. Hyperaccumulators are thus desirous for phytoextraction and remediation of soil heavy metals contamination.

The dark sides of conventional remediation approaches, such as excavation, soil washing and soil stabilization, include high cost of resources and energy coupled with its undesirous soil ecosystem disruption (Yadav *et al*., 2025). Conversely, phytoremediation, particularly, phytoextraction offers the economic, sustainable and eco-friendly alternative. Plants used for phytoextractions reduce metal loads by up taking, translocating and concentrating metals in harvestable above-ground tissues (Eben *et al*., 2024).

Nevertheless, low metal bioavailability in soil, slow plant growth, and insufficient biomass production can impede the efficiency of phytoextraction. To surmount these limitations, the use of soil enhancements strategies comes handy. The commonly utilised strategies are agronomic practices, use of microbial inoculants, synthetic chelators and soil amendments (Sabir *et al*., 2013). Soil amendments using biochar and organic materials like manure and compost have a dual of advantage of improving soil fertility and promoting metal mobility. Ultimately, these organic matters promote plant growth and metal uptake as they alter soil pH, provide essential nutrients and improve soil microbial activity (Hong *et al*., 2022).

Especially in urban and peri-urban areas, ornamental plants are increasingly recognized as potential candidates for phytoremediation. Since they are not edible crops, the risk of heavy metals entering the food chain is minimized. Simultaneously, they provide aesthetic, ecological, and economic benefits (Liu *et al*., 2018). *Bougainvillea spectabilis* and *Zinnia elegans* are particularly well-suited because of their rapid growth, substantial biomass production, resilience to environmental stress, and capacity to accumulate metals within their tissues (Neto *et al*., 2020). However, systematic studies examining the combined role of organic amendments on the phytoextraction capacity of these ornamental species are scarce.

The current investigation thus aims to assess the potential of *B. spectabilis* and *Z. elegans* for the phytoextraction of Pb and Al from contaminated soils, and to investigate the effect of organic fertilizer (5% farmyard manure) in improving their remediation efficacy.

This study specifically focuses on how metal stress and organic amendments influence plant growth, physiological performance, as well as the processes of metal accumulation and translocation. The outcomes are expected to support the development of sustainable, plant-based remediation strategies that combines soil improvement, landscape valorisation and pollution mitigation.

Materials and Methods

Plant materials and growth conditions: The study was carried out in a glasshouse at the of the Department of Biological Sciences, King Abdulaziz University (Jeddah, Saudi Arabia) to ensure controlled conditions. The greenhouse conditions maintained were a 12-hour photoperiod supplemented with artificial lighting, 25–27°C, and 60% relative humidity. The seeds of both ornamental species, *B. spectabilis* and *Z. elegans*, were gotten from a local store in Jeddah. Plants were grown in plastic pots of 30 cm height and 15 cm diameter, lined with polyethylene bags to prevent leaching. 6 kg of uniform soil was used to fill each pot. The soil was taken from the topmost layer (0–20 cm) of an uncontaminated agricultural field in Jeddah. It was sieved (2 mm), air-dried, and homogenized.

Initial physicochemical properties were:
- Texture: Sandy loam (62% sand, 28% silt, 10% clay; determined by the hydrometer method)
- pH: 7.4 ± 0.2 (in 1:2.5 soil:water suspension)
- Organic Matter: 1.2% ± 0.1% (by loss-on-ignition)
- Cation Exchange Capacity (CEC): 8.5 ± 0.5 $\text{cmol}^+\ \text{kg}^{-1}$
- Background Metals (Total): Pb: <15 mg kg^{-1}; Al: 1,200 ± 85 mg kg^{-1}.

Experimental design and treatments: The experimental setup used a factorial design of 2 × 2 × 3 × 3 and a completely randomised design. This involved both plant species of *B. spectabilis* and *Z. elegans* and two fertilizer conditions that is, with and without organic fertilizer (5% farmyard manure, FYM). While the two heavy metals (HM) in the study are Aluminum (Al) as $AlCl_2$ and Lead (Pb) as $Pb(NO_3)_2$, the three HM concentrations used were: 100, 200, and 300 mg kg^{-1}. Each treatment was replicated. Three replicates was used per treatment combination.

The experiment included the following treatment groups:

1. Control (C): Soil without HM addition.
2. HM-only treatments (T1, T2, T3): Soil spiked with Al or Pb at 100, 200, or 300 mg kg^{-1}.
3. HM + Organic Fertilizer (OF) treatments: Soil spiked with HM as above and amended with 5% (w/w) FYM.

Heavy metal solutions were prepared in distilled water and applied evenly to the soil surface. Pots were left for stabilization before transplanting uniform seedlings at the three-leaf stage. FYM was applied at a rate of 5% (w/w). For each pot (6 kg soil), 300 g of FYM was thoroughly incorporated into the top 15 cm of soil one week prior to transplanting. For metal+FYM treatments, FYM was incorporated after metal equilibration.

Data collection: After six weeks of treatment, plants were randomly selected from each replicate for morphological, physiological, and biochemical analyses.

Morphological parameters: Plant height (cm) was measured from the soil surface to the shoot apex. Leaf number was counted manually per plant. Leaf area (cm^2) was estimated using the formula by Fascella *et al*., (2017) based on length and width measurements.

For fresh and dry biomass measurements, shoots were separated from roots, weighed immediately for fresh weight, then dried at 80°C for 72 hours to determine dry weight.

Physiological parameters: Gas exchange and chlorophyll fluorescence were measured using a portable photosynthesis system (CIRAS-3, PP Systems). This includes stomatal conductance (Gs, $\text{mmol m}^{-2}\ \text{s}^{-1}$), transpiration rate (E, $\text{mmol m}^{-2}\ \text{s}^{-1}$), and chlorophyll fluorescence (Fv/Fm) i.e. the ratio of variable to maximum fluorescence of dark-adapted leaves.

Biochemical analyses: Total chlorophyll content was determined spectrophotometrically using 80% acetone extracts following the method of Coombs *et al.*, (1985). Absorbance was measured at 646 and 663 nm, and chlorophyll concentration was calculated using the Beer–Lambert equation. Heavy metal concentration in plant tissues: Shoots and roots were dried, ground, and digested in a 4:1 (v/v) mixture of HNO_3 and HCl at 200°C. Concentrations of Al and Pb were quantified using atomic absorption spectroscopy (PerkinElmer Optima 8000).

Translocation factor (TF) was calculated as:

$$\text{Translocation factor, TF}=\frac{\text{The metal concentration in shoot }(\frac{\text{mg}}{\text{kg}})}{\text{The metal concentration in root }(\frac{\text{mg}}{\text{kg}})}$$

Statistical analysis

Data were subjected to one-way analysis of variance (ANOVA) using SPSS version 25.0. Treatment means were compared using Duncan's Multiple Range Test (DMRT) at a significance level of $p \leq 0.05$. Results are presented as mean ± standard error (SE) of three replicates.

Results

Growth parameters: The growth of both *B. spectabilis* and *Z. elegans* was significantly $p \leq 0.05$ affected by heavy metal (Al and Pb) exposure and organic fertilizer (OF) amendment (Tables 1 and 2).

In *B. spectabilis*, increasing concentrations of Al and Pb reduced plant height, leaf number, leaf area, and shoot biomass (fresh and dry weight) in a dose-dependent manner. The highest concentration (300 mg kg^{-1}) of Pb caused the most severe reduction in plant height (37 cm vs. 69 cm in control) and leaf number (30.11 vs. 50.13 in control). Under these adverse conditions of Pb contamination, especially at 300 mg kg^{-1}, organic fertilizer (5% FYM) mitigated the bad consequences on the plants by improving the plant height by 4 cm (37 in HM only plants vs 41cm in HM+OF plants) and dry weight by up to 18 percent.

Similarly, *Z. elegans* exhibited growth inhibition under Al and Pb stress, with the most pronounced effects at 300 mg kg^{-1}. Organic fertilizer application improved growth metrics, particularly at lower metal concentrations. For example, under Pb stress at 100 mg kg^{-1}, plant height increased from 27.51 cm (HM-only) to 30.04 cm (HM+OF), and dry weight increased by 28%.

Physiological Parameters

Stomatal conductance (Gs): Stomatal conductance was significantly reduced by Al and Pb stress in both species $p \leq 0.05$. Organic fertilizer amendment mitigated this reduction, increasing Gs by 8–27% in *B. spectabilis* and 4–27% in *Z. elegans* relative to HM-only treatments (Figs. 1 and 2).

Transpiration rate (E): Transpiration rate followed a similar trend, with significant decreases under HM stress. Organic fertilizer increased E by 19–38% in *B. spectabilis* and 14–27% in *Z. elegans* across treatments (Figs. 3 and 4).

Chlorophyll fluorescence (Fv/Fm): The Fv/Fm ratio, an indicator of photosystem II efficiency, declined under HM stress. Organic fertilizer improved Fv/Fm by 8–16% in *B. spectabilis* and 11–25% in *Z. elegans* (Figs. 5 and 6).

Total chlorophyll content: Total chlorophyll content decreased with increasing HM concentrations. Organic fertilizer significantly restored chlorophyll levels, with increases of up to 32% in *B. spectabilis* and 28% in *Z. elegans* at the highest HM concentration (Figs. 7 and 8).

Heavy metal accumulation in plant tissues: Heavy metal accumulation in shoots and roots increased with rising external concentrations (Tables 3 and 4). Both species accumulated higher concentrations of Al and Pb in shoots than in roots. Organic fertilizer further enhanced metal accumulation, particularly in shoots.

Table 1. Effect of Al, Pb, and organic fertilizer (5% FYM) on growth parameters of Bougainvillea spectabilis.

Control (mg/Kg)

Elements + Treatments		Plant height (cm)	Number of leaves/ plant	Leaf area (cm^2)	Fresh shoot (g)	Dry shoot (g)
Al	T1	62 ± 5.4^{a}	47.25 ± 4.1^{a}	11.97 ± 1.1^{a}	38.11 ± 3.41^{a}	5.88 ± 5.3^{a}
	T2	50 ± 4.9^{b}	46.57 ± 5.4^{a}	10.19 ± 0.92^{b}	36.77 ± 3.23^{b}	5.27 ± 5.12^{b}
	T3	49.3 ± 4.8^{b}	35.91 ± 3.6^{b}	9.82 ± 5.4^{c}	34.36 ± 3.31^{c}	4.98 ± 5.31^{c}
Pb	T1	69 ± 5.8^{a}	50.13 ± 4.8^{a}	16.43 ± 1.5^{a}	39.22 ± 3.4^{a}	5.64 ± 5.5^{a}
	T2	63 ± 5.5^{b}	47.66 ± 4.5^{b}	13.57 ± 1.2^{b}	35.16 ± 3.12^{b}	5.01 ± 5.23^{b}
	T3	37 ± 3.2^{c}	30.11 ± 2.8^{c}	12.73 ± 1.12^{c}	34.17 ± 3.2^{c}	4.15 ± 5.32^{c}

Organic fertilizer 5% + Element (mg/Kg)

Elements + Treatments		Plant height (cm)	Number of leaves/ plants	Leaf area (cm^2)	Fresh shoot (g)	Dry shoot (g)
Al	T1	71 ± 6.7^{a}	56.10 ± 4.7^{a}	15.11 ± 1.2^{a}	45.79 ± 3.9^{a}	5.87 ± 0.4^{a}
	T2	61 ± 5.2^{b}	49.31 ± 4.7^{b}	14.88 ± 1.15^{a}	43.16 ± 3.8^{a}	5.11 ± 0.4^{b}
	T3	56 ± 5.1^{c}	43.83 ± 4.1^{c}	12.67 ± 1.2^{b}	41.23 ± 3.7^{b}	5.01 ± 4.3^{b}
Pb	T1	75 ± 5.3^{a}	52.17 ± 5.02^{a}	17.02 ± 1.13^{a}	48.55 ± 4.1^{a}	5.69 ± 0.3^{a}
	T2	67 ± 5.9^{b}	51.33 ± 4.3^{a}	15.60 ± 1.17^{b}	44.90 ± 3.4^{b}	5.57 ± 0.5^{a}
	T3	71 ± 6.7^{a}	56.10 ± 4.7^{a}	15.11 ± 1.2^{a}	45.79 ± 3.9^{a}	5.87 ± 0.4^{a}

Values are means ± SE (n=3). Different letters within columns indicate significant differences ($p \leq 0.05$) among treatments for each metal

Table 2. Effect of Al, Pb, and organic fertilizer (5% FYM) on growth parameters of Zinnia elegans.

Elements + Treatments		Plant height (cm)	Number of leaves/ plant	Leaf area (cm^2)	Fresh shoot (g)	Dry shoot (g)
Control (mg/Kg)						
Al	T1	27.53 ± 2.66^{a}	21.61 ± 2.22^{a}	5.8 ± 0.43^{a}	13.41 ± 1.46^{a}	3.18 ± 0.4^{a}
	T2	25.88 ± 2.46^{b}	20.19 ± 2.07^{b}	5.68 ± 0.88^{a}	11.09 ± 1.16^{b}	2.81 ± 0.22^{b}
	T3	24.16 ± 2.46^{b}	19.33 ± 2.12^{c}	5.09 ± 0.83^{b}	10.98 ± 1.33^{c}	2.67 ± 0.34^{b}
Pb	T1	27.51 ± 2.31^{a}	24.17 ± 2.4^{a}	6.39 ± 0.9^{a}	13.41 ± 1.31^{a}	3.18 ± 0.4^{a}
	T2	26.92 ± 2.25^{b}	22.63 ± 2.76^{b}	5.95 ± 0.37^{b}	11.09 ± 1.37^{b}	2.81 ± 0.2^{b}
	T3	25.09 ± 2.09^{c}	21.44 ± 2.3^{c}	5.13 ± 0.82^{c}	10.98 ± 1.39^{c}	2.67 ± 0.21^{b}
Organic Fertilizer 5% + Element (mg/Kg)						
Elements + Treatments		**Plant height (cm)**	**Number of leaves/ plants**	**Leaf area (cm^2)**	**Fresh shoot (g)**	**Dry shoot (g)**
Al	T1	29.44 ± 2.82^{a}	27.55 ± 2.71^{a}	7.52 ± 0.7^{a}	12.94 ± 1.1^{a}	4.02 ± 0.4^{a}
	T2	27.09 ± 2.56^{b}	25.13 ± 2.56^{b}	6.86 ± 0.66^{b}	11.33 ± 0.96^{b}	3.42 ± 0.32^{b}
	T3	26.85 ± 2.62^{c}	23.16 ± 2.3^{c}	6.99 ± 0.64^{b}	10.71 ± 1.0^{c}	3.20 ± 0.3^{b}
Pb	T1	30.04 ± 2.91^{a}	28.19 ± 2.72^{a}	7.29 ± 0.67^{a}	17.65 ± 1.3^{a}	4.08 ± 0.4^{a}
	T2	29.83 ± 2.89^{a}	25.46 ± 2.6^{b}	7.03 ± 0.68^{a}	16.37 ± 1.3^{b}	3.89 ± 0.29^{a}
	T3	28.61 ± 2.87^{b}	23.10 ± 2.56^{c}	5.9 ± 0.57^{b}	15.22 ± 1.2^{c}	3.40 ± 0.32^{b}

Values are means ± SE (n=3). Different letters within columns indicate significant differences ($p \leq 0.05$) among treatments for each metal

Table 3. Concentration of Al and Pb ($mg\ kg^{-1}$ dry weight) in shoot and root tissues of Bougainvillea spectabilis under different treatments.

Elements + Treatments		Control (mg/Kg)	organic fertilizer 5% + Element(mg/Kg)
Shoot			
Al	T1	5.12 ± 1.83^{c}	37.22 ± 4.99^{c}
	T2	12.01 ± 2.67^{b}	49.83 ± 4.60^{b}
	T3	25.05 ± 4.00^{a}	81.24 ± 6.66^{a}
Pb	T1	11.17 ± 2.66^{c}	56.08 ± 3.57^{c}
	T2	20.90 ± 1.55^{b}	60.55 ± 3.30^{b}
	T3	29.37 ± 2.88^{a}	96.85 ± 6.96^{a}
Root			
Al	T1	4.18 ± 0.80^{c}	9.65 ± 1.48^{c}
	T2	10.19 ± 1.78^{b}	18.91 ± 3.46^{b}
	T3	18.72 ± 3.20^{a}	27.94 ± 2.76^{a}
Pb	T1	9.40 ± 1.43^{c}	11.31 ± 1.76^{c}
	T2	16.98 ± 2.20^{b}	15.03 ± 2.92^{b}
	T3	23.58 ± 1.76^{a}	28.23 ± 2.56^{a}

Values are means ± SE (n=3). Different letters within columns indicate significant differences ($p \leq 0.05$) among treatments for each metal

Table 4. Concentration of Al and Pb ($mg\ kg^{-1}$ dry weight) in shoot and root tissues of Zinnia elegans under different treatments.

Elements + Treatments		Control (mg/Kg)	organic fertilizer 5% + Element(mg/Kg)
Shoot			
Al	T1	11.46 ± 1.89^{c}	35.93 ± 2.28^{c}
	T2	18.66 ± 4.13^{b}	65.80 ± 4.94^{b}
	T3	30.62 ± 5.47^{a}	83.94 ± 9.47^{a}
Pb	T1	9.08 ± 1.80^{c}	48.56 ± 0.90^{c}
	T2	17.92 ± 2.26^{b}	59.89 ± 4.20^{b}
	T3	30.32 ± 2.46^{a}	95.47 ± 5.68^{a}
Root			
Al	T1	11.46 ± 1.89^{c}	35.93 ± 2.28^{c}
	T2	18.66 ± 4.13^{b}	65.80 ± 4.94^{b}
	T3	30.62 ± 5.47^{a}	83.94 ± 9.47^{a}
Pb	T1	9.08 ± 1.80^{c}	48.56 ± 0.90^{c}
	T2	17.92 ± 2.26^{b}	59.89 ± 4.20^{b}
	T3	30.32 ± 2.46^{a}	95.47 ± 5.68^{a}

Values are means ± SE (n=3). Different letters within columns indicate significant differences ($p \leq 0.05$) among treatments for each metal

Translocation factor (TF): The translocation factor (TF) increased with rising HM concentrations and was further enhanced by organic fertilizer application (Figs. 9 and 10). For *B. spectabilis*, TF increased by 58–75% under Al and Pb stress with OF. In *Z. elegans*, TF increased by 32–72% under the same conditions. These results indicate improved root-to-shoot metal translocation in the presence of organic amendments.

Discussion

Generally, heavy metals abundance in the soil is a major menace in soil health globally. The usage of ornamental plants in phytoextraction combines the aesthetic appeal and a more cost-effective choice approach to conventional remediation. The present finding proves that both *B. spectabilis* and *Z. elegans* can accommodate and tolerate Al and Pb toxicity. It further establishes that the tolerance of both species is further enhanced by the application of organic fertilizer.

Organic fertilizer mitigates heavy metal-induced growth inhibition: According to Gupta *et al*., (2013), heavy metals have negative impacts on the growth of plants by disturbing their photosynthesis, root development and uptake of nutrients. In this experiment similarly, Al and Pb, considerably, reduced plant height, leaf surface area, leaf number and biomass in both *B. spectabilis* and *Z. elegans*. By way of comparison, it was evident that Pb toxicity was higher than Al toxicity. This outcome agrees with previous reports on metal-induced growth in ornamental species (Neto *et al*., 2020).

The application 5% FYM greatly relieve the plant of these unfavourable impacts. The perceived improvement in growth under OF amendment can be linked to several causes like nutrient availability (N, P, K) and improved soil fertility. Other factors are enhanced soil structure and water-holding capacity, stimulation of useful microbial activity in the rhizosphere chelation of metals by organic matter and reducing phytotoxicity. Similar favourable impacts of organic adjustments on plant growth under heavy metal stress have been documented for other species (Irin & Hasanuzzaman, 2024; Saleem *et al*., 2024).

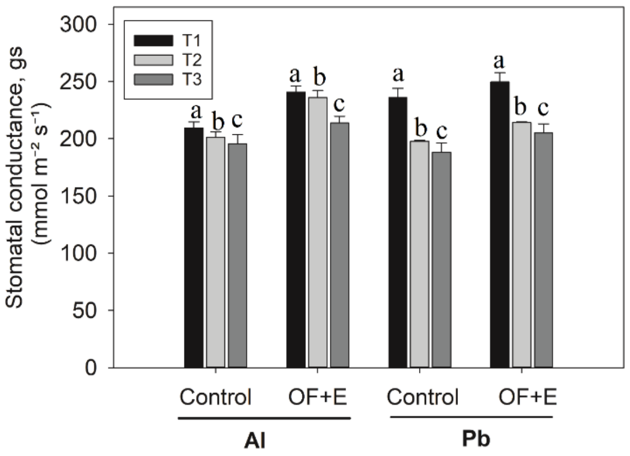

Fig. 1. Impact of heavy metals (Al, Pb) + organic fertilizer (5%) on stomatal conductance (Gs) of *Bougainvillea spectabilis*. The data that are being displayed are the means (±SE) of three replicates, and bars with different letters differ significantly from one another when compared at the p≤0.05 level of statistical significance.

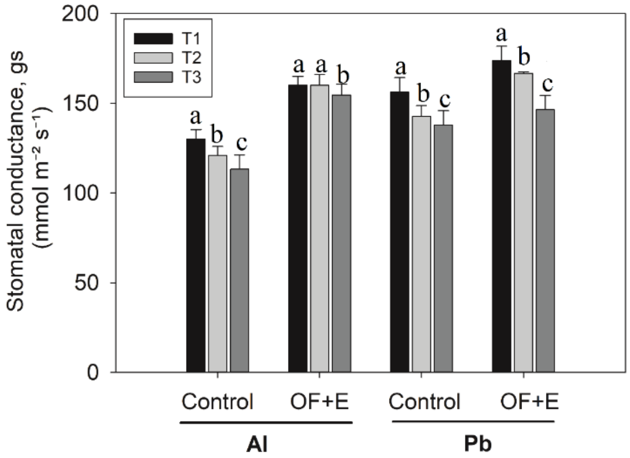

Fig. 2. Impact of heavy metals (Al, Pb) + organic fertilizer (5%) on stomatal conductance (Gs) of *Zinnia elegans*. The data that are being displayed are the means (±SE) of three replicates, and bars with different letters differ significantly from one another when compared at the p≤0.05 level of statistical significance.

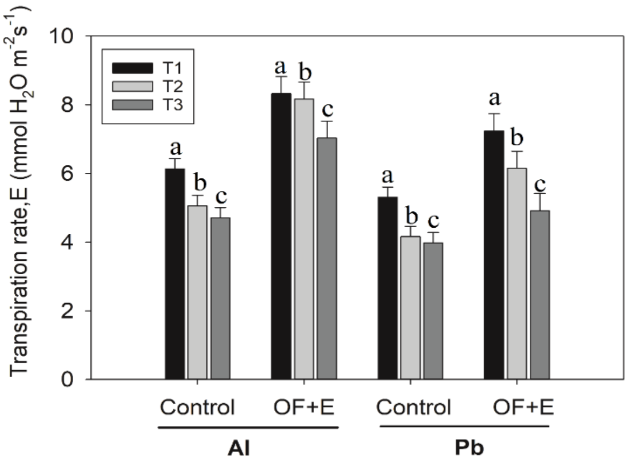

Fig. 3. Impact of heavy metals (Al, Pb) + organic fertilizer (5%) on transpiration rate (E) of *Bougainvillea spectabilis*. The data that are being displayed are the means (±SE) of three replicates, and bars with different letters differ significantly from one another when compared at the p≤0.05 level of statistical significance.

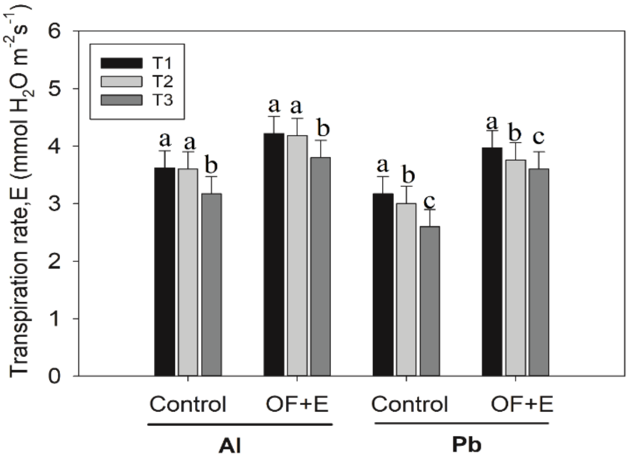

Fig. 4. Impact of heavy metals (Al, Pb) + organic fertilizer (5%) on transpiration rate (E) of *Zinnia elegans*. The data that are being displayed are the means (±SE) of three replicates, and bars with different letters differ significantly from one another when compared at the p≤0.05 level of statistical significance.

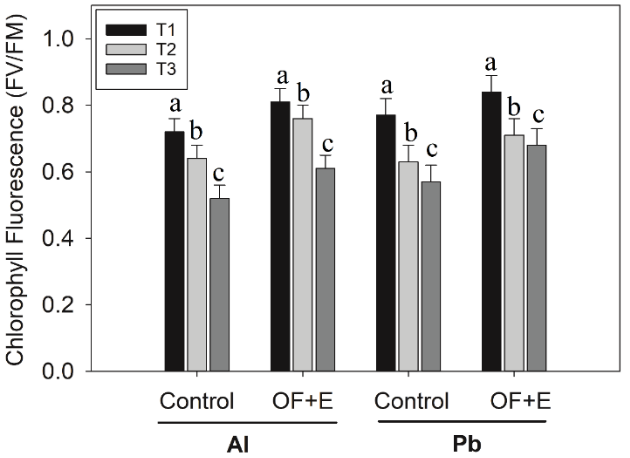

Fig. 5. Impact of heavy metals (Al, Pb) + organic fertilizer (5%) on chlorophyll fluorescence (FV/FM) of *Bougainvillea spectabilis*. The data that are being displayed are the means (±SE) of three replicates, and bars with different letters differ significantly from one another when compared at the p≤0.05 level of statistical significance.

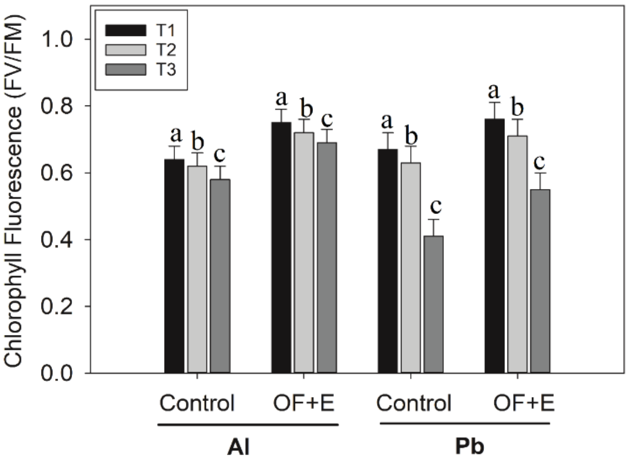

Fig. 6. Impact of heavy metals (Al, Pb) + organic fertilizer (5%) on chlorophyll fluorescence (FV/FM) of *Zinnia elegans*. The data that are being displayed are the means (±SE) of three replicates, and bars with different letters differ significantly from one another when compared at the p≤0.05 level of statistical significance.

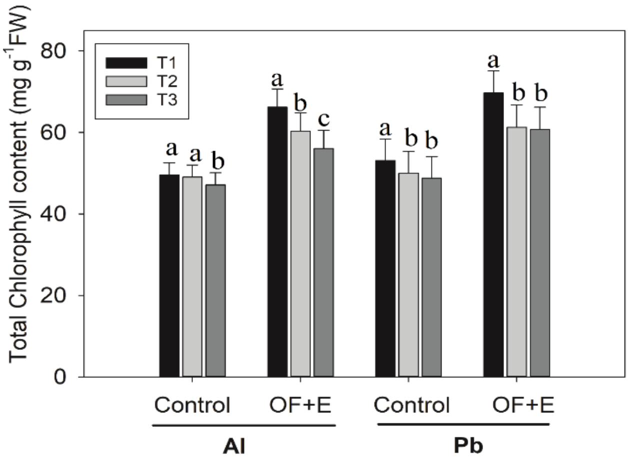

Fig. 7. Impact of heavy metals (Al, Pb) + organic fertilizer (5%) on total Chl of *Bougainvillea spectabilis.* The data that are being displayed are the means (±SE) of three replicates, and bars with different letters differ significantly from one another when compared at the p≤0.05 level of statistical significance.

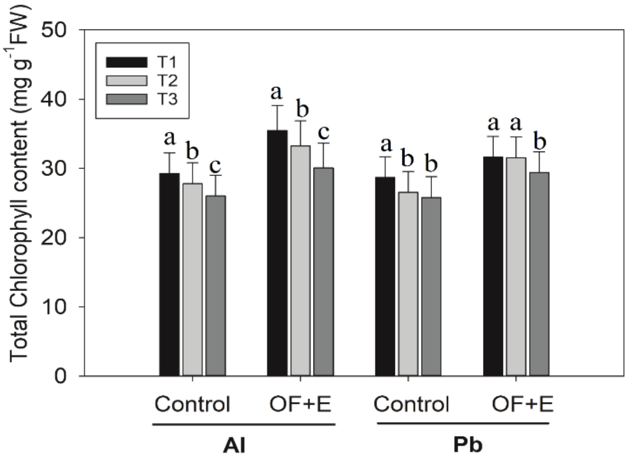

Fig. 8. Impact of heavy metals (Al, Pb) + organic fertilizer (5%) on total Chl of *Zinnia elegans.* The data that are being displayed are the means (±SE) of three replicates, and bars with different letters differ significantly from one another when compared at the p≤0.05 level of statistical significance.

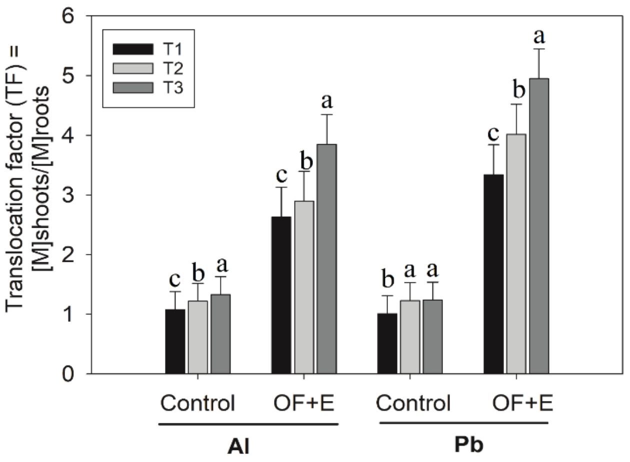

Fig. 9. Impact of heavy metals (Al, Pb) + organic fertilizer (5%) on the translocation factor (TF) of *Bougainvillea spectabilis.* The data that are being displayed are the means (±SE) of three replicates, and bars with different letters differ significantly from one another when compared at the p≤0.05 level of statistical significance.

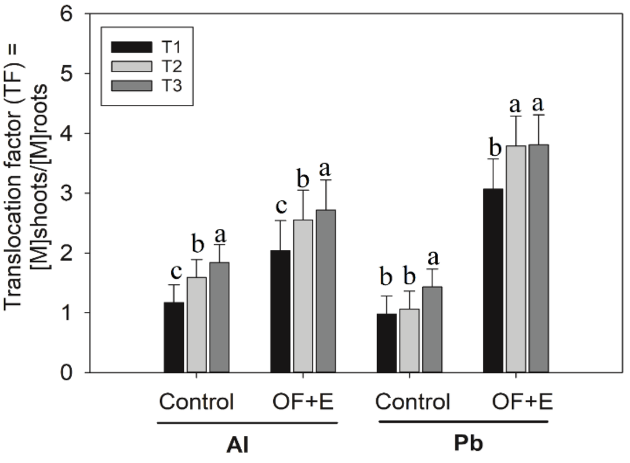

Fig. 10. Impact of heavy metals (Al, Pb) + organic fertilizer (5%) on the translocation factor (TF) of *Zinnia elegans.* The data that are being displayed are the means (±SE) of three replicates, and bars with different letters differ significantly from one another when compared at the p≤0.05 level of statistical significance.

Physiological responses to heavy metal stress and organic amendment: Heavy metals can negatively interfere with photosynthesis in plants via stomatal closure, chlorophyll degradation and impaired electron transport (Gao *et al*., 2022). Our report corroborates this assertion as reduced transpiration rate, chlorophyll fluorescence, stomatal conductance and total chlorophyll contents were recorded during Pb and Al stress.

Interestingly, organic fertilizer alleviated these physiological impairments, possibly through improved antioxidant defence systems, increased availability of elements like magnesium for chlorophyll synthesis, reduced oxidative stress via metal chelation and better water relations and nutrient balance

As stated by Landi & Guidi (2023), maintenance of Photosystem II integrity is essential for of ensuring photosynthetic efficiency vis-à-vis stress conditions. It is noted from our results that the Fv/Fm ratio which was negatively affected by the metal stress was restored in OF-treated plants. This serves as a vital indicator for the protection of Photosystem II. Consequently, these physiological improvements contribute directly to metal accumulation capacity and better biomass production.

Heavy metal accumulation and translocation patterns: Both *B. spectabilis* and *Z. elegans* had higher Al and Pb concentration in shoots than the roots. This may be due to efficient mechanisms of metal translocation. This may be important for phytoextraction, as metal removal may be easy. The concentration-dependent mechanism of metal uptake by plants is consistent with the literature on metal uptake by ornamental plants (Neto *et al*., 2020).

The application of organic fertilizer increased the concentration of metals in plant parts, especially shoots. This may be due to increased plant growth, resulting in increased metal uptake. Organic fertilizers may have increased the solubility of metals by generating organic acids, thereby increasing metal uptake by plants

The high value of the translocation factor (TF) for all treatments, especially those amended with organic fertilizer, where TF was higher than 1, shows that both plants can efficiently transport metals from the roots to the shoots—a condition necessary for efficient phytoextraction (Usman *et al*., 2019).

Species-specific performance and practical implications: *B. spectabilis* was more tolerant to metals and had greater potential for metal accumulation compared to *Z. elegans*, especially for Pb. This can be due to its perennial habit, more developed root system, and inherent physiological characteristics. Nevertheless, *Z. elegans* has great potential, especially when organic fertilizer was used.

The implications of the study for its potential applications are as follows:

The study has implications for the potential applications of the two plant species in the phytoremediation of Al and Pb in contaminated soils. It also has implications for the aesthetic value of using organic fertilizer in the process. In general terms, the implications of the study can be summed up as follows:

The two plant species have great potential for phytoremediation of Al and Pb in contaminated soils.
The use of organic fertilizer has aesthetic value in addition to its potential in phytoremediation.

Mechanisms of organic fertilizer enhancement: The positive effects of organic fertilizer in our study are probably mediated through several interacting processes:

1. Chemical: The formation of metal-organic complexes and changes in the speciation of the metals.
2. Physical: The improvement of the structure and aeration of the soil and the development of plant roots.
3. Biological: The stimulation of microorganisms that are involved in the transformation of the metals and the nutrients in the soil.
4. Nutritional: The delivery of nutrients that are vital for the metabolism of the plant and the development of stress tolerance.

These processes are likely to result in what can be referred to as "assisted phytoextraction."

Future research directions: Although the results of our study have shown the advantages of using organic fertilizer in the process of phytoextraction, some points need to be further explored. It is necessary to examine the results in long-term field experiments in different conditions of the environment. It is also important to examine the molecular processes that control the uptake, transport, and detoxification of metals in the plant species used. It is also important to examine the impact of different organic fertilizers and rates of their application. It is also important to examine the potential risks of using organic fertilizers in terms of leaching and the food chain. It is also important to conduct economic studies to examine the possibilities of using the mentioned methods in practice. It is also important to examine the potential for using organic fertilizers in combination with other methods for increasing the efficiency of phytoextraction.

Conflict of Interest: No conflict of interest to declare

Author's Contribution: Conceptualization: Y. A, methodology: H.A., formal analysis and data curation A.Y.A, writing—original draft preparation, K. R. H; writing—review and editing: A.S.A. All authors have read and agreed to the published version of the manuscript.

References

Coombs, J., G. Hind, R.C. Leegood, L.L. Tieszen and A. Vonshak. 1985. Analytical techniques. In: Techniques in bioproductivity and photosynthesis. *Pergamon*. pp. 219-228. https://doi.org/10.1016/B978-0-08-031999-5.50021-3

Eben, P., M. Mohri, S. Pauleit, S. Duthweiler and B. Helmreich. 2024. Phytoextraction potential of herbaceous plant species and the influence of environmental factors – A meta-analytical approach. *Ecol. Eng*., 199: 107169. https:// doi.org/ 10.1016/j.ecoleng.2023.107169

Gao, T., H. Wang, C. Li, M. Zuo, X. Wang, Y. Liu, Y. Yang, D. Xu, Y. Liu and X. Fang. 2022. Effects of heavy metal stress on physiology, hydraulics, and anatomy of three desert plants in the Jinchang Mining Area, China. *Int. J. Environ. Res. Public Health*, 19(23): 15873. https://doi.org/10.3390/ ijerph192315873

Generalova, A., S. Davidova and G. Satchanska. 2025. The mechanisms of lead toxicity in living organisms. *J. Xenobiot*., 15(5): 146. https://doi.org/10.3390/jox15050146

Gupta, A.K., S.K. Verma, K. Khan and R.K. Verma. 2013. Phytoremediation using aromatic plants: A sustainable approach for remediation of heavy metals polluted sites. *Environ. Sci. Technol*., 47(18): 10115-10116. https:// doi.org/10.1021/es403469c

Haghighizadeh, A., O. Rajabi, A. Nezarat, Z. Hajyani, M. Haghmohammadi, S. Hedayatikhah, S.D. Asl and A. Aghababai Beni. 2024. Comprehensive analysis of heavy metal soil contamination in mining environments: Impacts, monitoring techniques, and remediation strategies. *Arab. J. Chem*., 17(6): 105777. https://doi.org/10.1016/j.arabjc. 2024.105777

Hong, Y., D. Li, C. Xie, X. Zheng, J. Yin, Z. Li, K. Zhang, Y. Jiao, B. Wang, Y. Hu and Z. Zhu. 2022. Combined apatite, biochar, and organic fertilizer application for heavy metal co-contaminated soil remediation reduces heavy metal transport and alters soil microbial community structure. *Sci. Total Environ*., 851: 158033. https://doi.org/10.1016/ j.scitotenv.2022.158033

Irin, I.J. and M. Hasanuzzaman. 2024. Organic amendments: Enhancing plant tolerance to salinity and metal stress for improved agricultural productivity. *Stresses*, 4(1): 185-209. https://doi.org/10.3390/stresses4010011

Landi, M. and L. Guidi. 2023. Effects of abiotic stress on photosystem II proteins. *Photosynthetica*, 61(Special Issue): 148-156. https://doi.org/10.32615/ps.2022.043

Neto, A.R. da C., A.D.S. Ambrósio, M. Wolowski, T.B. Westin, K.P. Govêa, M. Carvalho and S. Barbosa. 2020. Negative effects on photosynthesis and chloroplast pigments exposed to lead and aluminum: A meta-analysis. *Cerne*, 26(2): 232-237. https://doi.org/10.1590/01047760202026022711

Ofoe, R., R.H. Thomas, S.K. Asiedu, G. Wang-Pruski, B. Fofana and L. Abbey. 2023. Aluminum in plant: Benefits, toxicity and tolerance mechanisms. *Front. Plant Sci.*, 13: 1085998. https://doi.org/10.3389/fpls.2022.1085998

Raj, K. and A.P. Das. 2023. Lead pollution: Impact on environment and human health and approach for a sustainable solution. *Environ. Chem. Ecotoxicol*., 5: 79-85. https://doi.org/10.1016/j.enceco.2023.02.001

Sabir, M., M.M. Hanafi, T. Aziz, H.R. Ahmad, M. Zia-Ur-Rehman, Saifullah, G. Murtaza and K.R. Hakeem. 2013. Comparative effect of activated carbon, pressmud and poultry manure on immobilization and concentration of metals in maize (*Zea mays*) grown on contaminated soil. *Int. J. Agric. Biol*., 15(3): 559-564. https://www.researchgate.net/publication/235949086

Saleem, A., H. Ur Rahim, U. Khan, M. Irfan, W.A. Akbar, Z. Akbar and J.M. Alatalo. 2024. Organic materials amendments can improve NPK availability and maize growth by reducing heavy metals stress in calcareous soil. *Int. J. Environ. Sci. Technol*., 21(3): 2533-2546. https://doi.org/10.1007/s13762-023-05135-w

Ur Rahman, S., A. Qin, M. Zain, Z. Mushtaq, F. Mehmood, L. Riaz, S. Naveed, M.J. Ansari, M. Saeed, I. Ahmad and M. Shehzad. 2024. Pb uptake, accumulation, and translocation in plants: Plant physiological, biochemical, and molecular response: A review. *Heliyon*, 10(6): e27724. https://doi.org/10.1016/j.heliyon.2024.e27724

Usman, K., M.A. Al-Ghouti and M.H. Abu-Dieyeh. 2019. The assessment of cadmium, chromium, copper, and nickel tolerance and bioaccumulation by shrub plant Tetraena qataranse. *Sci. Rep*., 9(1): 1-11. https://doi.org/10.1038/s41598-019-42029-9

Yadav, A.K., M. Hasan, S. Kour, R. Chandra, V.K. Singh, I.M. Noor, M.Z.A. Yahya, H.M. Singh and A. Tripathi. 2025. Heavy metal contamination in plants: Sources, monitoring, and data-driven insights. *Macromol. Symp*., 414(1): 202400239. https://doi.org/10.1002/masy.202400239