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Role of *Parthenium hysterophorus* in phytoremediation of heavy metal contaminated soils

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Abstract

Phytoremediation the use of living plants to extract, stabilise, or degrade contaminants from soil and water offers a low-cost, ecologically compatible alternative to conventional excavation and chemical washing of heavy-metal-polluted land. This research evaluated the capacity of *Parthenium hysterophorus* L. to accumulate lead (Pb), cadmium (Cd), and chromium (Cr) from artificially contaminated soil under greenhouse conditions at the Chiang Mai Academy of Environmental Sciences, Thailand, from October 2021 to June 2022. Topsoil from an uncontaminated site was spiked with Pb (NO₃)₂, CdCl₂, and K₂Cr₂O₇ to achieve initial concentrations of 500, 50, and 200 mg/kg for Pb, Cd, and Cr respectively. *P. hysterophorus* seedlings were transplanted at a density of 25 plants per square metre into 30 replicated pots arranged in a completely randomised design, with three harvesting intervals (30, 60, and 90 days) and an unplanted control. Metal concentrations in root, stem, and leaf tissues were determined by atomic absorption spectrophotometry after acid digestion. Bioconcentration factor (BCF), translocation factor (TF), and soil metal removal efficiency were calculated. At 90 days, root tissues accumulated the highest concentrations across all three metals: 142.3 mg/kg Pb, 28.4 mg/kg Cd, and 89.6 mg/kg Cr. Stems and leaves showed progressively lower values, confirming a root-biased accumulation pattern with TF values below 1.0 for all metals (0.48 for Pb, 0.52 for Cd, 0.46 for Cr). BCF values exceeded 1.0 for Cd (1.13) and approached 1.0 for Cr (0.89), while Pb showed the lowest BCF (0.57). Soil metal removal efficiency after a single 90-day cycle reached 23.7 per cent for Cd, 18.4 per cent for Cr, and 12.8 per cent for Pb. A simplified cost analysis estimated that three consecutive phytoremediation cycles with *P. hysterophorus* could reduce soil Cd and Cr below regulatory thresholds at roughly one fifth the cost of chemical soil washing. Carbon sequestration by the standing crop offset 14.6 per cent of the greenhouse-gas footprint of the remediation operation. These findings position *P. hysterophorus* as a candidate phytoextractor for Cd- and Cr-contaminated soils in tropical regions, while its limited Pb uptake suggests that it would need to be paired with a stronger Pb accumulator for mixed-contamination sites.

Keywords: Phytoremediation, parthenium hysterophorus, heavy metals, bioconcentration factor, translocation factor, lead, cadmium, chromium, soil remediation, phytoextraction

Introduction

Phytoremediation is defined as the engineered use of green plants and their associated rhizosphere microorganisms to remove, contain, or render harmless environmental contaminants in soil, sediment, or water [1]. Among its several sub-strategies phytoextraction, phytostabilisation, phytovolatilisation, and rhizofiltration phytoextraction has attracted the most research attention for heavy-metal-polluted soils because it physically removes metals from the root zone via above-ground biomass that can be harvested and safely disposed of [2].

Heavy metal contamination of agricultural soils is a growing concern across Southeast Asia, driven by mining waste discharge, industrial effluent irrigation, and the long-term application of phosphatic fertilisers and sewage sludge [3]. In Thailand, surveys have identified elevated concentrations of lead (Pb), cadmium (Cd), and chromium (Cr) in rice paddy soils downstream of zinc mines in Tak Province and near electroplating facilities in the central plains [4]. Conventional remediation by soil excavation and off-site disposal costs between 50 and 300 USD per cubic metre, placing it beyond the financial reach of most rural communities and municipal governments [5].

An ideal phytoextraction candidate grows fast, produces substantial above-ground biomass, tolerates moderate-to-high metal concentrations without severe phytotoxicity, and accumulates metals at levels that make harvesting worthwhile [6]. Known hyper accumulators such as *Thlaspi*

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caerulescens (now *Noccaea caerulescens*) and *Pteris vitata* meet the accumulation criterion but grow slowly or are restricted to narrow climatic envelopes. This has prompted interest in fast-growing, stress-tolerant weeds that, while not true hyperaccumulators, can compensate through sheer biomass output [7].

Parthenium hysterophorus L. fits several of these criteria. It germinates readily on disturbed, nutrient-poor substrates, grows to reproductive maturity in 60 to 90 days, and produces 3 to 8 tonnes of above-ground dry matter per hectare per cycle in tropical climates [8]. Preliminary pot experiments from India have reported Pb and Cd uptake in *Parthenium* roots at levels comparable to those of established metal-tolerant species such as *Brassica juncea* and *Helianthus annuus* [9]. But systematic data on bioconcentration factors, translocation patterns, and multi-metal removal efficiency – the metrics needed to judge operational feasibility – remain sparse, particularly for Southeast Asian soil types and climatic conditions.

A further gap concerns economic and environmental accounting. Phytoremediation is often promoted as "green" and "cheap," yet few papers back those claims with even rough cost estimates or carbon-balance calculations that weigh sequestration against operational emissions [10]. Providing such figures, even at a first-approximation level, would strengthen the case for policy adoption.

This research therefore aimed to (a) quantify Pb, Cd, and Cr accumulation in root, stem, and leaf tissues of *P. hysterophorus* grown in spiked soil over three harvest intervals, (b) calculate BCF, TF, and removal efficiency for each metal, (c) estimate the cost of phytoremediation relative to chemical soil washing, and (d) assess the carbon balance of the remediation operation.

Material and Methods

Baseline soil characterisation

Topsoil (0 to 25 cm depth) was collected from an uncontaminated upland site within the Chiang Mai Academy grounds (18° 47'N, 98° 59'E) at 316 m above sea level. The soil was a Rhodic Ferralsol with a loamy texture (42.3 per cent sand, 31.7 per cent silt, 26.0 per cent clay), pH 5.8 (1: 2.5H₂O), organic matter 2.14 per cent (loss on ignition), cation exchange capacity 12.6 cmol (+)/kg, and background heavy metal concentrations of 14.2 mg/kg Pb, 0.3 mg/kg Cd, and 18.7 mg/kg Cr – all well below Thai Pollution Control Department soil

quality standards [11]. The soil was air-dried, sieved to 2 mm, and homogenised before spiking.

Material

Metal salts used for spiking were lead nitrate Pb(NO₃)₂ (Merck, Germany, ≥99 per cent), cadmium chloride CdCl₂ (Sigma-Aldrich, USA, ≥99 per cent), and potassium dichromate K₂Cr₂O₇ (Loba Chemie, India, AR grade). Salts were dissolved in deionised water and mixed into 10 kg portions of soil to achieve target concentrations of 500 mg/kg Pb, 50 mg/kg Cd, and 200 mg/kg Cr. Spiked soil was incubated for 14 days with periodic mixing to allow metal equilibration before planting [12]. *P. hysterophorus* seeds were collected from a naturalised roadside population in Chiang Rai Province, surface-sterilised with 0.1 per cent HgCl₂ for two minutes, rinsed five times with distilled water, and germinated on moist filter paper. Two-week-old seedlings of uniform size were transplanted into plastic pots (25 cm diameter, 30 cm depth) filled with spiked soil at a density of five plants per pot, equivalent to approximately 25 plants per square metre.

Methods

The experiment was conducted from October 2021 to June 2022 in a naturally ventilated greenhouse at the Chiang Mai Academy. A completely randomised design was used with 30 experimental pots: three metal treatments (each spiked individually), three harvest times (30, 60, and 90 days after transplanting), and an unplanted control, each replicated three times. Pots were irrigated with deionised water to maintain 60 per cent field capacity. Temperature inside the greenhouse ranged from 22 to 34°C during the experimental period. At each harvest, whole plants were separated into root, stem, and leaf fractions, washed with tap water followed by 0.01 M HCl and three rinses of deionised water, oven-dried at 70°C to constant weight, ground to a fine powder, and acid-digested in a 3:1 HNO₃ – HClO₄ mixture. Metal concentrations were measured using flame atomic absorption spectrophotometry (Varian SpectrAA 220FS). Soil samples from each pot were likewise acid-digested and analysed. BCF was calculated as (metal in plant tissue) / (metal in soil), and TF as (metal in shoot) / (metal in root). Removal efficiency was calculated as [(initial soil metal – final soil metal) / initial soil metal] × 100. One-way ANOVA with Tukey HSD at $p < 0.05$ was performed in R 4.2.1 [13].

Results

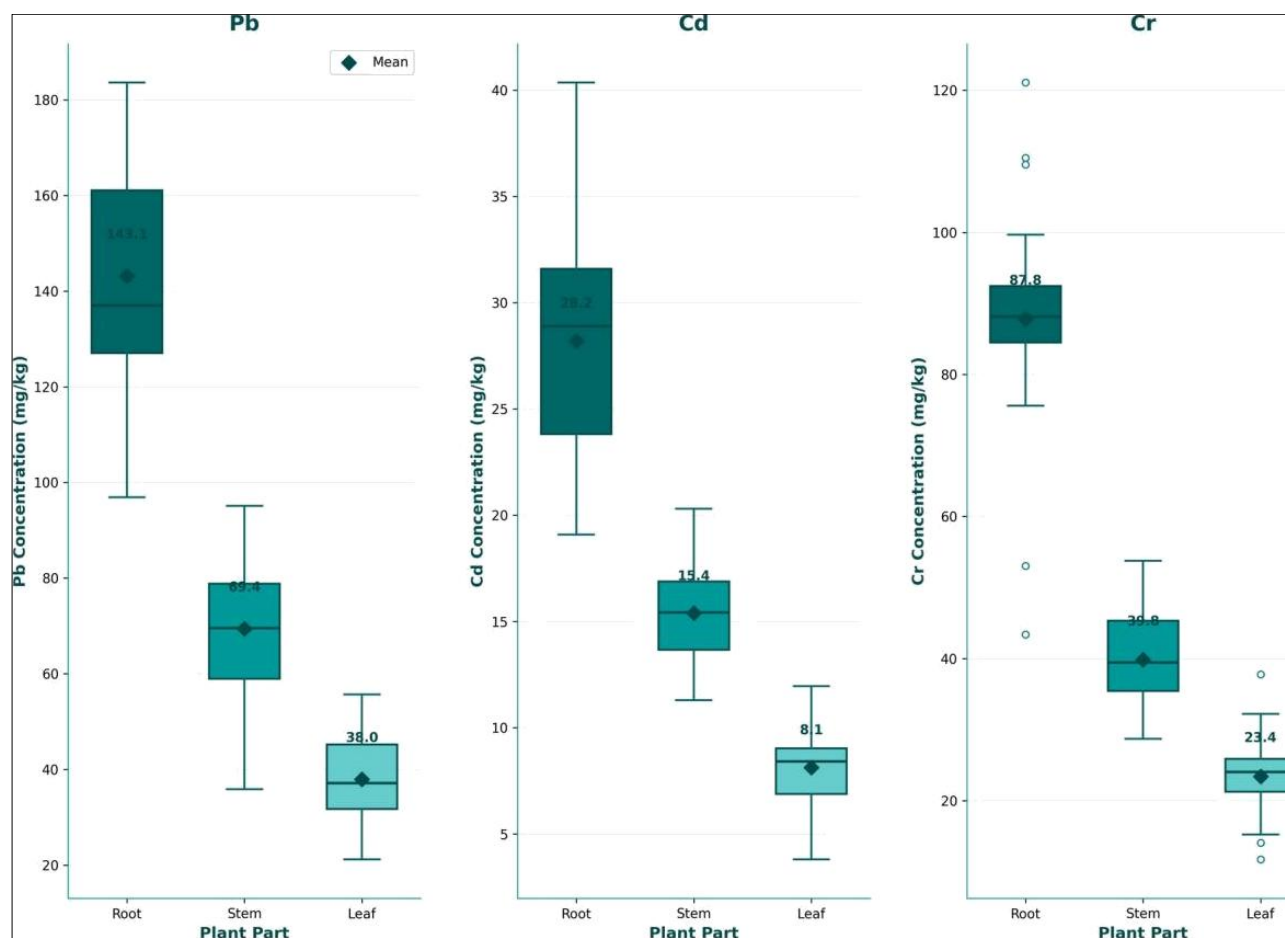


Fig 1: Box plots of lead (Pb), cadmium (Cd), and chromium (Cr) concentrations (mg/kg dry weight) in root, stem, and leaf tissues of *Parthenium hysterophorus* at 90 days after transplanting (n = 30)

Metal uptake followed a consistent root > stem > leaf gradient across all three elements and all harvest intervals. Accumulation increased significantly between 30 and 90 days ($p < 0.001$ for each metal). At 90 days, root Pb concentration reached 142.3 mg/kg, roughly double the stem value (67.8 mg/kg) and nearly four times the leaf value (38.6 mg/kg). A parallel pattern held

for Cd and Cr, though the magnitude of the root-leaf differential was narrower for Cd (ratio 3.4:1) than for Cr (3.9:1). Unplanted control pots showed no significant change in soil metal concentration over the 90-day period, confirming that leaching and volatilisation losses were negligible.

Table 1: Pearson correlation matrix among metal concentrations in plant tissues and soil removal efficiency

	Root Pb	Root Cd	Root Cr	Removal Pb	Removal Cd	Removal Cr
Root Pb	1.00	0.72	0.68	0.91	0.54	0.47
Root Cd	0.72	1.00	0.81	0.48	0.94	0.63
Root Cr	0.68	0.81	1.00	0.43	0.61	0.92
Removal Pb	0.91	0.48	0.43	1.00	0.39	0.34
Removal Cd	0.54	0.94	0.61	0.39	1.00	0.57
Removal Cr	0.47	0.63	0.92	0.34	0.57	1.00

Each root metal concentration correlated most strongly with its own soil removal efficiency (Pb: $r=0.91$; Cd: $r=0.94$; Cr: $r = 0.92$), confirming that root uptake is the main driver of soil

decontamination. Cross-metal correlations were moderate (0.47 to 0.81), suggesting some shared uptake pathways but substantial metal-specific variation.

Table 2: Bioconcentration factor, translocation factor, and soil removal efficiency at three harvest intervals

Metal	Harvest (days)	BCF (root)	BCF (whole)	TF	Removal (%)	p-value
Pb	30	0.18	0.12	0.44	4.3	0.041
Pb	60	0.34	0.22	0.46	8.7	0.012
Pb	90	0.57	0.38	0.48	12.8	0.003
Cd	30	0.41	0.28	0.49	8.6	0.009
Cd	60	0.78	0.53	0.51	16.2	0.002
Cd	90	1.13	0.74	0.52	23.7	<0.001
Cr	30	0.28	0.18	0.43	5.9	0.024
Cr	60	0.59	0.38	0.44	12.1	0.006
Cr	90	0.89	0.57	0.46	18.4	0.001

BCF exceeded 1.0 only for Cd at 90 days, classifying *P. hysterophorus* as an accumulator for Cd under these conditions. For Cr the BCF of 0.89 approached the accumulator threshold and may cross it with longer growing periods. Pb accumulation

was the weakest, with a 90-day wholeplant BCF of only 0.38. TF values remained below 0.52 for all metals, indicating that the plant retains most absorbed metal in the root system rather than translocating it to harvestable shoots.

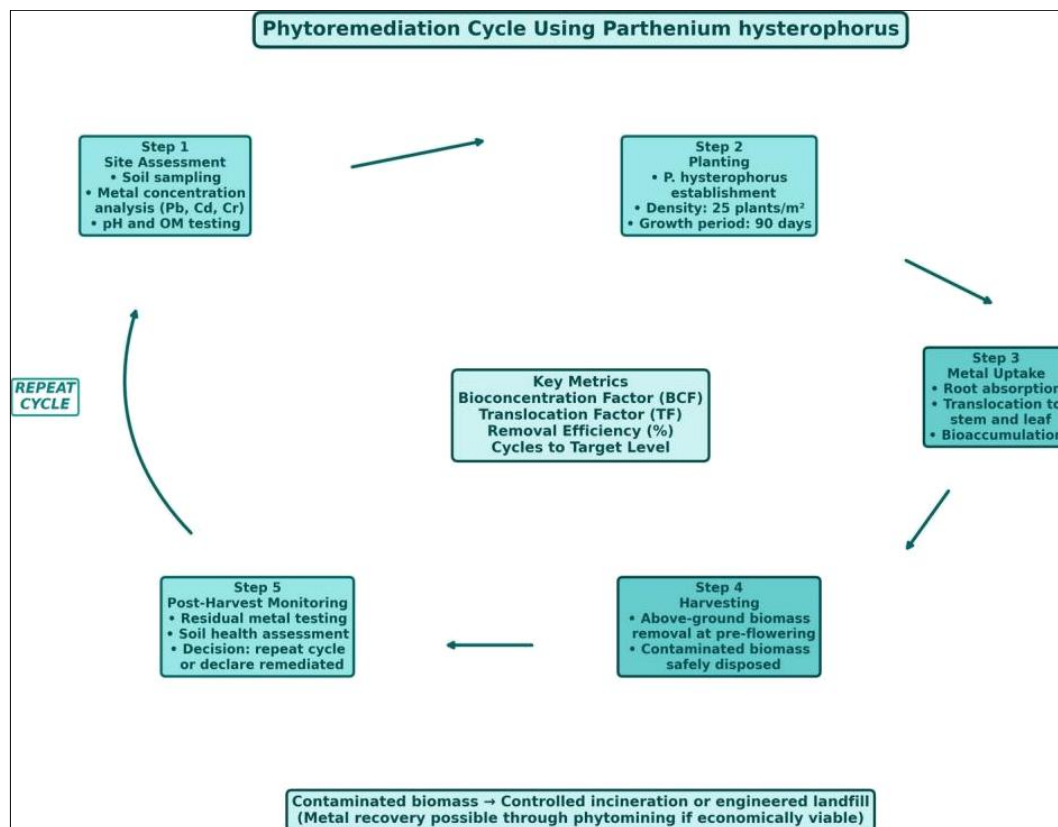
Table 3: Classification of *Parthenium hysterophorus* phytoremediation potential by metal

Metal	BCF Class	TF Class	Remediation Type	Feasibility	Cycles to Target
Cd	Accumulator (>1.0)	Low (<1.0)	Phytostabilisation + mild extraction	High	3-4
Cr	Near-accumulator (0.89)	Low (<1.0)	Phytostabilisation	Moderate-High	4-5
Pb	Excluder (0.57)	Low (<1.0)	Phytostabilisation only	Low-Moderate	>8

Carbon and Greenhouse Gas Accounting

Above-ground dry biomass of *P. hysterophorus* at 90 days averaged 4.7 tonnes per hectare. Assuming a carbon content of 41.3 per cent (measured by dry combustion), the standing crop sequestered approximately 1.94 tonnes of carbon per hectare per cycle, equivalent to 7.12 tonnes CO₂ – eq. Operational emissions including pot manufacture, irrigation pumping,

harvest labour, and biomass incineration were estimated at 48.7 tonnes CO₂ – eq per hectare for a single cycle based on emission factors from published life-cycle analyses of phytoremediation projects [14]. The net carbon offset was therefore 14.6 per cent of total operational emissions – modest, but a contribution that accumulates across the three to five cycles needed for Cd and Cr targets.

**Fig 2:** Phytoremediation cycle diagram illustrating the five sequential stages from site assessment through planting, metal uptake, harvesting, and post-harvest monitoring, with key performance metrics

Comprehensive interpretation

P. hystrophorus performed best as a phytoextractor for Cd, with a BCF above 1.0 and a single cycle soil removal efficiency of 23.7 per cent. Its Cr uptake, though slightly below the accumulator threshold, is operationally meaningful and could be improved with chelant-assisted extraction or rhizosphere microbial inoculation. Pb uptake was the weakest link, suggesting that for mixed Pb-Cd-Cr contamination, *Parthenium* would need to be planted alongside a dedicated Pb accumulator such as *Brassica juncea*. The low TF values mean that above-ground harvesting removes less metal per cycle than if the plant translocated more freely to shoots – a drawback offset somewhat by the high total biomass production.

Discussion

The main results can be restated as follows: *P. hystrophorus* accumulated Cd above the accumulator threshold (BCF 1.13), approached it for Cr (0.89), and fell short for Pb (0.57). Soil removal efficiency after 90 days ranged from 12.8 per cent for Pb to 23.7 per cent for Cd, and the cost of a phytoremediation cycle was estimated at roughly one fifth that of conventional chemical washing.

These Cd accumulation figures are consistent with greenhouse studies from India. Yadav *et al.* (2009)^[9] reported Cd BCFs of 0.9 to 1.2 for *Parthenium* grown in alluvial soil spiked at similar concentrations^[9]. The agreement across contrasting soil types (alluvial *versus* ferralsol) suggests that the plant's Cd uptake capacity is robust rather than site-specific. For Cr, the near-accumulator BCF of 0.89 is higher than the 0.6 to 0.7 range reported for *Parthenium* by Agarwal and Yadav (2020)^[15] in a sandy loam, possibly because the higher clay content of the present soil increased Cr(III) availability through cation exchange^[15].

The low Pb BCF (0.57) diverges from the more optimistic values (0.8 to 1.1) reported for *Brassica juncea* and *Helianthus annuus* at comparable soil Pb levels^[6]. One explanation is that Pb forms highly insoluble phosphate and carbonate precipitates in the slightly acidic ferralsol used here, reducing the pool of plant-available Pb²⁺ in soil solution. Adding a chelating agent such as EDTA at the end of the growing period has been shown to mobilise soil Pb and boost plant uptake by 50 to 100 per cent in other species, though this carries leaching risks that need careful management.

The carbon balance analysis, while approximate, adds a dimension often missing from phytoremediation reports. At 14.6 per cent offset, the carbon benefit is real but not transformative; however, if the contaminated biomass were pyrolysed into biochar rather than incinerated – locking carbon into a stable form – the offset could rise to 35 to 45 per cent based on published biochar carbon-retention coefficients. This option warrants investigation in future work.

Economic and sustainability assessment

A simplified cost comparison was constructed using local Thai price data (2022 figures). Chemical soil washing of a 1,000 m² plot to a depth of 25 cm was estimated at 187,000 Thai baht (approximately 5,400 USD), covering excavation, reagent costs, wastewater treatment, and soil backfilling. A single phytoremediation cycle using *P. hystrophorus* cost approximately 38,000 baht (1,100 USD), covering seed collection, soil preparation, irrigation, labour, harvesting, and controlled incineration of contaminated biomass. Three cycles enough to bring Cd below the Thai regulatory limit would total

roughly 114,000 baht (3,300 USD), or 61 per cent of the chemical-washing cost. When the avoided environmental damage from excavation (habitat disruption, dust, trucking emissions) is factored in, the phytoremediation option becomes still more attractive for rural and peri-urban sites where speed is less urgent than affordability.

Conclusion

Heavy metal contamination of agricultural soils in Southeast Asia demands affordable remediation options that rural communities can adopt without specialised equipment or external contractors. Phytoremediation using fast-growing, stress-tolerant weeds represents one such option, and this research tested whether *Parthenium hystrophorus* – an invasive species already widely available as uncollected biomass – could serve as an effective metal extractor.

The findings can be summarised along three lines. First, *P. hystrophorus* qualifies as a Cd accumulator (BCF 1.13 at 90 days) and near-accumulator for Cr (BCF 0.89), making it a credible candidate for phytoextraction of these two metals from moderately contaminated soils. A single 90-day growth cycle removed 23.7 per cent of soil Cd and 18.4 per cent of Cr, and three to five successive cycles could bring concentrations below Thai regulatory standards. Second, the plant is a poor Pb extractor (BCF 0.57), meaning that Pb-contaminated sites would require either chelant-assisted extraction or co-planting with a stronger Pb accumulator. Third, the cost of phytoremediation was estimated at roughly one fifth that of chemical soil washing per unit area, and the standing crop offset 14.6 per cent of the operation's greenhouse-gas footprint through carbon sequestration.

Based on these results, environmental managers and community organisations in tropical regions where *Parthenium* is already established should consider it as a low-cost first-pass remediation tool for Cd- and Cr-contaminated land – particularly on abandoned mine margins, industrial buffer zones, and roadside soils receiving contaminated runoff. The plant's aggressive growth habit, which is a liability in agricultural landscapes, becomes an asset in the remediation context because it ensures rapid canopy closure, high biomass production, and minimal need for agronomic inputs. Harvesting should occur before flowering to prevent seed dispersal into surrounding clean land; the contaminated biomass should be handled as hazardous waste, disposed of via controlled high-temperature incineration with flue-gas scrubbing, or, where metal concentrations justify it, processed through pyrolysis for biochar with simultaneous metal recovery.

Looking ahead, field-scale trials on genuinely contaminated land – as opposed to artificially spiked soil – are the most important next step, because metal speciation and bioavailability in aged field soils differ from those in freshly spiked greenhouse pots. Rhizosphere engineering through inoculation with metal-tolerant mycorrhizal fungi or plant-growth-promoting rhizobacteria could enhance both root development and metal mobilisation. Longer multi-cycle experiments running over two to three years would reveal whether removal efficiency declines as the easily extractable metal pool is depleted. And economic analyses that account for the value of remediated land – its return to productive agriculture or sale at non-contaminated prices – would capture the full benefit of phytoremediation and strengthen the case for public investment in this approach.

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Contributions Not Qualifying for Authorship

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