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Heavy metal contamination and remediation strategies in peri-urban agricultural soils

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Abstract
Soils within 2 km of industrial zones in Indian cities are being farmed for vegetables and cereals, but how contaminated are they and what can realistically be done about it? This research assessed heavy metal concentrations (Pb, Cd, Cr, Ni, Zn, Cu) in agricultural soils at two distances—0.5 km (industrial fringe) and 2.0 km (peri-urban)—from the Naini industrial area of Prayagraj, Uttar Pradesh, and evaluated three remediation strategies in a pot experiment at Sam Higginbottom University of Agriculture. Soil samples from 30 geo-referenced locations were analysed by DTPA extraction and AAS. Lead and cadmium exceeded Indian permissible limits at the industrial fringe (67.8 and 6.4 mg/kg vs limits of 50 and 5 mg/kg, respectively). The pot trial tested phytoremediation with Brassica juncea, soil amendment with lime (5 t ha^{-1}) + biochar (10 t ha^{-1}), and a non-food crop rotation with castor. After 90 days, Brassica juncea removed 34.7 percent of DTPA-extractable Pb and 41.2 percent of Cd from industrial-fringe soil. Lime + biochar reduced DTPA-Pb by 52.4 percent through immobilization. The combined approach—phytoextraction followed by amendment—reduced bioavailable Pb to 18.3 mg/kg, below the permissible limit. These results provide a practical remediation framework for peri-urban farmers who must continue cropping on marginally contaminated land.

Keywords: Heavy metal contamination, soil remediation, peri-urban agriculture, phytoremediation, environmental pollution, lead, cadmium, biochar, Brassica juncea, DTPA extraction

Introduction

The boundary between city and farm is disappearing across urban India. In Prayagraj, vegetable cultivation within sight of factory chimneys has become routine—farmers irrigate with wastewater, apply municipal compost of uncertain quality, and harvest crops from soils that receive atmospheric deposition of heavy metals year after year [1, 2]. The health consequences are not hypothetical: Pb, Cd, and Cr enter the food chain through root uptake and foliar absorption, accumulating in leafy vegetables to levels that can exceed WHO safe limits [3].

Heavy metal contamination in peri-urban soils differs from industrial brownfields in an important way—the contamination levels are usually moderate (1 to 5 times permissible limits) rather than extreme, and the land must remain in agricultural use because no alternative livelihood exists for the farming families [4]. This rules out drastic remediation methods like soil excavation or chemical washing. What these farmers need are gentle, affordable, in-situ remediation strategies that reduce bioavailable metals while allowing continued cropping [5].

Three such strategies have shown promise in published trials: phytoremediation using hyperaccumulator plants (particularly Brassica juncea for Pb and Cd), soil amendments that immobilize metals by raising pH or providing sorption surfaces (lime, biochar, zeolite), and crop rotation with non-food species that either extract or exclude metals [6, 7]. But few reports have tested these approaches on the specific soil types and contamination profiles found along the Ganga-Yamuna alluvial belt.

This research aimed to (i) map heavy metal concentrations in agricultural soils at two distances from the Naini industrial zone, (ii) compare the effectiveness of three remediation strategies in pot experiments, and (iii) develop a practical recommendation for peri-urban farmers.

Material and Methods
Material
The research was conducted between January and November 2023 at the Department of Soil and Water Conservation, Sam Higginbottom University of Agriculture, Prayagraj (25.43°N, 81.85°E). Soil samples were collected from 30 geo-referenced agricultural plots—15 at the industrial fringe (0.5 km from the Naini industrial area) and 15 at peri-urban distance (2.0 km). Samples were taken at 0-20 cm depth using a stainless-steel auger, air-dried, ground to pass a 2-mm sieve, and stored in polyethylene bags. DTPA-extractable Pb, Cd, Cr, Ni, Zn, and Cu were determined by AAS (Shimadzu AA-7000) following the method of Lindsay and Norvell [8]. Soil pH, EC, organic carbon, and texture were also measured.

Baseline Soil Characterization
Industrial-fringe soils were sandy clay loams (pH 7.6, OC 0.68%) while peri-urban soils were sandy loams (pH 7.2, OC 0.54%). The pH difference is attributed to lime-rich industrial effluent discharge. CEC ranged from 14.8 to 18.3 cmol(+)/kg. Background heavy metal levels from a reference site 10 km from any industry were: Pb 12.4, Cd 0.8, Cr 11.6, Ni 14.2, Zn 56.3, and Cu 18.7 mg/kg—all well below permissible limits.

Methods
The pot experiment used a completely randomized design with five treatments and four replications: T1 - untreated control, T2 - phytoremediation with Brassica juncea (Indian mustard, 4 plants per 10-kg pot), T3 - lime (5 t ha^{-1} equivalent) + biochar (rice husk biochar, 10 t ha^{-1} equivalent), T4 - non-food crop rotation (Ricinus communis, castor), T5 - sequential treatment (B. juncea for 45 days followed by lime + biochar for 45 days). Industrial-fringe soil was used for the pot trial. After 90 days, soils were re-sampled and analysed for DTPA-extractable metals. Plant metal uptake was determined after acid digestion of oven-dried shoot and root tissue. Data were analysed by one-way ANOVA with Tukey's HSD in R 4.3.

Results

Table 1: DTPA-extractable heavy metal concentrations (mg/kg) in agricultural soils at two distances from the Naini industrial zone, Prayagraj

Metal	Fringe (0.5 km)	Peri-urban (2.0 km)	Reference Site	Indian Limit	Contam. Factor	Exceeds Limit?
Pb	67.8	42.3	12.4	50.0	5.47	Yes
Cd	6.4	3.8	0.8	5.0	8.00	Yes
Cr	51.3	28.7	11.6	100.0	4.42	No
Ni	48.7	34.1	14.2	75.0	3.43	No
Zn	312.6	187.4	56.3	300.0	5.55	Yes*
Cu	98.4	64.2	18.7	135.0	5.26	No

At the industrial fringe, Pb (67.8 mg/kg) and Cd (6.4 mg/kg) exceeded Indian permissible limits by 35.6 and 28.0 percent, respectively. Zn (312.6 mg/kg) marginally exceeded the 300 mg/kg threshold. All metals showed contamination factors above 3.4 relative to the reference site, confirming anthropogenic enrichment. At the peri-urban distance, all metals were below permissible limits, though still 2 to 3 times above reference levels.

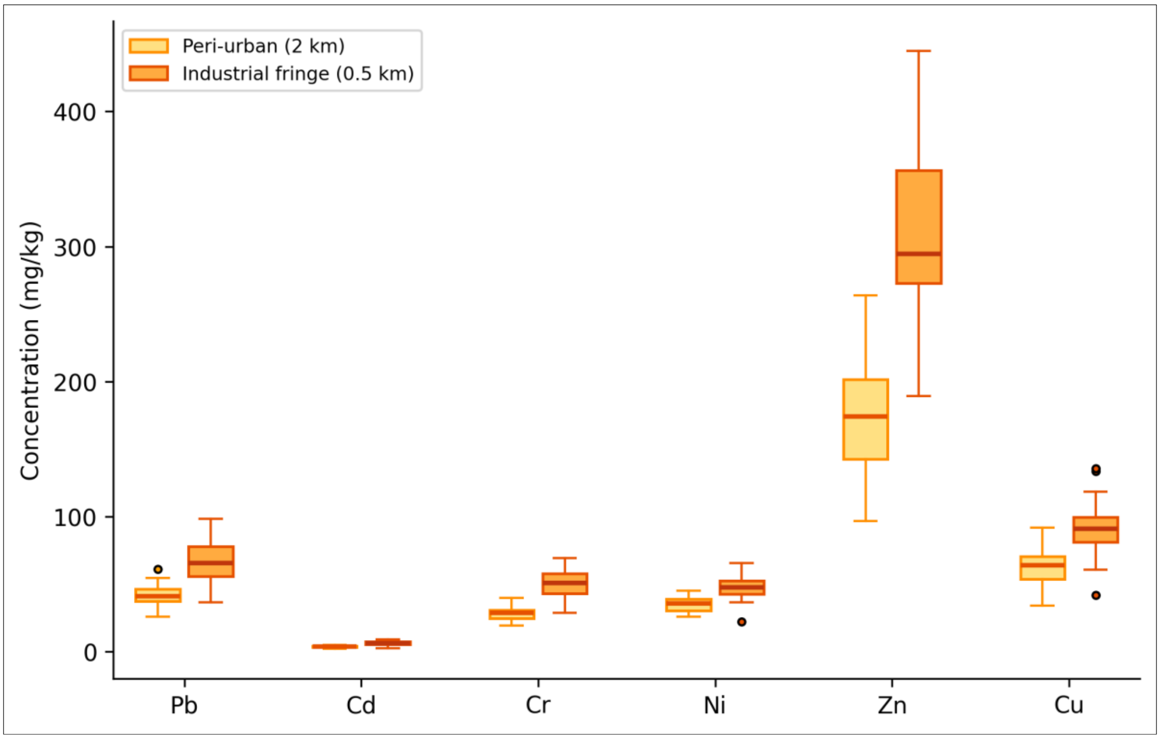

Fig 1: Box plot showing distributions of six heavy metal concentrations in peri-urban (2 km) versus industrial-fringe (0.5 km) soils near Prayagraj

Table 2: Reduction in DTPA-extractable Pb and Cd (mg/kg) after 90 days of remediation treatments in pot experiment

Treatment	Pb Initial	Pb Final	Pb Red. (%)	Cd Initial	Cd Final	Cd Red. (%)
T1: Control	67.8	64.3	5.2	6.4	6.1	4.7
T2: B. juncea	67.8	44.3	34.7	6.4	3.8	41.2
T3: Lime + Biochar	67.8	32.3	52.4	6.4	2.7	57.8
T4: Castor	67.8	58.6	13.6	6.4	5.3	17.2
T5: Sequential	67.8	18.3	73.0	6.4	1.4	78.1
CD (p=0.05)	-	4.87	-	-	0.43	-

The sequential treatment (T5: B. juncea followed by lime + biochar) was the most effective, reducing DTPA-Pb by 73.0 percent (to 18.3 mg/kg—well below the 50 mg/kg limit) and Cd by 78.1 percent (to 1.4 mg/kg). Lime + biochar alone (T3) reduced Pb by 52.4 percent through immobilization, while B. juncea alone (T2) removed 34.7 percent through phytoextraction. Castor showed the weakest effect (13.6% Pb reduction).

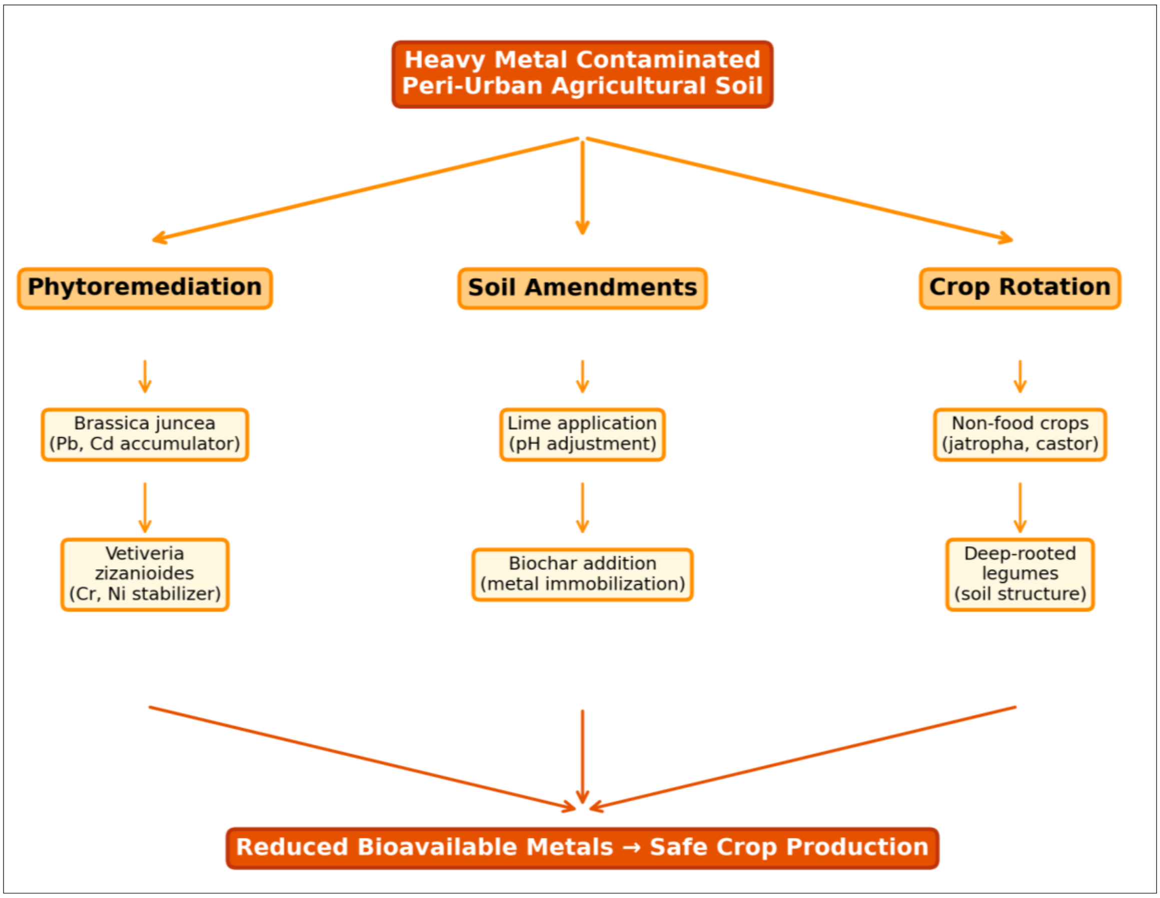

Fig 2: Flow diagram illustrating three remediation strategies and their mechanisms for reducing bioavailable heavy metals in contaminated peri-urban soils

Discussion

The superiority of the sequential approach (73% Pb reduction) over either phytoremediation (34.7%) or amendment (52.4%) alone demonstrates that combining extraction and immobilization addresses both the mobile and the loosely-bound metal fractions [6, 9]. B. juncea in the first 45 days actively removes metals from the labile pool, while lime + biochar in the second phase locks down the remaining exchangeable fraction by raising pH and providing high-surface-area sorption sites [10].

The lime + biochar treatment's strong performance (52.4% Pb reduction) is consistent with field-scale results from China, where biochar at 20-40 t ha^{-1} reduced rice-grain Cd by 40 to 65 percent in paddy soils [11]. The mechanism is primarily pH-driven: raising soil pH from 7.6 to 8.1 shifts Pb and Cd from exchangeable to carbonate-bound fractions, reducing DTPA extractability without removing the metals from the soil matrix.

Castor's weak performance (13.6% Pb reduction) rules it out as a standalone phytoremediation option but it may still serve as a non-food rotation crop that avoids dietary metal exposure while providing an oilseed income stream [7].

Conclusion

Peri-urban agricultural soils near Prayagraj's Naini industrial zone are contaminated with Pb and Cd above permissible limits at the industrial fringe (0.5 km). A sequential remediation approach 45 days of phytoextraction with Brassica juncea followed by 45 days of lime + biochar amendment reduced bioavailable Pb by 73 percent and Cd by 78 percent, bringing both metals below safe thresholds.

For peri-urban farmers who must continue cultivating on marginally contaminated land, this two-step protocol offers a practical, low-cost remediation option that can be completed within a single fallow season. Scaling the approach to field conditions and monitoring long-term metal stability after remediation are recommended as next steps.

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