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# AMENDMENT-ASSISTED PHYTOMANAGEMENT OF HEAVY METAL CONTAMINATED AGRICULTURAL SOIL USING MARIGOLD AND VETIVER

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**ABSTRACT:**
Industrial activities can introduce multiple heavy metals into agricultural soils, requiring management strategies that improve soil quality while limiting metal exposure. A pot-culture experiment was conducted using industrially contaminated agricultural soil from Perambalur district, Tamil Nadu, to assess various amendment treatments in combination with marigold (Tagetes erecta L.) and vetiver (Chrysopogon zizanioides (L.) Roberty). The experiment was arranged in a two-factor factorial completely randomised design with three replications. Amendment treatments significantly influenced soil properties, biological activity, residual metal concentrations and plant metal uptake. Biochar was the most effective amendment for reducing total soil metal concentrations, achieving reductions of 52.9% for Cr, 54.7% for Pb, 82.4% for Ni and 92.0% for Cd. Vermicompost produced the greatest improvement in soil microbial populations. Root and shoot metal concentrations generally declined under amendment treatments, with vetiver exhibiting greater root accumulation and higher removal efficiency than marigold. Bioconcentration factors remained below unity for all metals, while translocation factors indicated predominant retention of Cr, Pb and Ni in roots, suggesting phytostabilisation as the principal mechanism. Cadmium showed comparatively greater translocation to shoots. The results demonstrated that biochar was the most effective for reducing residual metal concentrations, whereas vermicompost was more effective in restoring soil biological activity. Overall, the biochar-vetiver combination showed the greatest potential for the phytomanagement of industrially contaminated agricultural soils.
**KEYWORDS:** Heavy metals; biochar; vermicompost; phytostabilisation; bioconcentration factor; removal efficiency

## INTRODUCTION

Heavy metal contamination of agricultural soil has become one of the most persistent environmental problems associated with industrial development. Unlike organic pollutants, metals are not biologically degraded; once introduced through effluent discharge, atmospheric deposition or solid-waste disposal, they persist in the soil matrix for decades, where they suppress microbial function, impair plant growth and enter the food chain (Saha et al., 2017; Vasanthrao et al., 2025). In Tamil Nadu, industrial and suburban regions have repeatedly documented enrichment of chromium (Cr), lead (Pb), nickel (Ni) and cadmium (Cd) in cultivated soils, with source apportionment confirming a substantial anthropogenic contribution (Sinduja et al., 2022; Karthikayini et al., 2024). Perambalur district exemplifies this situation, where industrial units adjoin land that remains under active cultivation, and where recent metagenomic evidence indicates measurable shifts in soil microbial community structure and resistome composition under anthropogenic pressure (Vasanthrao et al., 2025).

Therefore, remediation of such contaminated soils should simultaneously limit metal mobility and bioavailability while restoring the soil's biological activity and nutrient-supplying capacity impaired by contamination. In-situ immobilisation with organic and mineral amendments addresses the first objective. Biochar has attracted particular attention because its high specific surface area, cation-exchange capacity and alkaline reaction promote metal sorption, surface complexation and precipitation while contributing stable carbon to the soil (Ahmad et al., 2014), with concurrent fertility gains and reduced metal bioavailability reported across contrasting substrates (Rizwan et al., 2016; Bandara et al., 2017; Palansooriya et al., 2020). Zeolite and bentonite act through analogous ion-exchange and adsorption mechanisms, though their efficacy depends strongly on soil properties and metal identity (Vrînceanu et al., 2019). Organic inputs such as farmyard manure (FYM), vermicompost and humic substances improve structure, nutrient supply and microbial activity, but their effect on metal mobility is not uniformly favourable, since soluble organo-metallic complexes may immobilise or transiently mobilise metals depending on the soil-metal system (Nejad et al., 2018; Hamid et al., 2019).

On the other hand, phytoremediation addresses the second objective by using plants to alter the distribution and mobility of soil contaminants, either by phytoextraction into harvestable biomass or by phytostabilisation within the root zone. Vetiver (Chrysopogon zizanioides) is widely favoured for contaminated sites because its dense, deeply penetrating fibrous root system tolerates sustained metal stress and stabilises the rhizosphere (Danh et al., 2009; Banerjee et al., 2019). Marigold (Tagetes spp.), a non-edible ornamental, combines metal tolerance with metal-specific accumulation behaviour and offers a saleable product that provides an economic incentive for adoption on contaminated land (Mahmood-ul-Hassan et al., 2020; Madanan et al., 2021). Root and shoot metal concentrations, interpreted through the bioconcentration factor and the translocation factor, provide the standard framework for comparing the behaviour of such species (Galal and Shehata, 2014; Suganya et al., 2024).

Although amendment-assisted immobilisation and phytoremediation have each been studied extensively, few investigations have compared a broad range of organic, carbon-based and mineral amendments alongside plant species representing contrasting phytomanagement strategies within a single contaminated soil. Such comparison is essential under mixed-metal contamination, where the response of one metal cannot be extrapolated to another, and where improvements in fertility and biological activity may proceed independently of any change in the total metal pool (Khalid et al., 2017; Antoniadis et al., 2017). Integrated amendment-plant systems have recently been examined for contaminated soils, including biochar-assisted phytoremediation and combined biochar- humic acid systems under marigold (Anne et al., 2023; Parameswari et al., 2025), yet no comparable assessment has been reported for the industrially influenced soils of Perambalur district.

The present study was undertaken to evaluate the effectiveness of various organic and inorganic amendments in combination with marigold and vetiver for the phytomanagement of industrially contaminated soil from Perambalur district. The study aimed to assess the potential of these amendment-crop combinations to improve soil quality, reduce Heavy metal contamination, and enhance the overall remediation efficiency of the contaminated soil.

## 2. MATERIALS AND METHODS

### 2.1. Study area and soil sampling

The study was conducted during June 2025 on soils collected from the agricultural land adjacent to an unregistered quarry at Elambalur, Perambalur district, Tamil Nadu, India (11.26976771, 78.88772364), where quarrying and allied industrial activity have contributed to the enrichment of the surrounding cultivated land with Cr, Pb, Cd and Ni. Comparable enrichment of these elements has been reported across the industrial estates and suburban regions of Tamil Nadu, with source apportionment confirming a predominantly anthropogenic origin (Sinduja et al., 2022; Karthikayini et al., 2024).

Composite surface soil samples were collected from agricultural land at a depth of 0–15 cm. At each sampling location, five subsamples were collected at 10 m intervals along a linear transect and thoroughly homogenised to obtain a single representative composite sample. The bulked material was air-dried under shade, gently crushed, passed through a 2 mm sieve and stored for characterisation and pot filling. The soil was moderately alkaline and calcareous, with a pH of 8.31, an electrical conductivity (EC) of 0.51 dS $m^{-1}$, an organic carbon content of 0.92%, a calcium carbonate content of 1.31% and a cation exchange capacity (CEC) of 17.4 cmol (+) $kg^{-1}$. The total concentrations (mg $kg^{-1}$) of heavy metals in the soil were Cr (154), Pb (61.0), Ni (54.9) and Cd (0.319). The complete initial characterisation is presented in Table 1.

**Table 1. Initial physicochemical properties and heavy metal concentrations of the experimental soil.**

| Parameter | Value |
|---|---|
| pH | 8.31 |
| EC (dS m-1) | 0.51 |
| Organic carbon (%) | 0.92 |
| CaCO3 (%) | 1.31 |
| Available N (kg ha-1) | 61.4 |
| Available P (kg ha-1) | 9.21 |
| Available K (kg ha-1) | 114 |
| Available S (mg kg-1) | 8.75 |
| Exch. Ca (cmol (+) kg-1) | 10.5 |
| Exch. Mg (cmol (+) kg-1) | 3.22 |
| Exch. Na (cmol (+) kg-1) | 0.55 |
| CEC (cmol (+) kg-1) | 17.4 |
| Cr (mg kg-1) | 154 |
| Cd (mg kg-1) | 0.319 |
| Ni (mg kg-1) | 54.9 |
| Pb (mg kg-1) | 61.0 |

### 2.2. Plant species and growth conditions

Tagetes erecta L. (marigold) and Chrysopogon zizanioides (L.) Roberty (vetiver) were selected for this study because of their contrasting growth characteristics and potential for phytomanagement of contaminated soils. Marigold is a fast-growing, economically valuable, non-edible ornamental crop with a short growth cycle and demonstrated metal-specific accumulation potential. In contrast, vetiver is a perennial $C_4$ grass characterised by high biomass production, an extensive and deeply penetrating fibrous root system, and strong tolerance to environmental and metal stress. Together, these species represent complementary phytomanagement strategies, combining the metal accumulation potential of marigold with the stabilisation capacity and stress tolerance of vetiver (Danh et al., 2009; Mahmood-ul-Hassan et al., 2020; Madanan et al., 2021; Suganya et al., 2024).

Both species were raised under greenhouse conditions, and recommended agronomic practices were followed throughout with respect to irrigation, weeding and plant protection. Marigold grew for 90 days and vetiver for 180 days, reflecting the normal field duration of each crop. At harvest, plants were uprooted, separated into root and shoot fractions, washed free of adhering soil and oven-dried at 60-70 °C to constant weight before analysis.

### 2.3. Experimental design and treatments

The experiment was laid out as a two-factor factorial in a completely randomised design, with Treatment at eight levels and Crop at two levels, each combination replicated three times. The experimental layout and treatment details are presented in Figure 1. The amendments differed markedly in the properties governing their behaviour in soil. Biochar was strongly alkaline (pH 9.40), with a total carbon content of 62% and a CEC of 54 cmol (+) $kg^{-1}$, combining an extensive sorptive surface with a recalcitrant carbon pool. Vermicompost was near-neutral (pH 7.10), with 24% total carbon and the highest nitrogen and phosphorus contents among the organic materials (1.55 and 0.85% respectively), supplying readily decomposable substrate. Zeolite and bentonite contributed negligible carbon or nutrients but possessed the highest CECs of the series (120 and 85 cmol (+) $kg^{-1}$, respectively). Humic acid was acidic (pH 6.40) with 38% total carbon, while the biofertilizer consortium supplied nitrogen-fixing, phosphorus-solubilising and potassium-solubilising organisms at 8.2, 8.0 and 7.8 log CFU $g^{-1}$ respectively. The Cr, Pb, Cd and Ni contents of all amendments were well below the detection levels.

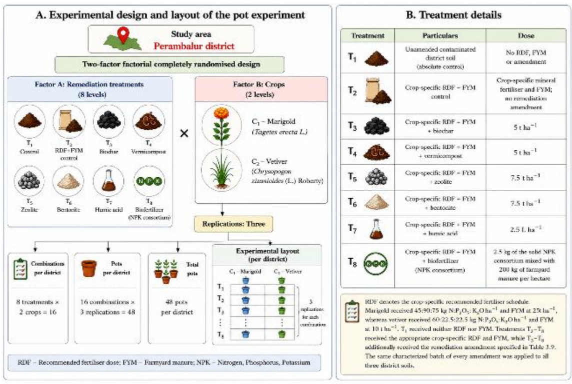


**Figure 1. Experimental design and treatment details of the pot experiment.**

### 2.4. Soil physicochemical and heavy metal analysis

Soil pH and EC were determined in a 1:2.5 soil-water suspension using a digital pH meter and conductivity bridge, respectively. Organic carbon was estimated by the wet-oxidation procedure of Walkley and Black (1934). The Cr, Pb, Cd and Ni concentrations were determined by digesting 1 g of air-dried, sieved soil in 20 mL of aqua regia ($HNO_3$: HCl, 3:1) until a clear digestate was obtained. The digestate was diluted to 50 mL with double-distilled water, filtered through Whatman No. 42 filter paper and analysed by microwave plasma atomic emission spectroscopy (MP-AES) against multi-element calibration standards of known concentration. Bacterial, actinomycete and fungal populations were enumerated by serial dilution and plate counting on selective media (Suganya et al., 2024; Parameswari et al., 2025).

### 2.5. Plant metal analysis and phytoremediation indices

Oven-dried root and shoot tissue was powdered, digested in aqua regia and analysed for Cr, Pb, Cd and Ni concentrations by MP-AES (Suganya et al., 2024). The bioconcentration factor (BCF) and translocation factor (TF) were computed as:

$$BCF = \frac{C_{root}}{C_{soil}} \quad (1)$$

$$TF = \frac{C_{shoot}}{C_{root}} \quad (2)$$

where Croot, Cshoot and Csoil are the heavy metal concentrations (mg $kg^{-1}$) in root tissue, shoot tissue and soil, respectively (Galal and Shehata, 2014; Suganya et al., 2024). Because the denominator of Eq. 1 is the total rather than the plant-available soil metal pool, the resulting values are small in absolute terms and are interpreted comparatively between crops and treatments rather than against the conventional threshold of unity. Metal removal efficiency was calculated as the percentage reduction in total soil metal concentration between the initial and post-harvest sampling, following Mahmood-ul-Hassan et al. (2020):

$$Removal\ efficiency\ (\%) = \left[\frac{C_{initial} - C_{residual}}{C_{residual}}\right] x\ 100 \quad (3)$$

### 2.6. Statistical analysis

The data were subjected to two-way analysis of variance with Treatment (A) and Crop (C) as fixed factors using OriginPro 2026. Treatment means were compared using the critical difference at p = 0.05, with the standard error of the difference reported for the Crop main effect, the Treatment main effect and their interaction; non-significant effects are denoted NS.

## 3. RESULTS

### 3.1. Physicochemical properties of post-harvest soil

Soil pH, EC and organic carbon were all significantly influenced by the different amendments used in the study (Table 2). Soil pH declined from 8.31 under control to 8.08 under biochar and 8.09 under vermicompost, the two lowest values recorded, against a critical difference of 0.093. EC decreased from 0.52 to 0.40 dS $m^{-1}$ under biochar, the lowest value recorded, with vermicompost and zeolite following at 0.41 dS $m^{-1}$. Organic carbon increased from 0.95% in control to 1.19% under biochar and 1.14% under vermicompost. The Crop effect was significant for EC and organic carbon but not for pH, and the Treatment × Crop interaction was non-significant for all three properties.

**Table 2. Effect of the amendments on soil pH, EC and OC under marigold and vetiver.**

| Treatment | pH | | | EC (dS m-1) | | | OC (%) | | |
|---|---|---|---|---|---|---|---|---|---|
| | C1 | C2 | Mean | C1 | C2 | Mean | C1 | C2 | Mean |
| T1 | 8.34 | 8.28 | 8.31 | 0.51 | 0.53 | 0.52 | 0.95 | 0.95 | 0.95 |
| T2 | 8.25 | 8.27 | 8.26 | 0.47 | 0.47 | 0.47 | 0.97 | 1.01 | 0.99 |
| T3 | 8.11 | 8.05 | 8.08 | 0.40 | 0.40 | 0.40 | 1.19 | 1.18 | 1.19 |
| T4 | 8.13 | 8.06 | 8.09 | 0.43 | 0.39 | 0.41 | 1.11 | 1.18 | 1.14 |
| T5 | 8.12 | 8.12 | 8.12 | 0.42 | 0.40 | 0.41 | 1.10 | 1.16 | 1.13 |
| T6 | 8.21 | 8.16 | 8.19 | 0.46 | 0.43 | 0.45 | 1.11 | 1.13 | 1.12 |
| T7 | 8.17 | 8.15 | 8.16 | 0.46 | 0.42 | 0.44 | 1.07 | 1.10 | 1.09 |
| T8 | 8.14 | 8.07 | 8.10 | 0.45 | 0.42 | 0.44 | 1.10 | 1.12 | 1.11 |
| Mean | 8.18 | 8.15 | 8.17 | 0.45 | 0.43 | 0.44 | 1.07 | 1.10 | 1.09 |
| | Crop (C) | Treatment (A) | C × A | Crop (C) | Treatment (A) | C × A | Crop (C) | Treatment (A) | C × A |
| S.Ed(±) | 0.023 | 0.046 | 0.065 | 0.006 | 0.013 | 0.018 | 0.011 | 0.023 | 0.032 |
| C.D (p=0.05) | NS | 0.093 | NS | 0.013 | 0.026 | NS | 0.023 | 0.046 | NS |

C1 = marigold; C2 = vetiver. EC = electrical conductivity (dS $m^{-1}$); OC = organic carbon (%). C = Crop, A = Treatment. C.D. at p = 0.05; NS = not significant.

### 3.2. Residual heavy metal concentrations in post-harvest soil

The total soil concentrations of all metals declined significantly under the amendment treatments, with biochar consistently producing the lowest concentrations (Table 3). Under biochar, Cr decreased from 150.5 mg $kg^{-1}$ in the control to 72.4 mg $kg^{-1}$, Pb from 56.7 to 27.7 mg $kg^{-1}$, Ni from 52.8 to 9.67 mg $kg^{-1}$, and Cd from 0.30 to 0.03 mg $kg^{-1}$. Vermicompost was the second most effective amendment across all four metals, followed by zeolite and bentonite, which showed comparable effects, whereas the biofertilizer consortium and humic acid were comparatively less effective. The crop effect was significant for all metals, with consistently lower residual concentrations observed in vetiver-grown pots than in marigold-grown pots. For example, mean total Cr concentration was 115.0 mg $kg^{-1}$ under vetiver compared with 126.7 mg $kg^{-1}$ under marigold. However, the Treatment × Crop interaction was non-significant for all four metals.

**Table 3. Effect of amendment on chromium, lead, cadmium and nickel concentrations (mg $kg^{-1}$) in soil under marigold and vetiver.**

| Treatment | Cr (mg kg-1) | | | Pb (mg kg-1) | | | Ni (mg kg-1) | | | Cd (mg kg-1) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C1 | C2 | Mean | C1 | C2 | Mean | C1 | C2 | Mean | C1 | C2 | Mean |
| T1 | 151.1 | 149.8 | 150.5 | 59.1 | 54.2 | 56.7 | 54.3 | 51.3 | 52.8 | 0.31 | 0.30 | 0.30 |
| T2 | 143.7 | 125.8 | 134.8 | 57.5 | 52.2 | 54.9 | 50.5 | 41.7 | 46.1 | 0.27 | 0.24 | 0.26 |
| T3 | 80.4 | 64.4 | 72.4 | 29.9 | 25.4 | 27.7 | 11.7 | 7.65 | 9.67 | 0.03 | 0.03 | 0.03 |
| T4 | 106.6 | 105.3 | 105.9 | 43.6 | 37.1 | 40.3 | 35.8 | 27.9 | 31.8 | 0.18 | 0.14 | 0.16 |
| T5 | 134.1 | 123.5 | 128.8 | 46.5 | 38.2 | 42.3 | 35.2 | 31.7 | 33.5 | 0.21 | 0.16 | 0.18 |
| T6 | 133.8 | 125.4 | 129.6 | 45.0 | 37.7 | 41.4 | 36.4 | 31.8 | 34.1 | 0.21 | 0.16 | 0.18 |
| T7 | 138.0 | 114.8 | 126.4 | 50.8 | 47.9 | 49.3 | 42.8 | 36.4 | 39.6 | 0.25 | 0.21 | 0.23 |
| T8 | 126.4 | 111.4 | 118.9 | 48.1 | 46.9 | 47.5 | 40.1 | 35.8 | 37.9 | 0.21 | 0.18 | 0.19 |
| Mean | 126.7 | 115.0 | 120.9 | 47.6 | 42.4 | 45.0 | 38.3 | 33.0 | 35.7 | 0.21 | 0.18 | 0.19 |

| Treatment | Cr (mg kg-1) | | | Pb (mg kg-1) | | | Ni (mg kg-1) | | | Cd (mg kg-1) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C1 | C2 | Mean | C1 | C2 | Mean | C1 | C2 | Mean | C1 | C2 | Mean |
| | Crop (C) | Treatment (A) | C × A | Crop (C) | Treatment (A) | C × A | Crop (C) | Treatment (A) | C × A | Crop (C) | Treatment (A) | C × A |
| S.Ed(±) | 1.855 | 3.709 | 5.246 | 0.821 | 1.642 | 2.322 | 0.791 | 1.582 | 2.238 | 0.004 | 0.008 | 0.011 |
| C.D (p=0.05) | 3.778 | 7.556 | NS | 1.672 | 3.344 | NS | 1.612 | 3.223 | NS | 0.008 | 0.016 | NS |

C1 = marigold; C2 = vetiver. C = Crop, A = Treatment. C.D. at p = 0.05; NS = not significant.

### 3.3. Soil microbial population dynamics

Microbial populations responded significantly to amendment, with vermicompost recording the highest counts followed by the biofertilizer consortium (Table 4). Bacterial counts increased from 0.37 × $10^6$ CFU $g^{-1}$ in the control to 4.73 × $10^6$ under vermicompost and 3.81 × $10^6$ under the biofertilizer consortium (C.D. = 0.490), with biochar at 1.90 × $10^6$. Actinomycete populations followed the same order, rising from 0.23 × $10^5$ to 1.22 × $10^5$ CFU $g^{-1}$ under vermicompost (C.D. = 0.097), as did fungal populations, which increased from 1.30 × $10^4$ to 5.57 × $10^4$ CFU $g^{-1}$ (C.D. = 0.748). The Crop effect and the Treatment × Crop interaction was non-significant for all three microbial groups.

**Table 4. Effect of the amendments on microbial enumeration of soil bacteria, actinomycetes and fungi.**

| Treatment | Bacteria (x106 CFU g-1) | | | Actinomycetes (x105 CFU g-1) | | | Fungi (x104 CFU g-1) | | |
|---|---|---|---|---|---|---|---|---|---|
| | C1 | C2 | Mean | C1 | C2 | Mean | C1 | C2 | Mean |
| T1 | 0.35 | 0.39 | 0.37 | 0.24 | 0.23 | 0.23 | 1.20 | 1.40 | 1.30 |
| T2 | 0.96 | 0.95 | 0.95 | 0.33 | 0.38 | 0.36 | 1.94 | 1.96 | 1.95 |
| T3 | 1.66 | 2.13 | 1.90 | 0.62 | 0.69 | 0.66 | 3.75 | 2.87 | 3.31 |
| T4 | 4.59 | 4.87 | 4.73 | 1.24 | 1.21 | 1.22 | 5.65 | 5.48 | 5.57 |
| T5 | 1.13 | 1.23 | 1.18 | 0.44 | 0.39 | 0.42 | 2.56 | 2.32 | 2.44 |
| T6 | 1.10 | 1.18 | 1.14 | 0.43 | 0.37 | 0.40 | 2.33 | 2.51 | 2.42 |
| T7 | 1.46 | 1.41 | 1.43 | 0.58 | 0.59 | 0.59 | 3.58 | 3.16 | 3.37 |
| T8 | 3.67 | 3.94 | 3.81 | 1.13 | 1.01 | 1.07 | 5.40 | 5.09 | 5.25 |
| Mean | 1.87 | 2.01 | 1.94 | 0.63 | 0.61 | 0.62 | 3.30 | 3.10 | 3.20 |
| | Crop (C) | Treatment (A) | C × A | Crop (C) | Treatment (A) | C × A | Crop (C) | Treatment (A) | C × A |
| S.Ed(±) | 0.120 | 0.241 | 0.340 | 0.024 | 0.048 | 0.067 | 0.184 | 0.367 | 0.520 |
| C.D (p=0.05) | NS | 0.490 | NS | NS | 0.097 | NS | NS | 0.748 | NS |

C = Crop, A = Treatment. C.D. at p = 0.05; NS = not significant. The Treatment × Crop interaction was non-significant for all parameters.

### 3.4. Heavy metal accumulation in roots and shoots

Root and shoot metal concentrations were markedly reduced by the amendment treatments in both crop species (Figure 2). Averaged across marigold and vetiver, biochar produced the greatest reduction, decreasing root Cr from 0.441 mg $kg^{-1}$ in the control to 0.063 mg $kg^{-1}$, root Pb from 0.191 to 0.020 mg $kg^{-1}$, and root Ni from 0.854 to 0.035 mg $kg^{-1}$. For Cr, Pb and Ni, metal concentrations were consistently lower in shoots than in roots, whereas Cd concentrations were of a similar magnitude in both plant parts. Vetiver generally exhibited greater root metal accumulation than marigold, with mean root Cr concentrations of 0.361 and 0.228 mg $kg^{-1}$, respectively, and corresponding root Ni concentrations of 0.427 and 0.328 mg $kg^{-1}$.

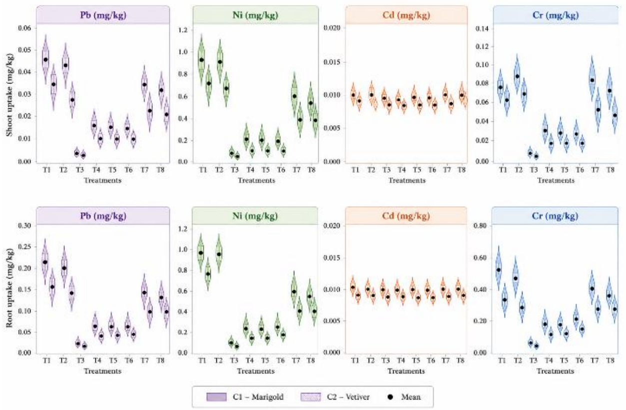


**Figure 2. Shoot and root uptake of Pb, Ni, Cd and Cr by marigold and vetiver under different treatments.**

### 3.5. Bioconcentration and translocation of heavy metals

Bioconcentration factors (BCFs), calculated relative to the soil heavy metal concentration, remained well below unity for all four metals (Figure 3). Cadmium exhibited the highest overall BCF (pooled mean: 0.0345), followed by Ni (0.0069), Cr (0.0019), and Pb (0.0017). Vetiver consistently recorded higher BCF values than marigold for all metals. All amendment treatments reduced BCF relative to the control, with biochar producing the lowest values for Cr, Pb, and Ni. For Cd, the lowest BCF was observed under zeolite (0.0303).

Translocation factors (TFs) were also below unity for Cr (pooled mean: 0.20), Pb (0.19), and Ni (0.63), whereas Cd exhibited comparatively greater translocation, with a pooled mean of 0.836 (Figure 4). The highest treatment means for Cd were recorded under zeolite (1.03). At the individual crop level, Cd TF reached 1.07 in marigold under zeolite and 1.000 in marigold under the biofertilizer consortium and in vetiver under zeolite. Treatment effects were significant only for Cd and Cr, while the crop effect was non-significant for all four metals.

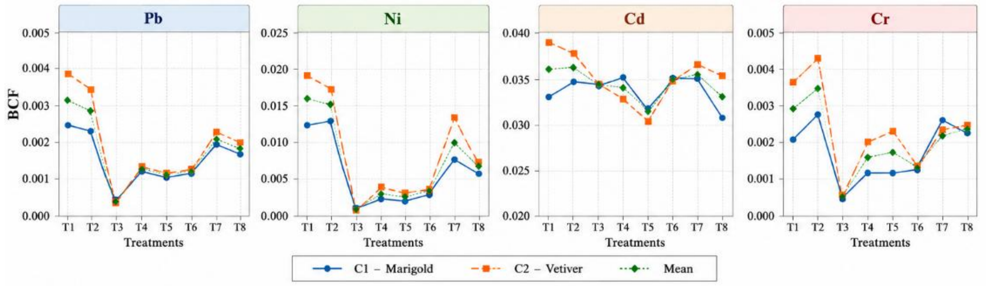


**Figure 3. Effect of amendments on the bioconcentration factor (BCF) of Pb, Ni, Cd and Cr in marigold and vetiver.**

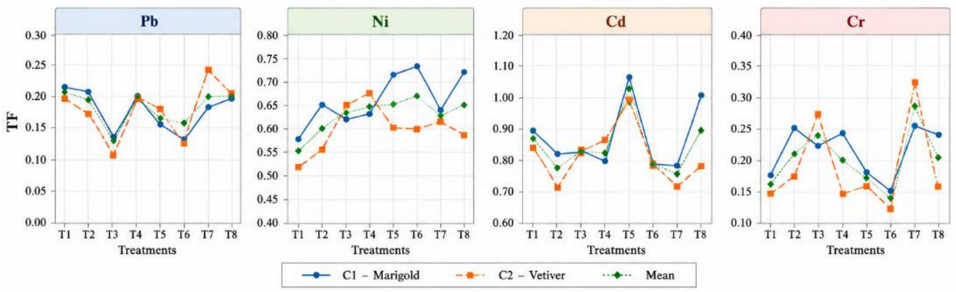


**Figure 4. Effect of amendments on the translocation factor (TF) of Pb, Ni, Cd and Cr in marigold and vetiver.**

### 3.6. Heavy metal removal efficiency of amendment-crop combinations

Heavy metal removal efficiency showed a consistent response to the amendment treatments across all four metals (Figure 5). Biochar was the most effective amendment, achieving mean removal efficiencies of 92.00% for Cd, 82.39% for Ni, 54.71% for Pb, and 52.90% for Cr across the two crops. Vermicompost ranked second, with corresponding removal efficiencies of 50.42%, 42.00%, 33.95%, and 31.05%, respectively. Zeolite and bentonite showed comparable performance, followed by the biofertilizer consortium and humic acid. In comparison, RDF with FYM alone resulted in removal efficiencies ranging from 10.15% to 19.55%, while the unamended control showed only 2.06% to 7.22% removal.

Removal efficiency was consistently higher in vetiver than in marigold across most metal–treatment combinations. Under biochar, vetiver achieved higher removal of Cr (58.1% versus 47.7%), Pb (58.5% versus 51.0%), and Ni (86.1% versus 78.8%) than marigold, whereas Cd removal reached 92.0% in both species. The difference between the two crops was particularly pronounced under some of the less effective amendments. For instance, under humic acid, Cr removal was 25.3% in vetiver compared with 10.2% in marigold, further demonstrating the comparatively greater remediation potential of vetiver under these treatment conditions.

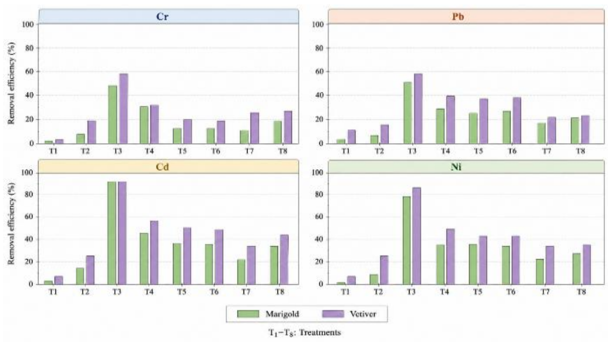


**Figure 5. Effect of different remediation treatments on the removal efficiency of Cr, Pb, Cd and Ni by marigold and vetiver.**

## 4. DISCUSSION

The post-harvest soil properties, microbial activity, metal availability, plant uptake, and removal efficiency for the various amendment-crop combinations are analyzed below. The reduction in soil pH observed with organic and carbon-based amendments cannot be ascribed to the amendments themselves, as the biochar applied was highly alkaline. Instead, it is more likely due to the organic acids and carbon dioxide produced during the microbial decomposition of the added organic materials, a mechanism extensively documented for organically amended contaminated soils (Lwin et al., 2018; Palansooriya et al., 2020). In a calcareous matrix where carbonate buffering is predominant and metal solubility is highly pH-dependent, such a shift is agronomically significant. It moderates the precipitation reactions that limit nutrient availability without shifting the soil into a range that would significantly increase metal mobility. The parallel reduction in EC reflected sorption of soluble salts onto the extensive internal surface of biochar (Rostamian et al., 2018), while the accompanying gain in organic carbon follows from its condensed aromatic structure, which resists rapid mineralisation (Rizwan et al., 2016). This carbon accretion is consequential because soil organic carbon governs both CEC and the abundance of oxygen-containing functional groups participating in metal complexation (Wang et al., 2020).

The microbial response exhibited a distinct divergence from the metal response, which represents a key finding of this study. Vermicompost, as opposed to biochar, resulted in the most significant increases across all enumerated microbial groups, with the biofertilizer consortium consistently ranking second. This outcome can be attributed to the nature of the substrate provided: vermicompost supplies readily decomposable carbon along with mineralisable nitrogen, directly supporting heterotrophic growth. In contrast, the biofertilizer consortium introduces an inoculum of nitrogen-fixing and nutrient-solubilising organisms. Biochar, on the other hand, primarily contributes recalcitrant carbon, which explains its superior ability to enhance soil organic carbon while only modestly stimulating microbial proliferation (Igalavithana et al., 2017). Notably, microbial recovery was most pronounced under treatments that retained a significantly higher residual metal burden, suggesting that substrate and nutrient availability, rather than alleviation from metal toxicity, predominantly influenced microbial abundance. This observation aligns with metagenomic evidence indicating that microbial community structure in soils contaminated by human activities is shaped by the combined effects of nutrient status and contaminant pressure, rather than solely by metal concentration (Vasanthrao et al., 2025).

Biochar emerged as the most effective amendment for reducing residual metal concentrations. This effectiveness is attributed to mechanisms such as sorption, inner-sphere complexation, and surface precipitation, which are enhanced by the elevated pH-dependent surface charge resulting from its alkalinity (Bandara et al., 2017; Beiyuan et al., 2017; Palansooriya et al., 2020). The response's metal-specific ordering is chemically coherent. Cd and Ni, which are relatively mobile divalent cations with a strong affinity for oxygen-containing functional groups and exchange sites on biochar surfaces, exhibited the largest proportional reductions. This finding aligned with the well-documented efficacy of carbon-based amendments in limiting cadmium mobility (Hamid et al., 2019). In contrast, Cr was the most resistant, as it predominantly exists in stable mineral-associated and residual phases within alkaline calcareous matrices, which are largely unresponsive to sorptive amendments over a single season (Guo et al., 2021).

The comparative behaviour of the amendment classes provided valuable insights. Zeolite and bentonite demonstrated moderate immobilisation with minimal microbial benefits, a result attributed to their negligible carbon and nutrient content, consistent with the immobilisation-without-fertility profile reported for mineral sorbents (Shaheen and Rinklebe, 2015; Vrinceanu et al., 2019). Humic acid was the least effective amendment for metal reduction, which is expected given the dual behaviour of humic substances: they can enhance short-term metal solubility through the formation of soluble organo-metallic complexes as easily as they immobilise metals under different conditions (Nejad et al., 2018; Hamid et al., 2019). The current findings suggest that, in this alkaline soil, the mobilising tendency was predominant. Such varied outcomes among amendment classes are typical of multi-metal systems, where the response of one element cannot be extrapolated to another (Khalid et al., 2017; Antoniadis et al., 2017).

The two species exhibited consistent differences in metal accumulation and removal efficiency, a pattern that corresponds with their distinct root architectures and growth durations. Vetiver demonstrated greater metal accumulation in root tissue and higher removal efficiency compared to marigold. This advantage is attributed to vetiver's extensive, finely divided, and vertically descending fibrous root system, which explores a larger soil volume and creates a correspondingly larger rhizosphere. Within this rhizosphere, exudate chemistry, redox status, and microbial activity are altered (Banerjee et al., 2019; Suganya et al., 2024). The longer growth duration of certain species contributed to observed differences and should be considered when comparing species on a per-cycle basis. The disparity between species was most pronounced under weaker amendments, suggesting that species selection is crucial when amendment resources are limited. The superior performance of the biochar-vetiver combination indicated complementary rather than merely additive processes. Nonetheless, marigold offers practical advantages: it is non-edible, completes a shorter growth cycle, and produces a marketable floral product. These characteristics have led several authors to recommend floricultural and energy species for the phytomanagement of contaminated land (Pandey et al., 2016; Mahmood-ul-Hassan et al., 2020).

Bioconcentration factors significantly below unity result from expressing root concentration relative to the total soil metal pool rather than the plant-available portion. This confirmed the enhanced root retention of metals by vetiver and the limited soil-to-root transfer under amendment conditions (Galal and Shehata, 2014; Antoniadis et al., 2017). Translocation factors served as a more diagnostic index of the mechanism. Values below unity for Cr, Pb, and Ni indicated that both species retained most of the absorbed metal in root tissue, rather than transferring it to harvestable shoots, which is characteristic of phytostabilisation rather than phytoextraction (Ashraf et al., 2019; Yan et al., 2020). Cadmium was a notable exception, aligning with the accumulator behaviour documented for Tagetes erecta (Madanan et al., 2021) and the recognised mobility of this element in the soil-plant continuum (Kumar et al., 2020). As both species are non-edible and their biomass is harvested and removed, this translocation poses no direct risk to the food chain. However, it would become a significant concern if the soil were returned to edible cropping without further remediation (Saha et al., 2017). The largely non-significant treatment effects on translocation suggested that the amendments influenced soil-phase availability rather than internal plant partitioning, which remains under physiological control. Therefore, the selection of amendments determined the amount of metal entering the plant, while species selection dictated its deposition. These decisions are complementary rather than interchangeable. (Sarwar et al., 2017; Anne et al., 2023; Parameswari et al., 2025).

## 5. CONCLUSION

This study evaluated the effectiveness of seven soil amendments in combination with marigold (Tagetes erecta L.) and vetiver (Chrysopogon zizanioides (L.) Roberty) for the phytomanagement of an industrially contaminated agricultural soil in Perambalur district. The results showed that amendment application substantially influenced soil quality, biological activity, residual metal concentrations and plant responses. Biochar was the most effective amendment for contaminant management, reducing total soil Cr, Pb, Ni and Cd by 52.9, 54.7, 82.4 and 92.0%, respectively, while also producing the greatest increase in soil organic carbon. In contrast, vermicompost resulted in the greatest improvement in soil biological properties, followed closely by the biofertilizer consortium. Besides, vetiver accumulated more metal in its roots and achieved higher removal efficiency than marigold across treatments, reflecting its extensive root system and longer growth period. Marigold, however, offers the advantages of a shorter cropping cycle and a marketable non-edible product. Translocation factors below unity for Cr, Pb and Ni indicated predominant retention in roots, suggesting phytostabilisation as the principal mechanism, whereas Cd showed greater translocation to the shoots. Overall, the findings demonstrate that combining suitable soil amendments with tolerant plant species can provide a practical approach to managing industrially contaminated agricultural soils. Biochar performed best in reducing residual metal concentrations, while vetiver showed greater potential for metal uptake and retention in the root zone. Together, these results identify the biochar–vetiver combination as a promising option for the phytomanagement of multi-metal-contaminated soils in Perambalur district. Further field-based studies would help determine the long-term effectiveness of this approach under actual agricultural conditions.

Author contributions

All authors contributed substantially to the conception and design of the study, data collection and analysis, interpretation of the results, and preparation and revision of the manuscript. All authors read and approved the final version of the manuscript.

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## DECLARATIONS

**Conflict of interest:** The authors declare that they have no competing interests.

**Ethical approval:** Not applicable.

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