



RESEARCH ARTICLE

Mitigation of heavy metal bioavailability and uptake by fodder crops using organic and mineral amendments in a sewage-irrigated peri-urban agroecosystem

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Received: 18 June 2026; Accepted: 14 August 2026; Available online: Version 1.0: 11 September 2026

Cite this article: Sai KK, Elayarajan M, Suganya S, Jothimani P, Thirunavukkarasu M, Sivamurugan AP. Mitigation of heavy metal bioavailability and uptake by fodder crops using organic and mineral amendments in a sewage-irrigated peri-urban agroecosystem. Plant Science Today. 2026; 13(sp5): 1-11. <https://doi.org/10.14719/pst.16191>

Abstract

Long-term irrigation with sewage wastewater can increase the bioavailability of potentially toxic metals in peri-urban soils and promote their entry into fodder-livestock systems. This greenhouse study evaluated six amendments namely biochar, bentonite, zeolite, humic acid, vermicompost and farmyard manure (FYM), for reducing lead (Pb), cadmium (Cd), nickel (Ni) and chromium (Cr) availability and uptake by fodder maize, fodder sorghum and Cumbu Napier grown in contaminated soil. Each crop was evaluated in a separate completely randomised experiment with 8 treatments and 3 replications. Zeolite was consistently the most effective amendment. Compared with the unamended control, it reduced post-harvest diethylenetriaminepentaacetic acid (DTPA)-extractable Pb, Cd, Ni and Cr by 66.7 % across the three crop soils and lowered metal concentrations in plant tissues by approximately 57.6 %. Vermicompost and farmyard manure (FYM) were the next most effective treatments, whereas recommended fertiliser alone and the unamended control retained the greatest metal availability. Metal concentrations followed the order root > leaf > stem, indicating restricted movement to above-ground tissues. Fodder maize had the lowest overall tissue concentrations, while Cumbu Napier accumulated more Pb, Cd and Ni; Cr accumulation was comparatively greater in sorghum and maize roots. All bioaccumulation and translocation factors were below one. The first two principal components explained 99.79 % of the variation and clearly separated low- and high-metal treatments. The integrated amendment-crop assessment identifies zeolite-amended maize as the lowest-transfer combination under the tested conditions and provides a practical basis for safer fodder production in sewage-irrigated peri-urban soils.

Keywords: bioaccumulation; fodder crops; metal immobilisation; sewage irrigation; soil amendments; translocation

Introduction

Due to increasing freshwater scarcity, municipal and sewage wastewater is increasingly used for irrigation in peri-urban agriculture. Wastewater can supply water and nutrients, but potentially toxic metals present in it may exert phytotoxic effects depending on their concentrations, chemical forms and duration of exposure. Repeated irrigation can increase soil metal concentrations and alter soil organic carbon, pH and metal bioavailability (1–3). Even when visible toxicity is absent, metal transfer through the soil-plant-animal-human continuum can threaten livestock health and food safety (4).

Fodder production is a critical link in this transfer pathway because contaminated feed can expose livestock and, indirectly, consumers of milk and meat. Fodder maize (*Zea mays* L.), fodder sorghum (*Sorghum bicolor* (L.) Moench) and Cumbu Napier hybrid (*Cenchrus purpureus* × *C. americanus*) are widely cultivated in peri-urban dairy systems because of their high biomass production. Their extensive root systems and high nutrient demand may also increase

metal uptake under contaminated conditions. Species differ in root sorption, uptake, internal sequestration and root-to-shoot transport; therefore, both crop selection and soil management influence transfer through the soil-fodder chain (5–8).

In situ immobilisation using organic and mineral amendments is a practical approach for reducing metal mobility without removing the contaminated soil. Farmyard manure (FYM), vermicompost, humic acid and biochar can increase soil organic carbon, cation exchange capacity and the abundance of metal-binding functional groups (9). Zeolite and bentonite provide negatively charged exchange surfaces and internal pores that retain metal cations through ion exchange, adsorption and surface complexation (10–12). Amendment performance, however, depends on soil properties, contamination intensity, metal chemistry and crop species.

So far, most previous studies focused on individual soil indicators, such as diethylenetriaminepentaacetic acid (DTPA)-extractable metals, pH, electrical conductivity, organic carbon or

cation exchange capacity (12, 13). These measurements are useful but do not fully describe the transfer of metals into fodder tissues. A more complete assessment should combine residual soil availability with root, leaf and stem concentrations and with indices of soil-to-root accumulation and root-to-shoot movement (14).

Direct comparisons of biochar, bentonite, zeolite, humic acid, vermicompost and FYM under the same contaminated-soil conditions remain limited, particularly across fodder crops with contrasting uptake and translocation behaviour. This limits the selection of amendment-crop combinations that can minimise metal entry into livestock feeding systems (15–17). The present study therefore evaluated six organic and mineral amendments in a sewage-irrigated peri-urban soil using fodder maize, fodder sorghum and Cumbu Napier. The objectives were to quantify amendment-induced changes in DTPA-extractable lead (Pb), cadmium (Cd), nickel (Ni) and chromium (Cr), determine their distribution among plant tissues, compare root bioaccumulation and root-to-shoot translocation and integrate the soil and plant responses using principal component analysis. The study provides a single experimental framework for identifying a low-transfer amendment-crop combination for safer fodder production.

Materials and Methods

Soil collection and experimental setup

Surface soil samples (0–15 cm) were taken from the agricultural fields that had been continuously irrigated with septic effluents and industrial effluents for more than 10 years in the peri-urban areas of Coimbatore, Tamil Nadu, India (11°06'44.71" N, 76°46'14.74" E). Composite soil samples were collected from contaminated sites and air-dried at room temperature, gently crushed and sieved through a 2 mm mesh for further analysis. The physicochemical properties of the initial physicochemical properties of the soil are presented in Table 1.

Table 1. Baseline physicochemical characteristics of the experimental soil

Soil parameter	Value
pH	7.80
EC (dS m ⁻¹)	1.50
Organic matter (%)	2.01
CEC [c mol (p+) kg ⁻¹]	45.0
CaCO ₃ equivalent (%)	3.51
Clay (%)	35.8
Silt (%)	20.0
Fine sand (%)	20.9
Coarse sand (%)	19.2
Soil texture	Clay loam
Soil type	Vertic ustropept
Available P (mg kg ⁻¹)	58.0
DTPA-extractable Fe (mg kg ⁻¹)	207.5
DTPA-extractable Mn (mg kg ⁻¹)	64.0
DTPA-extractable Zn (mg kg ⁻¹)	23.4
DTPA-extractable Cu (mg kg ⁻¹)	83.8
Total Fe (mg kg ⁻¹)	1481
Total Zn (mg kg ⁻¹)	207
Total Mn (mg kg ⁻¹)	209
Total Cu (mg kg ⁻¹)	508
DTPA-extractable Cd (mg kg ⁻¹)	12.0
DTPA-extractable Pb (mg kg ⁻¹)	69.4
DTPA-extractable Cr (mg kg ⁻¹)	6.20
DTPA-extractable Ni (mg kg ⁻¹)	32.5
Total Cd (mg kg ⁻¹)	16.4
Total Pb (mg kg ⁻¹)	246
Total Cr (mg kg ⁻¹)	109
Total Ni (mg kg ⁻¹)	120

EC: electrical conductivity; CEC: cation exchange capacity; DTPA: diethylenetriaminepentaacetic acid; Fe: iron; Mn: manganese; Zn: zinc; Cu: copper; Cd: cadmium; Pb: lead; Cr: chromium; Ni: nickel.

Six organic and mineral amendments, namely FYM, vermicompost, humic acid, biochar, zeolite and bentonite, were incorporated into the contaminated soil at an application rate of 6 g kg⁻¹ soil (Table 2). The 8 treatments were T₁, recommended dose of fertiliser (RDF) + biochar; T₂, RDF + bentonite; T₃, RDF + zeolite; T₄, RDF + humic acid; T₅, RDF + vermicompost; T₆, RDF + FYM; T₇, RDF alone; and T₈, unamended control (Fig. 1). Ten kilograms of treated

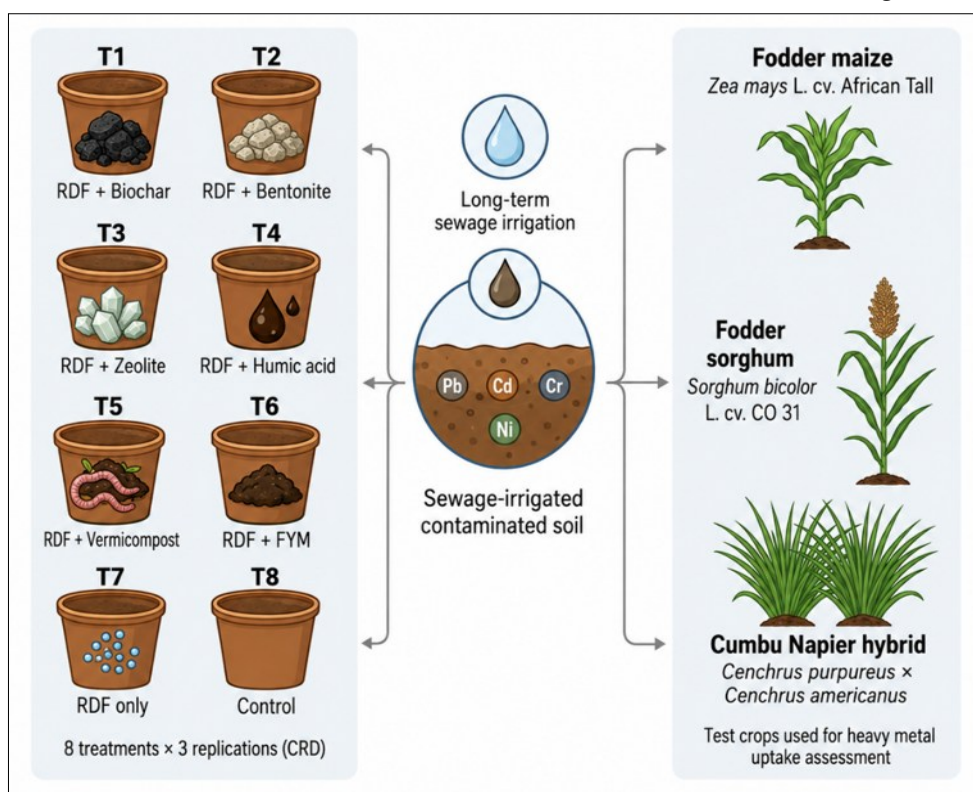


Fig. 1. Schematic diagram of the treatment details conducted to evaluate the effectiveness of different amendments.

soil were placed in each plastic pot and maintained near field capacity for two months before planting. This pre-incubation period was selected to permit amendment-soil reactions, including pH equilibration, ion exchange, adsorption and complexation, to develop before crop establishment (12).

Table 2. Properties of organic and inorganic amendments employed in the study

Amendments	pH	EC (dS m ⁻¹)	OC (%)	CEC (c mol (+) kg ⁻¹)	Specific surface area (m ² g ⁻¹)
FYM	7.15	0.20	12.2	80.0	5.00
Vermicompost	6.70	4.88	15.8	93.0	20.0
Humic acid	6.80	2.23	45.0	353	50.0
Biochar	8.81	1.88	-	90.5	150
Zeolite	8.95	0.50	-	138	412
Bentonite	9.46	0.76	-	110	543

FYM: farmyard manure; EC: electrical conductivity; OC: organic carbon; CEC: cation exchange capacity.

Three independent pot experiments were conducted, one each for fodder maize (*Zea mays* L. cv. African Tall), fodder sorghum (*Sorghum bicolor* (L.) Moench cv. CO 31) and Cumbu Napier hybrid (*Cenchrus purpureus* × *C. americanus*). Each experiment followed a completely randomised design with eight amendment treatments and three replications. Seeds or stem setts (Cumbu Napier) were established and thinned to one healthy plant per pot. Plants were maintained under natural light in a greenhouse and soil moisture was kept near field capacity with deionised water. Because the crop experiments were established and analysed separately, crop was not treated as a factorial factor and an amendment × crop interaction was not tested.

Sample preparation and analysis

At harvest, plants were carefully uprooted and separated into roots, leaves and stems. Samples were washed thoroughly with distilled water, oven-dried at 65 °C to constant mass, ground and digested with a nitric acid-perchloric acid mixture (HNO₃-HClO₄). Initial soil samples were analysed for iron (Fe), zinc (Zn), manganese (Mn) and copper (Cu), Cd, Pb, Ni and Cr by atomic absorption spectrophotometry. Subsequent soil and plant analyses focused on Cd, Pb, Ni and Cr because these were selected as priority contaminants owing to their persistence, toxicity and relevance to the soil-fodder-livestock pathway; Fe, Zn, Mn and Cu were retained as baseline micronutrient indicators. Total metal concentrations were determined by acid digestion and the bioavailable soil fraction was extracted with 0.005 M DTPA (18). Post-harvest soil analysis was limited to DTPA-extractable metals to quantify amendment-induced changes in the potentially available fraction.

Statistical analysis

Data from each crop experiment were analysed separately using one-way analysis of variance in OriginPro 2026. Residual normality and homogeneity of variance were evaluated using the Shapiro-Wilk and Levene tests, respectively. When the assumptions were satisfied, treatment means were separated using Fisher's least significant difference test at $p \leq 0.05$. Values in the tables are treatment means of 3 replications; the standard error of difference (SEd) and critical difference at 5 % (CD, $p = 0.05$) are provided.

Principal component analysis

Principal component analysis (PCA) was used to examine relationships among soil metal availability, metal concentrations in roots, leaves and stems and treatment clustering across the three crops. Sixteen variables were included: Soil_Pb, Soil_Cd, Soil_Ni,

Soil_Cr, Root_Pb, Root_Cd, Root_Ni, Root_Cr, Leaf_Pb, Leaf_Cd, Leaf_Ni, Leaf_Cr, Stem_Pb, Stem_Cd, Stem_Ni and Stem_Cr. Variables were standardised to z-scores and PCA was performed in R using the correlation matrix. Components with eigenvalues greater than one were retained according to the Kaiser criterion (19).

Bioaccumulation and translocation indices

To evaluate the uptake and mobility of heavy metals in fodder crops, the bioaccumulation factor (BAF) and translocation factor (TF) were calculated using the following expression:

$$\text{BAF} = \frac{\text{Metal concentration in root (mg kg}^{-1}\text{)}}{\text{Metal concentration in soil (mg kg}^{-1}\text{)}} \quad \text{Eq. (1)}$$

$$\text{TF} = \frac{\text{Metal concentration in root (mg kg}^{-1}\text{)}}{\text{Metal concentration in soil (mg kg}^{-1}\text{)}} \quad \text{Eq. (2)}$$

Only root BAF values were calculated and reported. BAF > 1 denotes enrichment in roots relative to the extractable soil pool, whereas TF > 1 denotes greater above-ground than root concentration. Values below one indicate limited accumulation or translocation; evidence of phytostabilisation was interpreted jointly from TF, root retention and the reduction in DTPA-extractable soil metals rather than from TF alone (19–21).

Results

The application of amendments significantly altered post-harvest DTPA-extractable heavy metals and their concentrations in fodder-crop tissues. The response was consistent across the three crop experiments, although the predominant metal and the magnitude of tissue accumulation differed among species.

Effect of different amendments on DTPA-extractable heavy metal concentrations in post-harvest soil

Post-harvest DTPA-extractable metal concentrations differed significantly among treatments in all three crop soils (Table 3). The unamended control (T₈) recorded the highest Pb, Cd, Ni and Cr concentrations, whereas zeolite (T₃) consistently recorded the lowest. Relative to T₈, T₃ reduced each of the four extractable metals by 66.7 % in the Cumbu Napier, fodder sorghum and fodder maize soils. Ni remained the most abundant extractable metal, followed by Pb, Cd and Cr. Amendment effectiveness followed the order T₃ (zeolite) > T₅ (vermicompost) > T₆ (FYM) > T₄ (humic acid) > T₂ (bentonite) > T₁ (biochar) > T₇ (RDF alone) > T₈ (unamended control). Across treatments, fodder maize pots retained lower extractable metal concentrations than the corresponding sorghum and Cumbu Napier pots.

Effect of amendments on heavy metal accumulation in Cumbu Napier at harvest

Metal concentrations in Cumbu Napier differed significantly among amendments (Table 4). The T₈ produced the highest concentrations in every tissue, while T₃ produced the lowest and reduced tissue concentrations by approximately 57.6 % relative to T₈. Concentrations followed the order root > leaf > stem, confirming strong root retention. Ni was the predominant root metal (0.475–1.121 mg kg⁻¹), followed by Pb, Cd and Cr. The treatment ranking was consistent among roots, leaves and stems: T₃ was most effective, followed by T₅, T₆, T₄, T₂ and T₁, while T₇ and T₈ showed substantially greater accumulation. This pattern corresponded closely with the post-harvest DTPA-extractable metal pool.

Table 3. Effect of different amendments on diethylenetriaminepentaacetic acid (DTPA)-extractable heavy metal content in post-harvest soil (mg kg⁻¹)

Treatments	Cumbu Napier				Sorghum				Maize			
	Pb	Cd	Ni	Cr	Pb	Cd	Ni	Cr	Pb	Cd	Ni	Cr
T ₁	11.8	3.25	17.3	1.03	10.55	2.95	15.75	0.93	7.1	1.98	10.5	0.625
T ₂	10.5	2.90	15.4	0.92	9.35	2.62	13.95	0.825	6.25	1.74	9.25	0.550
T ₃	7.80	2.16	11.4	0.68	6.88	1.92	10.20	0.60	4.6	1.28	6.80	0.400
T ₄	9.20	2.55	13.5	0.805	8.15	2.28	12.15	0.72	5.5	1.53	8.10	0.480
T ₅	8.10	2.25	11.9	0.71	7.15	2.00	10.65	0.63	4.85	1.35	7.15	0.425
T ₆	8.40	2.35	12.3	0.74	7.45	2.08	11.10	0.66	5.05	1.4	7.45	0.445
T ₇	19.5	5.40	28.6	1.7	17.20	4.80	25.50	1.50	11.5	3.2	17.0	1.000
T ₈	23.4	6.48	34.2	2.04	20.64	5.76	30.60	1.80	13.8	3.84	20.4	1.200
SEd	0.3005	0.0844	0.2665	0.0335	0.2513	0.0609	0.2186	0.0199	0.1883	0.0478	0.2851	0.0125
CD 5 %	0.6370	0.1789	0.5650	0.0710	0.5327	0.1291	0.4634	0.0421	0.3991	0.1014	0.6045	0.0265

Pb: lead; Cd: cadmium; Ni: nickel; Cr: chromium; SEd: standard error of difference; CD: critical difference.

Table 4. Effect of different amendments on heavy metal content (mg kg⁻¹) in Cumbu Napier at harvest

Treatments	Leaf				Stem				Root			
	Cd	Cr	Ni	Pb	Cd	Cr	Ni	Pb	Cd	Cr	Ni	Pb
T ₁	0.0328	0.0055	0.1747	0.0491	0.0215	0.0034	0.1115	0.03	0.1248	0.0234	0.741	0.187
T ₂	0.0286	0.0048	0.1523	0.0428	0.0187	0.003	0.0972	0.0262	0.1088	0.0204	0.646	0.163
T ₃	0.021	0.0035	0.112	0.0315	0.0138	0.0022	0.0715	0.0193	0.0800	0.015	0.475	0.120
T ₄	0.0244	0.0041	0.1299	0.0365	0.0160	0.0025	0.0829	0.0223	0.0928	0.0174	0.551	0.139
T ₅	0.022	0.0037	0.117	0.033	0.0145	0.0023	0.075	0.0202	0.0840	0.0158	0.499	0.126
T ₆	0.023	0.0038	0.122	0.0345	0.0150	0.0024	0.078	0.0210	0.0880	0.0165	0.523	0.132
T ₇	0.042	0.0070	0.224	0.063	0.0275	0.0044	0.143	0.0385	0.1600	0.0300	0.950	0.240
T ₈	0.0496	0.0083	0.2643	0.0743	0.0324	0.0052	0.1687	0.0454	0.1888	0.0354	1.121	0.283
SEd	0.0008	0.0001	0.0026	0.0010	0.0005	0.0001	0.0020	0.0007	0.0031	0.0006	0.0149	0.0038
CD 5 %	0.0017	0.0002	0.0054	0.0021	0.0010	0.0002	0.0043	0.0016	0.0066	0.0013	0.0317	0.0081

Cd: cadmium; Cr: chromium; Ni: nickel; Pb: lead; SEd: standard error of difference; CD: critical difference.

Effect of different amendments on heavy metal content in fodder sorghum at harvest

In fodder sorghum, T₈ recorded the highest and T₃ the lowest metal concentrations in all tissues (Table 5). Zeolite reduced tissue concentrations by approximately 57.6 % compared with the unamended control. Roots contained substantially more metal than leaves or stems. In contrast to Cumbu Napier, Cr was the dominant root metal (0.375–0.885 mg kg⁻¹), followed by Ni, Pb and Cd. Vermicompost and FYM were the next most effective amendments after zeolite. Recommended dose of fertiliser (RDF) alone provided only limited reduction relative to the unamended control, indicating that fertiliser application without an immobilising amendment did not adequately restrict metal uptake.

Effect of different amendments on heavy metal content in fodder maize at harvest

Fodder maize showed the lowest overall tissue concentrations among the three crops (Table 6). As in the other crops, T₈ recorded the highest and T₃ the lowest values; zeolite lowered tissue concentrations by approximately 57.6 % relative to T₈. Root concentrations ranged from 0.045–0.106 mg kg⁻¹ for Pb,

0.009–0.021 mg kg⁻¹ for Cd, 0.290–0.684 mg kg⁻¹ for Cr and 0.070–0.165 mg kg⁻¹ for Ni. Metal partitioning again followed root > leaf > stem. The Cr was the predominant accumulated metal in maize, followed by Ni, Pb and Cd. The lower absolute concentrations in maize, particularly under T₃, identified zeolite-amended maize as the lowest-transfer treatment-crop combination under the tested conditions.

Principal component analysis of soil-fodder metal dynamics

The first two principal components explained 99.79 % of the total variation: PC1 accounted for 73.72 % and PC2 for 26.07 %. The scree plot showed a sharp decline after PC2, confirming that these two components captured the dominant structure of the dataset (Fig. 2). The PCA biplot separated treatments primarily according to crop species and metal burden (Fig. 3). Cumbu Napier treatments occupied the positive side of PC1 and were associated with greater overall tissue concentrations, particularly under T₇ and T₈. Maize and sorghum treatments were positioned mainly on the negative side of PC1. Within each crop, T₃, T₅ and T₆ clustered towards the lower-metal region, whereas T₇ and T₈ were separated towards the high-metal region.

Table 5. Effect of different amendments on heavy metal content in fodder sorghum (mg kg⁻¹) at harvest

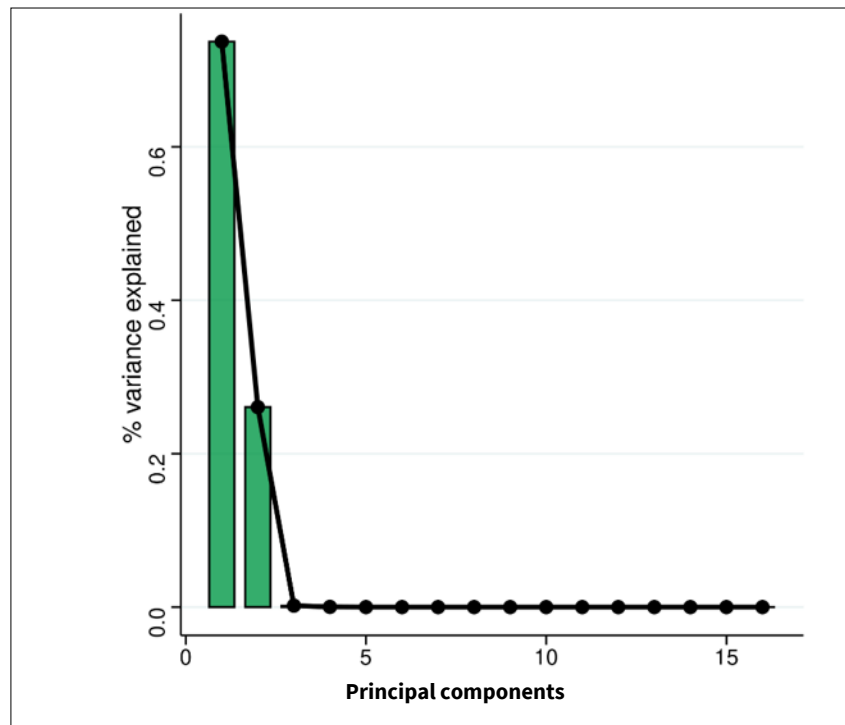
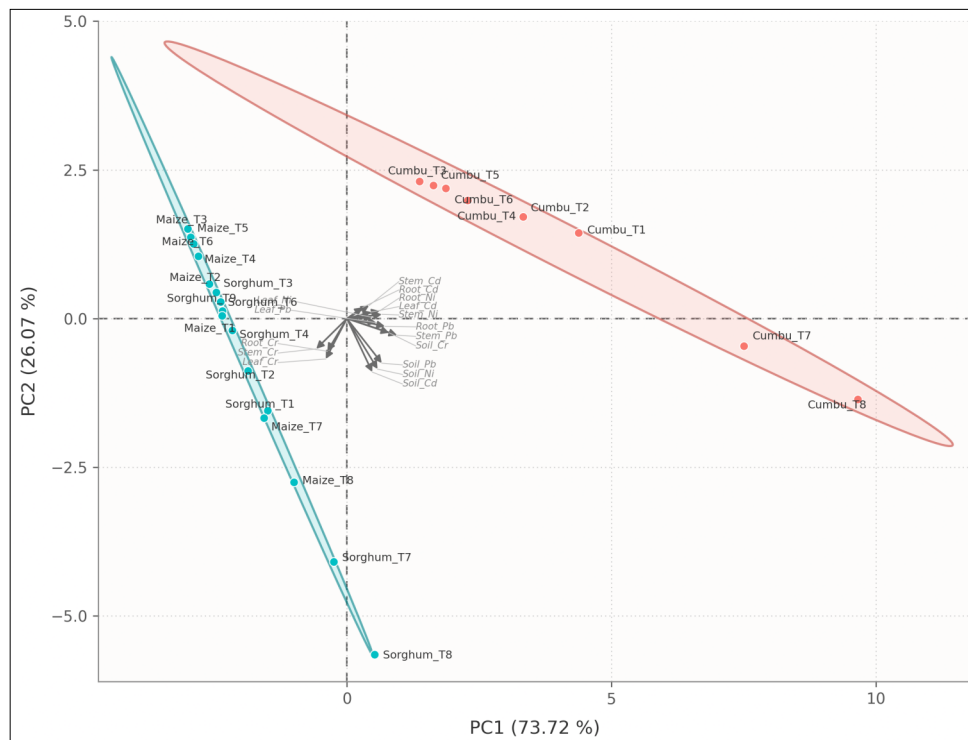
Treatments	Leaf				Stem				Root			
	Pb	Cd	Cr	Ni	Pb	Cd	Cr	Ni	Pb	Cd	Cr	Ni
T ₁	0.0246	0.0043	0.1256	0.0382	0.015	0.0026	0.0815	0.0236	0.0936	0.0156	0.585	0.1404
T ₂	0.0214	0.0038	0.1095	0.0333	0.0131	0.0023	0.0711	0.0206	0.0816	0.0136	0.51	0.1224
T ₃	0.0158	0.0028	0.0805	0.0245	0.0096	0.0017	0.0523	0.0151	0.06	0.01	0.375	0.09
T ₄	0.0183	0.0032	0.0934	0.0284	0.0112	0.0019	0.0606	0.0175	0.0696	0.0116	0.435	0.1044
T ₅	0.0165	0.0029	0.084	0.0255	0.01	0.0018	0.0545	0.0158	0.063	0.0105	0.394	0.0945
T ₆	0.0172	0.003	0.0875	0.0265	0.0105	0.0019	0.057	0.0165	0.066	0.011	0.413	0.099
T ₇	0.0315	0.0056	0.161	0.049	0.0193	0.0033	0.1045	0.0303	0.12	0.02	0.75	0.18
T ₈	0.0372	0.0066	0.19	0.0578	0.0227	0.0039	0.1233	0.0357	0.1416	0.0236	0.885	0.2124
SEd	0.0004	0.0004	0.0001	0.0021	0.0010	0.0003	0.0002	0.0016	0.0003	0.0015	0.0002	0.0108
CD 5 %	0.0009	0.0002	0.0045	0.0021	0.0007	0.0005	0.0034	0.0005	0.0032	0.0005	0.0230	0.0056

Cd: cadmium; Cr: chromium; Ni: nickel; Pb: lead; SEd: standard error of difference; CD: critical difference.

Table 6. Effect of different amendments on heavy metal content (mg kg⁻¹) in fodder maize at harvest

Treatments	Leaf				Stem				Root			
	Pb	Cd	Cr	Ni	Pb	Cd	Cr	Ni	Pb	Cd	Cr	Ni
T ₁	0.0164	0.0033	0.0928	0.0273	0.0107	0.0017	0.0601	0.0172	0.0702	0.014	0.4524	0.1092
T ₂	0.0143	0.0029	0.0809	0.0238	0.0094	0.0015	0.0524	0.015	0.0612	0.0122	0.3944	0.0952
T ₃	0.0105	0.0021	0.0595	0.0175	0.0069	0.0011	0.0385	0.011	0.045	0.009	0.29	0.07
T ₄	0.0122	0.0024	0.069	0.0203	0.008	0.0013	0.0447	0.0128	0.0522	0.0104	0.3364	0.0812
T ₅	0.011	0.0022	0.062	0.0183	0.0072	0.0012	0.0402	0.0115	0.047	0.0094	0.304	0.0735
T ₆	0.0115	0.0023	0.065	0.019	0.0075	0.0012	0.042	0.012	0.0495	0.0099	0.32	0.077
T ₇	0.021	0.0042	0.119	0.035	0.0138	0.0022	0.077	0.022	0.09	0.018	0.58	0.14
T ₈	0.0248	0.005	0.1404	0.0413	0.0162	0.0026	0.0909	0.026	0.1062	0.0212	0.6844	0.1652
SEd	0.0002	0.0001	0.0020	0.0007	0.0002	0.0002	0.0012	0.0005	0.0011	0.0002	0.0075	0.0022
CD 5 %	0.0004	0.0002	0.0042	0.0014	0.0004	0.0004	0.0024	0.0011	0.0023	0.0004	0.0160	0.0046

Cd: cadmium; Cr: chromium; Ni: nickel; Pb: lead; SEd: standard error of difference; CD: critical difference.

**Fig. 2.** Scree plot showing the percentage variance explained by the principal components.**Fig. 3.** Principal component analysis (PCA) biplot illustrating treatment clustering and relationships among soil and plant heavy metal variables.

Soil Pb, Cd, Ni and Cr showed strong positive loadings and were associated with Pb, Cd and Ni concentrations in roots, leaves and stems. Tissue Cr variables followed a distinct loading pattern, indicating that Cr accumulation differed from that of the other three metals. The correlation matrix supported the PCA pattern (Fig. 4). The Pb, Cd and Ni were strongly and positively correlated across plant compartments, while Cr showed weaker or negative relationships with these metals in tissue variables. Thus, treatment clustering reflected both the size of the extractable soil metal pool and species-specific tissue partitioning. The multivariate analyses distinguished the amendment treatments and confirmed that zeolite, vermicompost and FYM produced the most consistent reductions in the soil-plant system.

Bioaccumulation factor of heavy metals in Cumbu Napier, fodder sorghum and fodder maize

Root BAF values were below one for all metals, treatments and crops (Fig. 5). In Cumbu Napier, BAF ranged from 0.0076–0.0154 for Pb, 0.0183–0.0370 for Cd, 0.0109–0.0221 for Cr and 0.0206–0.0417

for Ni. Chromium BAF was considerably higher in fodder sorghum (0.309–0.625) and fodder maize (0.358–0.725) than the BAF values of Pb, Cd and Ni.

Translocation factor of heavy metals in Cumbu Napier, fodder sorghum and fodder maize

The translocation factor (TF) values varied only slightly among amendment treatments, indicating that amendments influenced soil availability and root entry more strongly than internal root-to-shoot partitioning (Fig. 5). All TF values remained below one. The TF ranged from 0.422–0.423 for Pb, 0.434–0.435 for Cd, 0.386–0.387 for Cr and 0.379–0.382 for Ni in Cumbu Napier. Corresponding ranges in sorghum were 0.423–0.424, 0.440–0.450, approximately 0.354 and 0.440–0.441, while maize recorded 0.384–0.387, 0.354–0.362, 0.334–0.338 and 0.403–0.408, respectively. The consistently low TF values demonstrated restricted root-to-shoot movement. Cadmium showed the greatest relative translocation in Cumbu Napier and sorghum, whereas Cr showed the strongest root retention in sorghum and maize.

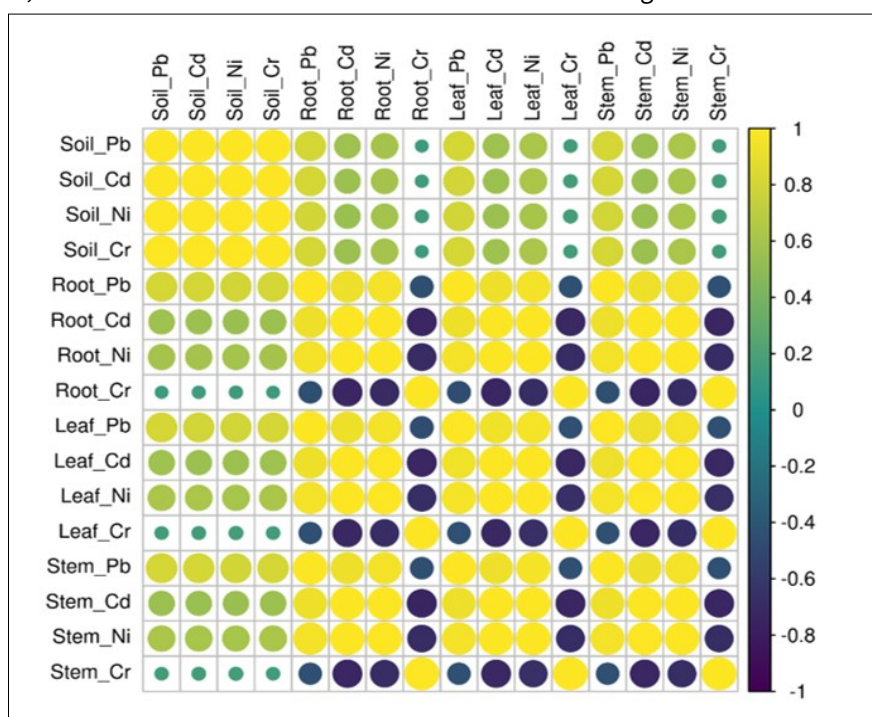


Fig. 4. Correlation matrix showing associations among soil, root, leaf and stem heavy metal concentrations.

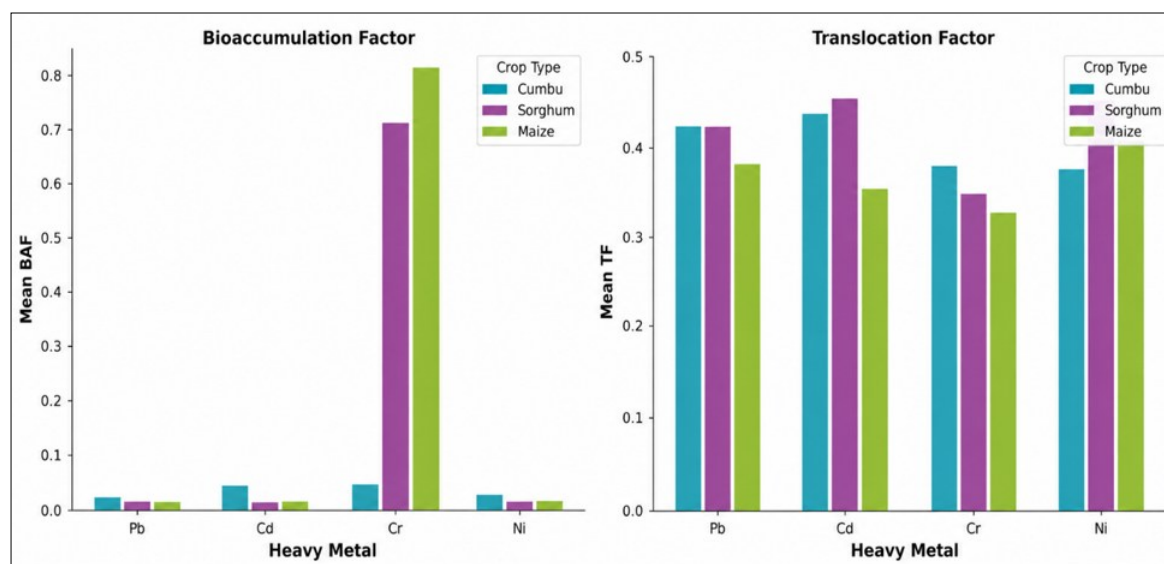


Fig. 5. Comparison of mean bioaccumulation factor and translocation factor among fodder crops grown in sewage-contaminated soil.

Discussion

The application of organic and mineral amendments significantly reduced the DTPA-extractable fractions of Pb, Cd, Ni and Cr in soils cultivated with Cumbu Napier, fodder sorghum and fodder maize. Zeolite produced the greatest and most consistent reduction in DTPA-extractable Pb, Cd, Ni and Cr, lowering their concentrations by 66.7 % relative to the unamended control in each crop soil. Its performance can be explained by the combined effects of an alkaline reaction, high cation exchange capacity and a porous aluminosilicate framework that provides internal and external sites for ion exchange and surface complexation. These properties favour the retention of cationic metals and reduce the fraction accessible to plant roots (11, 12, 22, 23). Although bentonite had a greater specific surface area (Table 2), surface area alone does not determine immobilisation; pore accessibility, exchange selectivity, mineral structure and amendment–soil interactions also regulate metal retention (24).

Vermicompost and FYM ranked immediately after zeolite. Their effectiveness is attributable to organic functional groups, humified carbon and exchange sites that bind metals through complexation and adsorption. Organic amendments may also alter pH and promote the formation of less soluble metal-organic associations (10, 21, 22). Biochar reduced metal availability relative to RDF alone and the control, but it was less effective than zeolite under the present soil conditions. This result shows that amendment performance cannot be predicted from a single property and must be evaluated in relation to the contaminated soil matrix (25). The strong root > leaf > stem pattern across all crops indicates that roots were the principal barrier to entry into harvestable tissues. Metals may be retained by adsorption to cell-wall components, precipitation in the rhizosphere, chelation in the cytoplasm and sequestration in vacuoles, thereby limiting movement through the xylem (26, 27). However, TF values below one should not be treated as independent proof of phytostabilisation. In this study, the interpretation is supported jointly by low TF, preferential root retention and amendment-induced reductions in DTPA-extractable soil metals.

Crop-specific patterns were also evident. Cumbu Napier accumulated comparatively more Pb, Cd and Ni, whereas maize had the lowest overall tissue concentrations. The extensive root system and high biomass demand of Cumbu Napier may increase contact with the contaminated soil and the uptake of mobile ions. Maize may restrict entry through root exclusion, binding at the root surface and controlled loading into the xylem (28–30). Metal dominance also differed among crops: Ni was greatest in Cumbu Napier roots, while Cr was predominant in sorghum and maize roots. These contrasts probably reflect differences in rhizosphere chemistry, transporter activity and the redox-sensitive behaviour of Cr (25, 28, 31). The BAF results further demonstrate why ratio-based indices should be interpreted cautiously. A treatment can produce a slightly greater BAF even when it lowers absolute uptake because both the plant concentration and the DTPA-extractable soil concentration change simultaneously. The relatively high Cr BAF in sorghum and maize therefore reflects strong root accumulation relative to the small extractable soil Cr pool, not greater shoot exposure (32, 33). Absolute tissue concentrations, residual soil availability and TF should be considered together when evaluating amendment performance and fodder safety (34–37).

The narrow treatment range in TF indicates that the amendments acted mainly before or during root uptake rather than altering internal transport after metals entered the plant. Low TF reduces the proportion reaching leaves and stems, but it does not by itself establish that fodder is safe for livestock (38). Feed safety requires comparison with species-specific maximum permissible concentrations, intake rates and animal exposure or health-risk indices (27, 39). The present data therefore indicate reduced transfer potential rather than the absence of risk. The PCA integrated the soil and tissue responses and reinforced the univariate results. The PC1 represented the overall metal burden, separating the low-metal T₃, T₅ and T₆ treatments from RDF alone and the unamended control. The co-loading of soil Pb, Cd and Ni with their tissue concentrations indicates that decreasing the extractable soil pool translated directly into lower plant accumulation. The distinct behaviour of tissue Cr along PC2 is consistent with its redox-dependent speciation and strong root retention (25, 40–42).

For peri-urban fodder producers using sewage-affected soils, the findings support combining an immobilising amendment with a crop that limits tissue accumulation. Under the greenhouse conditions tested, zeolite-amended maize provided the lowest-transfer combination. Nevertheless, the 6 g kg⁻¹ amendment rate, its cost and availability, effects on crop yield and nutritive value and the long-term stability of immobilised metals must be evaluated under field conditions before broad recommendation. The study was limited to one contaminated soil, one amendment rate, a single growth cycle and greenhouse conditions. Future work should test multiple soils and amendment rates, monitor metal remobilisation over successive seasons, include crop yield and fodder-quality responses and conduct livestock dietary risk assessments. Field-scale economic analysis is also required to determine whether zeolite or locally available organic amendments offer the most practical long-term strategy.

Conclusion

The current study demonstrated that the application of organic and mineral amendments effectively reduced the bioavailability and subsequent transfer of lead (Pb), cadmium (Cd), nickel (Ni) and chromium (Cr) from sewage-irrigated soils to fodder crops. Zeolite was the most effective of the six amendments evaluated, reducing post-harvest diethylenetriaminepentaacetic acid (DTPA)-extractable Pb, Cd, Ni and Cr by 66.7 % and lowering plant-tissue concentrations by approximately 57.6 % compared with the unamended control. Vermicompost and farmyard manure (FYM) were the next most effective options. Metal retention was strongly tissue-specific, with roots containing more metal than leaves or stems, while crop responses also differed: fodder maize showed the lowest overall accumulation, Cumbu Napier accumulated comparatively more Pb, Cd and Ni and Cr accumulation was greater in sorghum and maize roots. These findings identify zeolite-amended maize as the lowest-transfer combination under the tested greenhouse conditions. For farmers managing sewage-affected peri-urban soils, amendment-assisted immobilisation combined with careful crop selection may reduce metal entry into fodder systems. However, the results should not be interpreted as proof of livestock safety without feed-standard and dietary-risk assessment. Multi-season field trials are needed to validate amendment rates, economic feasibility, effects on yield and fodder quality and the long-term stability of immobilised metals.

Acknowledgements

The authors are grateful to Tamil Nadu Agricultural University for providing the library sources for the collection of relevant literature.

Authors' contributions

SKK contributed to manuscript writing and conceptualisation. EM contributed to manuscript review and supervision. SS, JP, TM and SAP contributed to manuscript review and visualisation. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflicts of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Quillbot and Claude AI to assist with language editing. After using this tool, the authors reviewed and validated all content as needed and take full responsibility for the content of the publication.

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