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Heavy Metal Dynamics in Crops Grown on Municipal Solid Waste Compost-Amended Soils

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ABSTRACT

Growing interest in using compost derived from municipal solid waste (MSW) in agriculture raises critical questions about its ecological safety, particularly the accumulation pattern of potentially toxic heavy metals in food and fodder crops. This study assessed the effects of a single application of MSW compost on soil heavy-metal dynamics and plant uptake in Napier grass (*Pennisetum purpureum*), ragi (*Eleusine coracana*), maize (*Zea mays*), and hyacinth bean (*Lablab purpureus*). The compost complied with the maximum permissible heavy-metal limits prescribed under the Fertilizer (Control) Order (FCO), 1985. Statistical analysis (Welch's t-test with multiple-comparison correction) revealed significant crop-specific changes in soil metal concentrations following compost amendment, with reductions observed for certain metals such as Zn, Cu, Pb, and Cr. Bioconcentration and translocation factor results indicated elevated translocation ($TF > 1$) and accumulation in edible parts, particularly for Pb in maize and for Zn, Cu, Ni, and Cd in hyacinth bean. Essential metals (Zn and Cu) showed regulated uptake, while potentially toxic metals (Pb, Cd, and Cr) were variably immobilized or translocated depending on crop type. Overall, the findings demonstrate that the impact of MSW compost on heavy-metal mobility and plant uptake is crop-dependent. Although compost application may reduce the bioavailability of certain metals, it does not universally prevent their transfer to edible plant parts. These results highlight the need for crop-specific risk assessment and monitoring to ensure the safe and sustainable use of MSW compost in agricultural systems.

1. INTRODUCTION

Rising populations, rapid urbanization, and industrialization have intensified MSW generation across cities worldwide (Soni et al. 2023). Global MSW production is projected to increase from 2.89 to 4.54 billion tons by 2050 (Maalouf & Mavropoulos 2023). Composting has emerged as a viable and widely accepted strategy for efficiently recycling organic fractions of MSW and is increasingly promoted as a sustainable approach to waste management. The organic fraction of MSW contributes essential soil nutrients (Rodríguez-Espinosa et al. 2023) and is an important source of soil organic matter that enhances microbial activity, soil fertility, structure, and water-holding capacity (Adugna 2016). In Sri Lanka, composting and recycling organic waste have been estimated to generate US\$191 million in waste management and fertilizer cost savings (Roy et al. 2021). Redirecting waste from landfill disposal to composting not only reduces MSW volume but also mitigates greenhouse gas (GHG) emissions compared with incineration and landfilling (Manea et al. 2024, Qdais et al. 2019).

Despite its agronomic benefits, MSW compost raises concerns about ecological safety, as it may also contain appreciable concentrations of toxic heavy metals such as zinc (Zn), copper (Cu), cadmium (Cd), lead (Pb), nickel (Ni), and chromium (Cr), originating from household waste, batteries, electronic residues, and urban refuse (Ishchenko & Vasylykivskyi 2019). These metals can bioaccumulate and biomagnify through the food chain, intensifying their toxicity. They can interfere with various metabolic processes by accumulating in vital organs such as the liver, heart, brain, and kidneys, thereby disrupting their normal functions (Kiran et al. 2022). This highlights the need to explore methods for mitigating their presence in the environment.

While compost-derived organic matter can immobilize certain metals through complexation and adsorption, thereby reducing their bioavailability, it may simultaneously enhance the availability of others, particularly Zn and Cu, which are more mobile under agricultural conditions (Huang et al. 2016). These contrasting effects highlight the need for site-specific and crop-specific assessments.

Plants differ markedly in their ability to absorb and translocate heavy metals. Bioconcentration factor (BCF) and translocation factor (TF) are widely used indices to evaluate metal uptake from soil and subsequent transport from roots to aerial parts (Bose & Bhattacharyya 2008, Buscaroli 2017). They also help distinguish the phytostabilization and phytoextraction potential of plant species. Plants with $BCF > 1$ and $TF > 1$ are generally considered suitable for phytoextraction, whereas plants with $BCF > 1$ and $TF < 1$ are more appropriate for phytostabilization (Eben et al. 2024).

Field-based (in situ) studies are particularly valuable because they reflect realistic soil–plant–environment interactions that controlled pot experiments cannot fully replicate. However, data on heavy metal uptake under true agricultural conditions remain limited. Such studies are critical for evaluating the environmental safety of MSW compost application and its role in sustainable agriculture. Therefore, this study investigates heavy metal accumulation, bioconcentration, and translocation in selected plant species grown in MSW compost-amended soils under in situ conditions.

2. MATERIALS AND METHODS

The study was conducted across multiple sites in Bengaluru, where waste management practices and MSW-derived compost are used in agriculture. Bengaluru is located in the heart of the South Deccan Plateau in the southeastern corner of Karnataka State, between latitudes $12^{\circ}39' \text{ N}$ and $13^{\circ}18' \text{ N}$ and longitudes $77^{\circ}22' \text{ E}$ and $77^{\circ}52' \text{ E}$, covering an area

of 2,196 km² with an average elevation of about 900 m. The city, with a population of 1.3 million, generates around 5,000–6,000 t day⁻¹ of MSW, including bulk generation, with a per capita generation of 400 g day⁻¹ (BBMP 2022). Source-separated wet waste, or the organic fraction of the waste, is sent to Wet-Waste Processing Plants (WPPs), where it is transformed into compost that farmers subsequently apply as a soil amendment.

Samples of compost were collected from six operational MSW composting facilities located in Bengaluru (Fig. 1). Compost sampling was conducted during the post-monsoon season (November–December 2023), when ambient temperatures ranged between 18–28 °C and relative humidity was moderate. No temporal variation was assessed, and the results represent conditions specific to the sampling period. Soil and plant samples were collected in situ from two distinct field types: MSW compost-amended fields and conventional-practice fields (control). Compost-amended fields were agricultural fields with documented use of MSW compost for at least one cropping season. No controlled plot experimentation was conducted; instead, the study relied on existing farmer-managed systems to capture real-world agricultural conditions. Compost was reported to have been applied once, approximately 20–30 days before sowing, at 5–12 t acre⁻¹. Adjacent conventional fields, or comparable fields in the vicinity managed using traditional fertilization practices, including chemical fertilizers and farmyard manure, and with no history of compost application were considered controls. Both field types were maintained under similar cropping systems and agronomic practices to ensure comparability. The outline map (Fig. 2) shows four compost-amended sites along with four control sites, where soil samples and plants, including *Pennisetum purpureum* (fodder, Napier grass), *Eleusine coracana* (millet, ragi), *Zea mays* (cereal, maize), and *Lablab purpureus* (pulse, hyacinth bean), were collected from Bengaluru Urban for the study. Plant and soil samples were collected once during June–December 2023.

2.1. Sampling and Analysis of MSW Compost, Soil, and Plant Samples

Composite samples comprising several grab samples from ten different points of the final compost heap (<4 mm particle size) were collected from each WPP in sterile polythene bags to minimize changes in moisture content and transported immediately under ice-cooled conditions to the laboratory for further analysis. A subsample of each composite sample was immediately analyzed in the laboratory for moisture content because delaying analysis may alter this property. All samples were air-dried in the shade, ground,

and passed through a 2 mm sieve for physicochemical analysis.

Compost samples were analyzed for pH and electrical conductivity (EC) using a digital pH and EC meter (FAI 2006). Organic matter content was determined by the loss-on-ignition method. The C:N ratio was determined using a CHNS elemental analyzer (Elementar, Vario-Micro model). A 10 mg portion of each dried and ground sample was placed in a tin capsule and combusted to the respective oxide forms, which were measured using a thermal conductivity detector (TCD) for C, N, H, and S (Komilis et al. 2012). For metal analysis, 1 g of the sample was dry-ashed in a muffle furnace at 550°C for 5 h, cooled, and the residue was dissolved in 5 mL of 20% HCl, filtered, and diluted to 50 mL in a volumetric flask with deionized water. Metal content was quantified using inductively coupled plasma optical emission spectrometry (ICP-OES; Thermo Fisher Scientific iCAP 7000).

Whole-plant samples, together with the associated soil samples, were collected from compost-amended and non-amended plots (control), labeled, and taken to the laboratory for analysis. Five soil subsamples from a rectangular grid with a surface area of 0.5 m² were collected to a depth of 5–20 cm, corresponding approximately to plant-root depth, to yield a representative soil sample. Representative whole-plant samples were obtained by randomly selecting individuals within each sampled field, ensuring spatial coverage and avoiding border rows or atypical plants. For ragi and hyacinth bean, 10–15 plants were collected; for maize, 10–20 plants; and for Napier grass, 5–10 clumps. All plants from each plot were pooled to form a single composite sample, which was subsampled into three portions and treated as technical triplicates during analysis. Samples were cleaned, sealed, labeled, and transported to the laboratory for analysis. Subsamples of soil and plant parts were analyzed for moisture content immediately in the laboratory using the gravimetric method.

Plant samples were separated into roots, leaves, and fruits (when present at the time of sampling) and further subsampled for analysis. Root samples were thoroughly washed under running tap water to remove adhering soil particles. All samples were then gently rinsed with deionized water, air-dried at room temperature, ground to a powder, and analyzed for total concentrations of major and micronutrients using the standard procedure. Heavy metals were analyzed using ICP-OES as described for compost samples.

The soil samples were air-dried at room temperature, finely ground, sieved through a 2.0 mm mesh, and stored in suitable, properly coded and labeled bottles. Soil pH, EC, and total dissolved solids (TDS) were measured in

1:2.5 soil:water extracts using a pH and conductivity meter (Jackson 1962). Organic matter (OM) content was determined by the Walkley and Black wet-oxidation method (Jackson 1962). The C:N ratio was determined using a CHNS analyzer (Marathe & Chavan 2022). Soil micronutrient cations were extracted with DTPA and quantified as Zn, Cu, Pb, Cd, Cr, and Ni by ICP-OES.

2.2. Quality Assurance and Quality Control (QA/QC)

QA/QC procedures were employed throughout the study to ensure analytical accuracy, precision, and reproducibility. The ICP-OES was calibrated with certified standards before each batch of measurements, and multielement calibration standards were used to cover all analytes simultaneously. Analytical accuracy was validated using certified reference materials (CRMs) and spiked samples, with recoveries maintained within 90–120%. Precision was assessed through duplicate analyses, with relative standard deviations (RSDs) generally <5%. Procedural blanks were included to monitor contamination, and limits of detection (LOD) and quantification (LOQ) were established for each element. Values reported as nondetect (ND) were treated as below the detection limit and substituted with half of the respective LOD (LOD/2) for calculations of the bioconcentration factor (BCF) and translocation factor (TF), to ensure that measured values were reproducible and comparable across sample types.

2.3. Bioconcentration Factor (BCF) and Translocation Factor (TF)

The BCF and TF are key indices in studies of heavy metal uptake and internal mobility within plants (Bose & Bhattacharyya 2008, Marchiol et al. 2004). The BCF (Eq. (1)) expresses the proportion of heavy metal concentration in individual plant parts (root, leaf, and fruit) relative to that in the soil reservoir. TF (Eq. (2)) is determined by comparing the heavy metal concentration in the aerial parts of the plant to that in the roots (Buscaroli 2017).

2.4. Statistical Analysis

As only one composite sample per crop type was collected from each farmer's field, statistical comparisons were confined to replicate measurements within composites rather than biological replication across plots. Spatial variability across sites was not assessed, and the results represent site-level composites. Consequently, the findings are interpreted as indicative of heavy-metal dynamics under compost-amended versus conventional practices rather than as replicated field trials.

To assess statistical significance and compare means between conventional and compost-amended groups,

parametric analyses were performed after normality checks (Shapiro–Wilk test) and variance comparisons (F-test). For soil baseline characteristics, results are reported as means, standard deviations (SD), and p-values. For soil metal concentrations, Welch's t-test was applied, and results are presented as means $\pm$ SD together with 95% confidence intervals (CI), effect sizes (Cohen's d), and false discovery rate (FDR)-adjusted p-values to account for multiple comparisons. Statistical significance was set at $p < 0.05$. For plant metal concentrations, results are reported as means $\pm$ SD derived from technical replicates of composite samples. Values below detection limits were treated as ND and handled consistently. For calculations of BCF and TF, ND values were substituted with LOD/2 to enable computation of indices. All analyses were performed using R version 4.4.3, with supplementary data handling in Microsoft Excel 2019.

3. RESULTS AND DISCUSSION

3.1. Heavy metal Dynamics in Plants and MSW Compost-Amended Soil

To evaluate the influence of municipal solid waste (MSW) compost on soil–plant interactions, this section presents the physicochemical properties of soil and compost, the resulting changes in heavy metal concentrations in control and amended soils, and the subsequent uptake, bioconcentration, and translocation of metals in plants.

3.1.1. Physicochemical Properties of Soil and MSW Compost

The MSW compost exhibited pH values ranging from 5.2 to 7.6, compared with the stated FCO-recommended range of 6.5–7.5. Electrical conductivity (EC) varied between 1.4 and 2.5 dS m⁻¹, remaining below the permissible limit of 4 dS m⁻¹. Moisture content ranged from 14 to 49%, with most samples aligning with the FCO guideline of 15–25%. Organic matter content was high (51–69%), exceeding the minimum requirement of 28%. The C:N ratio ranged between 8.3 and 14.8, well below the FCO threshold of <20, indicating rapid decomposition and nutrient mineralization potential (FAI 2006).

Soil parameters under control and amended conditions varied significantly across Napier grass, ragi, maize, and hyacinth bean crops, with pH, EC, moisture, organic matter, and C:N ratios showing crop-specific responses (Table 1). MSW compost-amended soil generally showed lower soil EC and altered pH, while effects on moisture, organic matter, and C:N differed by crop. EC increased in Napier grass soil but decreased sharply in ragi, maize, and hyacinth bean soils. Moisture was lower in Napier grass soil but higher in ragi, maize, and hyacinth bean soils. Amendments generally

enhanced moisture retention except in Napier grass soil. Organic matter was higher in Napier grass soil but lower in ragi, maize, and hyacinth bean soils. The C:N ratio remained similar in Napier grass soil, was lower in ragi and maize soils, and was higher in hyacinth bean soil than in the corresponding control soils.

3.1.2. Heavy metals in Compost, Control, and MSW Compost-Amended Soils

Heavy metal concentrations were quantified in compost, control soil, and compost-amended soils to determine enrichment levels and changes in metal availability following amendment. The metal concentrations in the MSW compost (Table 2, Fig. 3) followed the order: Zn > Cu > Cr > Pb > Cd > Ni. All measured metals were below the maximum permissible limits set by the FCO (FAI 2006), thereby meeting regulatory quality standards. Although minor variability was observed among samples, none of the metals approached critical thresholds, reflecting effective waste segregation and composting practices. Compliance with FCO limits confirms the regulatory safety of MSW compost for agricultural use; however, regulatory thresholds alone do not fully capture environmental risk. The ecological relevance of compost quality is better understood when linked to metal bioavailability and plant uptake, as indicated by BCF and TF values.

Bioavailable metal concentrations in conventional-practice (control) and MSW compost-amended soils are given in Table 3. Statistical comparisons were performed using Welch's t-test after normality and variance checks. Results are reported as mean $\pm$ SD, together with 95% confidence intervals (CI), FDR-adjusted p-values, and effect sizes (Cohen's d) to account for multiple comparisons and quantify the magnitude of differences. Results revealed that MSW compost amendment significantly altered heavy-metal concentrations across soils cultivated with Napier grass, ragi, maize, and hyacinth bean.

Bioavailable Zn levels were consistently and markedly reduced in all soils ($p < 0.001$), while Cu concentrations declined in Napier grass, ragi, and hyacinth bean soils but increased slightly in maize soil. Ni was significantly reduced in ragi, maize, and hyacinth bean soils ($p < 0.05$), with no difference observed in Napier grass soil. Pb concentrations decreased in Napier grass, ragi, and maize soils ($p < 0.01$), but changes in hyacinth bean soil were not significant. Cd responses were variable: Napier grass soil exhibited a significant increase ($p = 0.001$), hyacinth bean soil a significant decrease ($p = 0.01$), and ragi and maize soils showed no significant differences. Cr concentrations were significantly lower in Napier grass and ragi soils ($p < 0.05$) but remained unchanged in maize and hyacinth bean soils.

Overall, MSW compost amendment generally lowered Zn, Cu, Ni, Pb, and Cr concentrations, although element-specific and crop-specific variations were evident, particularly for Cd and Cu.

Compost amendments significantly reduced heavy-metal concentrations in soils under Napier grass, ragi, maize, and hyacinth bean compared with conventional controls, with Zn, Cu, Ni, Pb, and Cr showing consistent declines across most crops ($p < 0.05$), while Cd effects varied. Effect sizes (Cohen's d) indicated large reductions for Zn and Cu in hyacinth bean, and FDR-adjusted q -values confirmed significance after multiple testing.

3.1.3. Heavy Metals in Plants: Bioconcentration and Translocation Factors

Heavy-metal concentrations in crop roots, leaves, and seeds (where applicable) showed distinct patterns between conventional controls and compost amendments across Napier grass, ragi, maize, and hyacinth bean, with roots generally accumulating higher levels than aerial parts. Compost amendments often increased root uptake of Zn, Cu, Ni, and Cd while reducing or stabilizing levels in edible leaves and seeds, indicating retention in roots or the rhizosphere (Table 4).

Roots of Napier grass, ragi, maize, and hyacinth bean had higher Zn under compost amendment. In contrast, leaves of Napier grass, ragi, and maize had lower Zn under compost amendment, while hyacinth bean leaves showed similar values and seeds showed comparable Zn. Cu followed similar trends: roots of all crops had higher Cu, and leaves generally had lower Cu under compost amendment, except hyacinth bean leaves. Hyacinth bean seeds showed slightly higher Cu under compost amendment. Ni was higher in Napier grass and maize roots under compost amendment, while ragi and hyacinth bean roots had lower values. Leaves of Napier grass and maize had lower Ni under compost amendment, while hyacinth bean leaves had slightly higher values and seeds had lower Ni. Roots of all four crops had higher Pb under compost amendment. Napier grass leaves showed ND under compost amendment (vs. 0.54 in the control), maize leaves had higher Pb, while ragi and hyacinth bean leaves showed similar values. Hyacinth bean seeds had higher Pb under compost amendment. Roots of all four crops had higher Cd, whereas amended leaves/seeds often showed ND or low Cd values. Cr showed variable patterns, with root concentrations increasing in Napier grass and maize, decreasing in ragi, and remaining similar in hyacinth bean, while leaf and seed concentrations were lower.

Metal uptake by plants was assessed using BCF and TF indices, which together illustrate the degree of root accumulation and mobility of metals toward aerial tissues

under compost-amended conditions. A BCF greater than 1 reflects effective metal uptake from soil, while a TF exceeding 1 denotes efficient translocation from roots to aerial tissues (Carbonell et al. 2011), underscoring potential implications for food-chain transfer and ecological risk.

Root accumulation (BCF_{root}) was higher under amended conditions for all metals in Napier grass, with notably greater values for Cr (79.03), followed by Cd, Zn, and Pb, indicating strong accumulation capacity (Table 5). Ni and Cu also showed higher BCF_{root} under amendment than under conventional practice. Leaf accumulation (BCF_{leaf}) was lower under amended conditions for most metals (Pb, Cd, Zn, and Ni), while Cu showed comparable levels and Cr recorded higher BCF_{leaf} under amended conditions. TF_{leaf} values were consistently lower under amended conditions for all metals. Conversely, Cu and Ni showed TF > 1 in control soils despite relatively low BCF values, reflecting active mobility at lower concentration levels. This pattern positions Napier grass as a root-dominant accumulator, particularly effective for phytostabilization of Cr and Zn, while minimizing food-chain transfer.

BCF and TF values for ragi indicate that roots strongly accumulated Ni and Cr (Ni BCF = 11.56; Cr BCF = 26.31 in control soils), yet TF values for Ni were extremely low (TF = 0.0002 in amended soils), confirming exclusion from aerial tissues (Table 6). Leaf accumulation showed mixed trends, with lower values for Zn and Cd, while Cu and Pb remained higher. Ni remained extremely low and comparable (0.001) under both treatments. TF values were lower under amended conditions for most metals; Ni values remained negligible. Pb displayed TF > 1 in control conditions (TF = 1.74), despite low root BCF, indicating higher mobility than uptake capacity. Overall, the treatment demonstrated selective root sequestration of Ni and Cr, with limited aerial transfer.

Maize roots showed higher BCF values for Zn, Ni, and Cr (Zn = 41.15; Ni = 20.25; Cr = 107.64 in amended soils), while TF values remained low (Zn = 0.07; Cr = 0.06), confirming root sequestration. Notably, Pb and Cd exhibited TF > 1 (Pb = 2.74 in amended soils; Cd = 1.97 in control soils), indicating aerial mobility despite moderate root uptake. This dual behavior suggests that maize is effective for root stabilization of Zn and Cr, but Pb and Cd mobility may pose risks to edible tissues (Table 7).

Hyacinth bean showed higher root and leaf BCF values for most metals, except Cr, which was lower under amendments (Table 8). Seed accumulation showed higher values under amended conditions for Zn, Cu, and Pb, while Ni, Cd, and Cr were lower under amendment. TF_{leaf} was lower under amended conditions for Zn, Pb, and Cr, remained

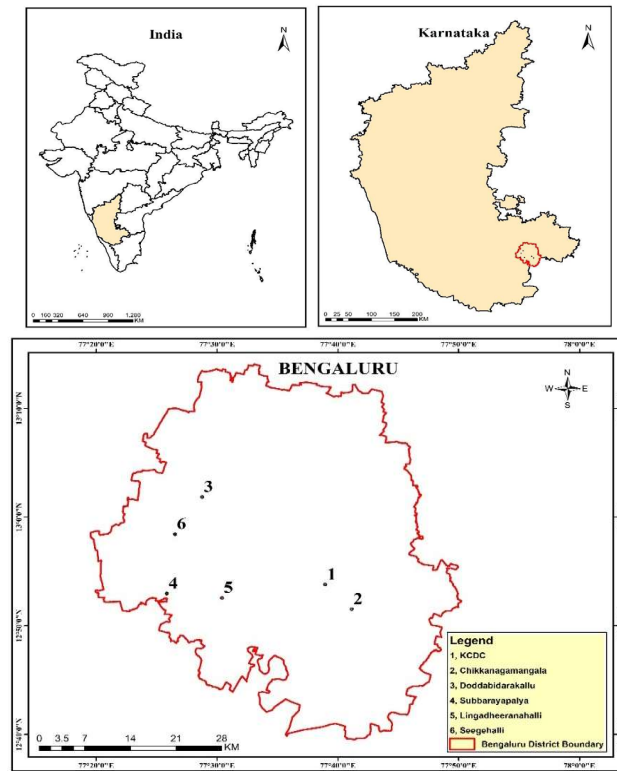


Fig. 1: Compost sampling locations in Bengaluru.

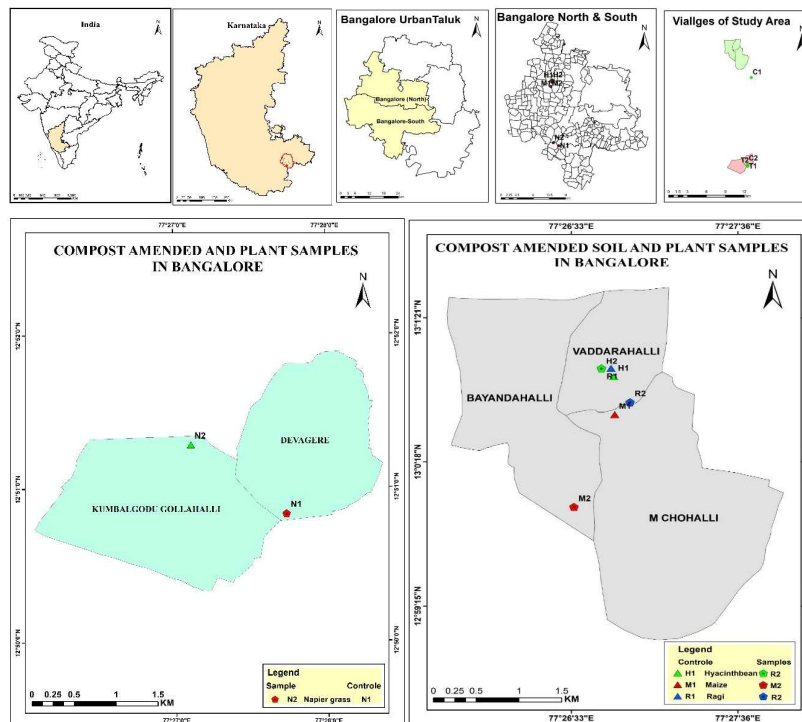


Fig. 2: Compost-amended and non-amended sites in Bengaluru.

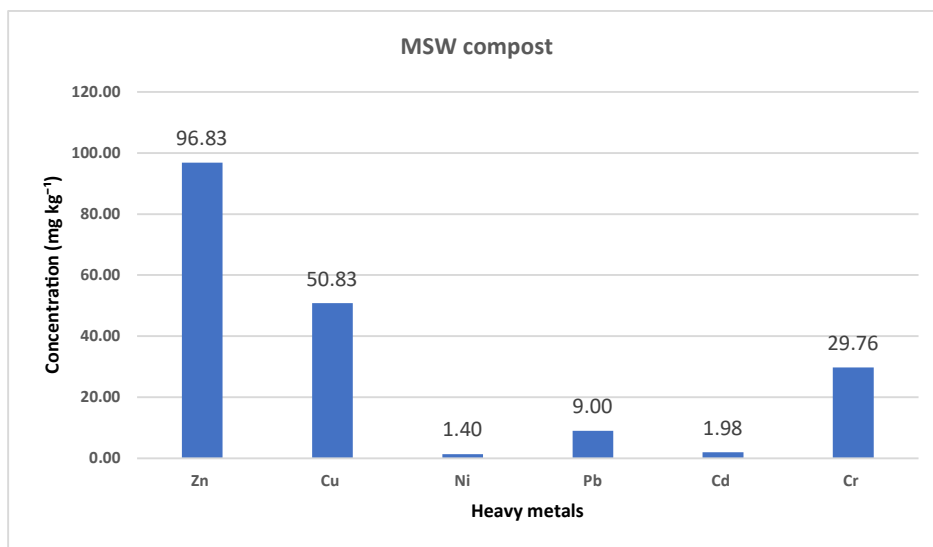


Fig. 3: Heavy-metal concentrations in MSW compost.

Table 1: Physicochemical properties of control and compost-amended soils.

Crop	Soil parameters	Control (Mean ± SD)	Amended (Mean ± SD)	<i>p-value</i>
Napier grass	pH	8.30±0.14	7.84±0.12	0.01245
	EC (µS/cm)	391.92±9.01	474.3±9.96	4.67E-04
	Moisture	11.90±0.19	11.00±0.16	3.34E-03
	Organic matter	2.40±0.08	2.90±0.08	1.62E-03
	C:N	8.89±0.16	8.81±0.15	0.5795
Ragi	pH	7.88±0.13	7.80±0.12	4.68E-01
	EC	374.9±9.33	250.0±8.10	7.18E-05
	Moisture	7.40±0.12	8.91±0.14	0.0001713
	Organic matter	2.00±0.06	1.52±0.03	1.27E-03
	C:N	7.84±0.13	7.62±0.11	9.14E-02
Maize	pH	8.04±0.13	7.86±0.11	0.1434
	EC	364.3±9.40	209.0±8.69	3.19E-05
	Moisture	8.80±0.14	9.80±0.17	0.001585
	Organic matter	3.20±0.09	1.70±0.06	7.22E-05
	C:N	10.45±0.18	7.63±0.11	8.79E-05
Hyacinth bean	pH	6.94±0.11	7.97±0.11	3.48E-04
	EC	500.7±12.46	303.1±10.1	3.98E-05
	Moisture	6.80±0.12	7.10±0.12	0.03352
	Organic matter	2.50±0.06	1.70±0.06	7.44E-05
	C:N	7.28±0.13	9.14±0.17	0.0002065

Sample size (n) = 3; SD = standard deviation.

similar for Cu, and was higher under amendment for Ni and Cd. Seed TF values were >1 for Zn, Cu, Ni, and Cd in control soils, confirming systemic transport into edible parts. This aligns with elevated seed BCF values (Zn =

18.05; Cu = 10.58), raising potential food-safety concerns. Unlike Napier grass and maize, which predominantly restrict metals to roots, hyacinth bean facilitates greater systemic distribution.

Across species, soil amendments generally increased BCF values, reflecting enhanced metal bioavailability. In contrast, TF values tended to decline under amendment, pointing to a physiological restriction of translocation that may serve as a protective mechanism. Pb in maize was an exception, where TF increased, highlighting species-specific variability in responses to contamination stress.

3.2. Bioconcentration and Translocation Equations

$$BCF = \frac{C_p \text{ (root,shoot,leaves,grains)}}{C_{soil}} \quad \dots(1)$$

$$TF = \frac{C_p \text{ (shoot,leaves,seeds)}}{C_{root}} \quad \dots(2)$$

Where Croot, Cleaf, Cseed, and Csoil represent metal concentrations (mg kg⁻¹, dry weight basis) in roots, leaves,

Table 2: Heavy-metal concentrations in MSW compost.

Heavy metal (mg kg ⁻¹)	Min	Max	Mean ± SD	Quality control*
Zn	41.9	183.3	96.83 ± 55.73	≤ 1000
Cu	17.7	111.5	50.83 ± 34.61	≤ 300
Ni	0.5	8.6	1.4 ± 4.45	≤ 50
Pb	2.88	23.01	9 ± 7.5	≤ 100
Cd	0.67	3.91	1.98 ± 1.33	≤ 5
Cr	19.5	41.23	29.76 ± 7.9	≤ 50

*Fertilizer (Control) Order, 1985; SD = standard deviation.

Table 3: Metal concentrations (mg kg⁻¹ dry weight) in control and MSW compost-amended soils.

Crop	Heavy metal	Control (Mean ± SD)	Amended (Mean ± SD)	<i>p</i> -value	95% confidence intervals	FDR (<i>q</i>)	Effect size (<i>d</i>)
Napier grass	Zn	6.76±0.19	3.48±0.12	5.59E-05	2.9–3.7	0.000335	-20.55
	Cu	4.21±0.02	3.92±0.03	0.0003527	0.2–0.4	0.001058	-11.77
	Ni	1.32±0.16	1.31±0.20	0.9513	-0.4–0.5	0.9513	-0.06
	Pb	0.86±0.07	0.45±0.15	0.02788	0.1–0.7	0.04182	-3.58
	Cd	0.041±0.01	0.091±0.02	0.03579	-0.1–0.01	0.04295	3.13
	Cr	0.20±0.009	0.039±0.001	0.00103	0.1–0.2	0.00206	-24.41
Ragi	Zn	4.04±0.17	2.35±0.03	0.0027820	1.3–2.1	0.014421	-13.54
	Cu	1.31±0.16	0.78±0.02	0.02752	0.1–0.9	0.04128	-4.64
	Ni	0.45±0.02	0.35±0.03	0.01477	0.03–0.2	0.02954	-3.87
	Pb	0.99±0.02	0.81±0.08	0.04566	0.01–0.3	0.05479	-3.22
	Cd	0.016±0.01	0.02±0.003	0.4446	-0.02–0.01	0.4446	0.79
	Cr	0.22±0.02	0.14±0.02	0.004807	0.04–0.1	0.014421	-4.61
Maize	Zn	3.55±0.16	1.99±0.10	0.001521	1.1–1.8	0.009126	-12.86
	Cu	1.21±0.15	1.53±0.05	0.04864	-0.6–0.004	0.07296	2.93
	Ni	0.40±0.03	0.28±0.05	0.04045	0.01–0.2	0.07296	-2.69
	Pb	0.87±0.05	0.59±0.07	0.004925	0.1–0.4	0.014775	-4.70
	Cd	0.014±0.002	0.02±0.006	0.8057	-0.01–0.01	0.8057	0.23
	Cr	0.17±0.02	0.14±0.06	0.3948	-0.1–0.2	0.47376	-0.86
Hyacinth bean	Zn	10.52±0.03	1.50±0.05	4.96E-09	8.9–9.1	2.98E-08	-226.67
	Cu	9.94±0.06	0.72±0.02	5.50E-07	9.1–9.3	1.65E-06	-216.75
	Ni	0.74±0.03	0.34±0.05	0.0004977	0.3–0.5	0.000995	-9.65
	Pb	0.84±0.06	0.77±0.05	0.1704	-0.05–0.2	0.20448	-1.36
	Cd	0.050±0.01	0.011±0.01	0.01251	0.02–0.1	0.018765	-4.54
	Cr	0.12±0.02	0.14±0.03	0.3526	-0.1–0.04	0.3526	0.86

Sample size (*n*) = 3; SD = standard deviation; FDR = false discovery rate

Table 4: Heavy-metal concentrations (mg kg⁻¹ dry weight) in plant parts of Napier grass, ragi, maize, and hyacinth bean.

Crop	Plant part	Heavy metal	Zn	Cu	Ni	Pb	Cd	Cr
Napier grass	Root	Control	87.97±2.12	2.07±0.07	1.73±0.06	1.49±0.04	0.10±0.005	2.81±0.08
		Amended	95.8±2.45	4.30±0.09	4.06±0.08	2.01±0.06	1.33±0.04	3.08±0.05
	Leaves	Control	15.96±0.43	2.40±0.05	2.41±0.05	0.54±0.04	1.05±0.02	1.12±0.03
		Amended	3.75±0.08	2.07±0.06	1.40±0.05	ND	ND	0.57±0.005
Ragi	Root	Control	24.12±0.54	3.81±0.10	5.20±0.14	0.27±0.005	0.03±0.001	5.68±0.16
		Amended	32.0±0.91	6.37±0.18	3.04±0.11	0.58±0.04	0.11±0.01	3.26±0.12
	Leaves	Control	17.0±0.51	2.15±0.06	ND	0.46±0.03	0.01±0.002	0.79±0.007
		Amended	9.67±0.25	1.49±0.05	ND	0.50±0.004	ND	0.68±0.005
Maize	Root	Control	45.13±0.84	2.90±0.09	3.10±0.14	0.43±0.03	0.03±0.002	6.68±0.19
		Amended	81.88±1.05	5.30±0.16	5.67±0.17	0.44±0.04	0.11±0.006	14.75±0.34
	Leaves	Control	8.36±0.19	3.73±0.15	1.14±0.05	0.48±0.03	0.07±0.003	1.01±0.04
		Amended	5.99±0.18	1.41±0.05	0.99±0.03	1.20±0.04	0.06±0.002	0.87±0.08
Hyacinth bean	Root	Control	24.47±0.42	6.87±0.18	3.36±0.13	0.67±0.07	0.08±0.002	4.04±0.14
		Amended	27.62±0.49	8.11±0.21	1.85±0.05	1.38±0.04	0.09±0.003	4.15±0.15
	Leaves	Control	23.52±0.37	5.71±0.14	2.35±0.08	0.97±0.08	ND	1.81±0.06
		Amended	22.81±0.31	6.71±0.15	2.70±0.09	0.93±0.07	0.03±0.001	1.12±0.04
	Seeds	Control	27.23±0.52	7.28±0.18	3.57±0.14	0.36±0.007	0.16±0.005	0.73±0.06
		Amended	27.07±0.49	7.62±0.19	0.93±0.09	0.75±0.02	ND	0.54±0.03

ND = below detection limit; n = 3.

Table 5: Bioconcentration factor (BCF) and translocation factor (TF) of Napier grass.

Heavy metal	BCF _{root}		BCF _{leaf}		TF _{leaf}	
	Control	Amended	Control	Amended	Control	Amended
Zn	13.01	27.37	2.36	1.07	0.18	0.04
Cu	0.49	1.10	0.57	0.53	1.16	0.48
Ni	1.31	3.10	1.83	1.07	1.39	0.34
Pb	1.73	4.48	0.63	0.001	0.36	0.0002
Cd	2.34	14.66	1.27	0.005	0.54	0.0004
Cr	14.35	79.03	5.73	14.62	0.40	0.18

Table 6: Bioconcentration factor (BCF) and translocation factor (TF) of ragi.

Heavy metal	BCF _{root}		BCF _{leaf}		TF _{leaf}	
	Control	Amended	Control	Amended	Control	Amended
Zn	5.97	13.62	4.21	4.11	0.70	0.30
Cu	2.91	8.17	1.64	1.91	0.57	0.23
Ni	11.56	8.68	0.001	0.001	0.0001	0.0002
Pb	0.27	0.72	0.47	0.62	1.74	0.87
Cd	1.69	5.30	0.56	0.03	0.33	0.005
Cr	26.31	23.80	3.66	4.97	0.14	0.21

seeds, and soil, respectively.

3.3. Discussion

Application of municipal solid waste (MSW) compost in agriculture has gained traction as a sustainable resource-

recovery strategy; however, concerns remain about heavy-metal accumulation in soils and the potential transfer of contaminants into the food chain (Hargreaves et al. 2008, Yuksel 2015). These concerns necessitate field-based evaluations, such as the present study, that reflect

Table 7: Bioconcentration factor (BCF) and translocation factor (TF) of maize.

Heavy metal	BCF _{root}		BCF _{leaf}		TF _{leaf}	
	Control	Amended	Control	Amended	Control	Amended
Zn	12.71	41.15	2.35	3.01	0.19	0.07
Cu	2.39	3.46	3.08	0.92	1.29	0.27
Ni	7.76	20.25	2.86	3.55	0.37	0.18
Pb	0.50	0.75	0.56	2.05	1.12	2.74
Cd	2.43	7.00	4.79	3.67	1.97	0.52
Cr	38.63	107.6	5.83	6.32	0.15	0.06

Table 8: Bioconcentration factor (BCF) and translocation factor (TF) of hyacinth bean.

Heavy metal	BCF _{root}		BCF _{leaf}		BC _{Seed}		TF _{leaf}		TF _{Seed}	
	C	A	C	A	C	A	C	A	C	A
Zn	2.33	18.41	2.24	15.21	2.59	18.05	0.96	0.83	1.11	0.98
Cu	0.69	11.27	0.57	9.31	0.73	10.58	0.83	0.83	1.06	0.94
Ni	4.53	5.45	3.17	7.92	4.83	2.73	0.70	1.45	1.06	0.50
Pb	0.79	1.80	1.14	1.21	0.43	0.97	1.44	0.67	0.54	0.54
Cd	1.54	8.27	0.01	2.82	3.14	0.05	0.006	0.34	2.04	0.005
Cr	33.9	29.02	15.24	7.80	6.15	3.74	0.45	0.27	0.18	0.13

C = Control; A = MSW compost-amended soil

realistic agronomic conditions rather than short-term pot or laboratory experiments. In this in situ study, a single application of FCO-compliant MSW compost did not elevate soil heavy-metal concentrations. On the contrary, compost-amended soils exhibited statistically significant reductions in Zn, Cu, Pb, and Cr compared with conventional controls, particularly in hyacinth bean, Napier grass, and ragi systems. These reductions, supported by strong effect sizes and narrow confidence intervals, suggest that the amendment may influence metal redistribution between soil and plant compartments, potentially through enhanced plant uptake, immobilization, or transformation processes in the rhizosphere (Seshadri et al. 2015). However, the magnitude of reduction varies across crops, indicating that root architecture, exudation patterns, and rhizosphere interactions differ among species, thereby influencing metal availability and retention (Podar & Maathuis 2022).

Nonetheless, prior evidence indicates that higher or repeated compost applications can increase the availability of Cu, Zn, Pb, and Ni in soils, underscoring the need to limit excessive amendments to avoid contamination risks (Yuksel 2015, Jordão et al. 2006). Furthermore, crop-specific responses identified through Welch's t-test highlight the importance of soil–plant interactions in shaping metal dynamics after compost addition. This reinforces the need to evaluate compost safety across diverse cropping systems rather than relying solely on soil metrics (Xu et al. 2022, Abd-Elhalim et al. 2025). Cadmium exhibited a more

variable response across cropping systems, with higher concentrations in amended soils for Napier grass but no significant differences in ragi and maize. This variability indicates higher mobility and sensitivity of Cd to local soil and crop conditions, as also reflected in its inconsistent uptake and translocation patterns in plant tissues. Similarly, Ni and Cr showed crop-dependent differences, with significant reductions in some systems (ragi and hyacinth bean) but not in others (e.g., maize), further emphasizing the role of plant–soil interactions in controlling metal behavior.

The observed differences in soil metal concentrations can be partially explained by the measured soil properties. Variations in pH, EC, moisture, organic matter, and C:N ratio across cropping systems indicate that each crop creates a distinct soil environment under amendment. For instance, lower EC in amended soils for ragi, maize, and hyacinth bean suggests reduced soluble metal fractions, which may contribute to lower measured concentrations. Differences in moisture and pH further influence metal solubility and speciation, thereby affecting their persistence in soil (Bravo et al. 2017). Interestingly, despite lower organic matter in amended soils for some cropping systems (ragi, maize, and hyacinth bean), reductions in metal concentrations were still observed. This suggests that metal dynamics are governed by multiple interacting factors rather than organic matter alone, including rhizosphere-mediated processes such as root uptake, microbial activity, and localized chemical transformations. Such findings are consistent with studies

showing that plant species can significantly influence metal availability through root-induced changes in soil chemistry, as reported by Houben & Sonnet (2015) and Seshadri et al. (2015).

BCF and TF values provide complementary insights into heavy-metal uptake and internal distribution in the studied plant species, revealing species-specific strategies of sequestration and mobility and their implications for phytoremediation and food safety. Relatively higher BCF values in roots, coupled with consistently low TF values (<1) for most metals, indicate dominant root retention and restricted movement to aboveground tissues, as reported by Bose & Bhattacharyya (2008). Such uptake is characteristic of phytostabilization rather than phytoextraction (Li et al. 2021), suggesting that the applied MSW compost did not enhance metal mobility within the soil-plant continuum. Root-level immobilization is attributed to metal binding to cell-wall components, vacuolar sequestration, and precipitation with compost-derived organic ligands, mechanisms that are particularly effective for nonessential and potentially toxic metals such as Pb, Cd, and Cr (Hall 2002, Bolan et al. 2014). Part of the reduction in soil metal concentration may be associated with enhanced uptake and retention in plant roots rather than solely with immobilization within the soil matrix.

A crop-specific comparison further clarified species-specific uptake behavior. Napier grass exhibited higher root metal accumulation but minimal shoot transfer, highlighting its strong stabilization capacity. Ragi and maize showed regulated uptake of essential micronutrients (Zn and Cu) with controlled translocation, probably because of effective homeostasis and limited transfer to edible portions. Although MSW compost application generally reduced soil metal bioavailability, maize exhibited $TF > 1$ for Pb, and hyacinth bean seeds showed elevated accumulation of Zn, Cu, Ni, and Pb, indicating potential metal transfer to edible parts. While most metal concentrations in edible parts were within the cited permissible limits, Pb (0.75 mg kg^{-1}) in hyacinth bean was reported to exceed the limit of 0.1 mg kg^{-1} (Codex Alimentarius Commission 1995; Altarawneh 2021). This suggests that the safety of MSW compost-amended soils is crop-specific. Crops such as hyacinth bean, which showed higher translocation to edible tissues, may pose food-chain risks, and their cultivation in such soils requires caution.

From both regulatory and agronomic viewpoints, combining soil statistical analysis with BCF and TF indices provides field-level evidence relevant to the heavy-metal limits set under the FCO (FAI 2006). Unlike controlled pot studies that might overestimate metal availability, the present field evidence shows that applying MSW compost

can alter soil properties and bioavailable metal fractions; however, metal uptake and translocation vary depending on the crop, as some crops may accumulate metals in edible parts, requiring careful crop selection and monitoring to ensure safe agricultural practices. These findings support the sustainable use of MSW compost in farming, emphasizing the importance of regulatory compliance, appropriate crop choice, and ongoing monitoring for long-term or repeated applications.

A limitation of this study is that plant samples were pooled at the plot level to form composite samples, and technical replicates (three subsamples) were derived from each composite. As only one plot per crop type was sampled from different farmers' fields, biological replication within sites was not possible, and spatial variability across sites could not be statistically partitioned. Consequently, the results represent site-level composites rather than replicated field trials. While this approach provides useful insights into nutrient and contaminant dynamics under compost-amended versus conventional practices, future studies should incorporate replicated plots across multiple sites to enable more robust statistical treatment of spatial heterogeneity.

4. CONCLUSIONS

MSW compost used in this study met FCO heavy-metal limits, with statistical analysis showing crop-specific changes in soil metal concentrations following amendment. Significant reductions in certain metals, such as Zn, Pb, and Cr, suggest potential immobilization effects; however, these responses were not consistent across all metals and cropping systems. BCF and TF analyses further indicated that while several crops exhibited restricted movement of metals to aerial tissues, instances of elevated translocation ($TF > 1$) and accumulation in edible parts highlight the possibility of food-chain transfer under amended conditions.

Overall, the findings demonstrate that the behavior of heavy metals in MSW compost-amended soils is strongly crop-dependent. While compost application may reduce the bioavailability of certain metals, it does not universally prevent their uptake and translocation. Therefore, the use of MSW compost can be considered conditionally safe, provided that crop selection, site characteristics, and potential accumulation in edible tissues are carefully monitored. These results highlight the need for crop-specific risk assessment to ensure the safe and sustainable use of MSW compost in agricultural systems.

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