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Original Research Paper

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 Fertilizers 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 factors indicated elevated translocation (TF > 1) and accumulation in edible parts were observed, 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.

INTRODUCTION

Rising populations, rapid urbanization, and industrialization have intensified the 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 and 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 (Rodr 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 and Vasylkivskyi 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 (Bharti and Sharma 2021). 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. Bio-concentration 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 and 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 the latitudinal parallels of 12° 39' N and 13° 18' N and the longitudinal meridians of 77° 22' E and 77° 52' E, covering an area of 2196 sq. km with an average elevation of about 900 meters. This city, with a population of 1.3 million, generates around 5,000-6,000 TPD of MSW, including bulk generation, with a per capita generation of 400 g/day (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 refer to agricultural fields with a documented use of MSW compost application for at least one cropping season. No controlled plot experimentation was conducted; rather, it relied on existing farmer-managed systems to capture real-world agricultural conditions. In here, compost was reported to be applied once, approximately 20 -30 days before sowing, at 5 to 12 tonnes/acre. Adjacent conventional fields or comparable fields in the vicinity being managed using traditional fertilization practices, including chemical fertilizers, farmyard manure, with no history of compost application, were considered as controls. Both field types were maintained under a similar cropping system 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* (Pulses- Hyacinth Bean) were collected from Bengaluru Urban for the study. All these plant and soil samples were collected once from June 2023 to December 2023.

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

Composite samples of several grab samples from ten different points of the final compost (<4 mm size) heap were collected from each WPP in sterile polythene bags to inhibit any susceptible changes in moisture level and transported immediately under ice refrigeration to the lab for further analysis. A subsample of each was immediately analysed in the laboratory for moisture content, as delaying analysis alters its characteristic properties. All the 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). 10 mg of the dried and ground samples in tin capsules were combusted to their respective oxide forms, which were finally measured using a thermal conductivity detector (TCD) as 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 hours, 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; Thermofisher Scientific ICAP 7000).

Whole plant samples, together with the associated soil samples, were collected from compost-amended and non-amended plots (control), labelled, and taken to the laboratory for analysis. Five soil sub-samples from a rectangular grid with a surface area of 0.5 m^2 were dug to a depth of 5–20 cm, at the same depth as plant roots, 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, individually and subsampled into three portions, and considered as a triplicate during analysis. Samples were cleaned, sealed, labelled, and transported to the laboratory for analysis. Sub-samples of soil and plant parts were analysed for their 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 analyses. Root samples were thoroughly washed under running tap water to remove soil particles adhering to the roots. All samples were gently rewashed with deionized distilled water to remove soil particles adhering to the plants, air-dried at room temperature, ground into a powder, and analyzed for total concentrations of major and micronutrients using the Standard Procedure. Heavy metals were analysed using ICP-OES as described for compost samples.

The soil samples were air-dried at room temperature, finely ground, sieved using a 2.0 mm mesh, and stored in a suitable, properly coded, and labeled bottle. Soil pH, EC, and TDS were measured in 1:2.5 soil: water extracts using a pH and conductivity meter (Jackson 1962). OM content was determined by the Walkley and Black's wet oxidation method (Jackson 1962). The C: N ratio was determined using a CHNS analyzer (Marathe and Chavan 2022). Soil micronutrient cations were extracted with DTPA and quantified as Zn, Cu, Pb, Cd, Cr, and Ni by ICP-OES.

Quality Assurance and Quality Control (QA/QC)

QA/QC procedures were employed throughout the study to ensure analytical accuracy, precision, and reproducibility. The instrument (ICP-OES) was calibrated with certified standards before each batch of measurement, and multi-element 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 (RSD) generally <5%. Procedural blanks were included to monitor contamination, and limits of detection (LOD) and quantification (LOQ) were established for each element. Negative values besides Non-detect (ND) were treated as below detection limits and substituted with half of the respective LOD (LOD/2) for calculations of bioconcentration (BCF) and translocation factors (TF), to ensure that measured values were robust, reproducible, and comparable across sample types.

Bio-concentration (BCF) and Translocation Factors (TF)

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

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 results represent site-level composites. Consequently, the findings are interpreted as indicative of heavy metal dynamics under compost-amended versus conventional practices, rather than replicated field trials to avoid any confusion in interpretation.

To assess statistical significance and compare means between conventional and compost-amended groups, parametric analyses were performed after conducting normality checks (Shapiro–Wilk test) and variance comparisons (F-test). For soil baseline characteristics, results are reported as averages, standard deviations (SD), and p-values. For soil metal concentrations, Welch's t-test was applied, and results are presented as means ± 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 ± SD derived from technical replicates of composite samples.

Negative values (below detection limits or due to baseline correction) 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 without biasing results. This approach is consistent with standard environmental chemistry practices for handling censored data. All analyses were performed using R version 4.4.3, with supplementary data handling in Microsoft Excel 2019.

3. RESULTS

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. Physico-chemical properties of Soil and MSW compost

The MSW compost exhibited pH values ranging from 5.2 to 7.6, which fall broadly within the FCO recommended range of 6.5–7.5. Electrical conductivity (EC) varied between 1.4 and 2.5 dS/m, remaining below the permissible limit of 4 dS/m. 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.

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 indicated lower soil EC and altered pH, while effects on moisture, organic matter, and C: N differed by crop. Amendments showed a significantly lower pH in Napier grass and a higher pH in hyacinth bean, with no changes in ragi or maize. EC was higher in Napier grass, decreasing sharply in ragi, maize, and hyacinth bean. Moisture was lower in Napier grass but higher in ragi, maize, and hyacinth bean. Amendments typically enhanced moisture retention except for Napier biomass. However, organic matter was high in Napier grass but declined in ragi, maize, and hyacinth bean. Rapid turnover explains losses in fertile crop soils. The C: N remained the same in Napier grass, lower in ragi and maize, and higher in hyacinth bean compared to the control soil. Narrower ratios signal faster N release by most crops.

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 ± SD, together with 95% confidence intervals (CI), false discovery rate (FDR)-adjusted p-values, and effect sizes (Cohen's d) to account for multiple comparisons and to 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, Ragi, and Hyacinth bean soils but increased slightly in maize. 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, 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. Chromium concentrations were significantly less in Napier 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, though 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 to conventional control methods, 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 ($d > 200$), 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 control 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 for Zn, Cu, Ni, and Cd while reducing or stabilizing levels in edible leaves and seeds, indicating immobilization in rhizospheres (Table 4).

Roots of Napier, Ragi, Maize, and Hyacinth bean had higher Zn under compost amendment. In contrast, leaves of Napier, 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; the 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 and Maize roots under compost amendment, while Ragi and Hyacinth bean had lower values. Leaves of Napier and Maize had lower Ni under compost amendment, while Hyacinth bean leaves had slightly higher values, and seeds had lower Ni under compost amendment. Roots of Napier, Ragi, Maize, and Hyacinth bean had higher Pb under compost amendment. Leaves of Napier showed ND under compost amendment (vs. 0.54 in control), Maize leaves had higher Pb, Ragi, and Hyacinth bean leaves were similar. Hyacinth bean seeds had higher Pb under compost amendment. Roots of Napier, Ragi, Maize, and Hyacinth bean had higher Cd and often ND or low in amended leaves/seeds. Cr variable with root increases in Napier and Maize, low in Ragi, and similar in Hyacinth bean but leaves and seeds had lower Cr.

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 1denotes efficient translocation from roots to aerial tissues (Carbonell et al. 2011) underscoring potential implications for food-chain transfer and ecological risk.

Root accumulation (BCFroot) was higher under amended conditions for all metals, in Napier grass with notably greater values for Cr (79.03), followed by Cd, Zn, and lead, indicating strong accumulation capacity (Table 5). Ni and Cu also showed higher BCF_{root} under amendment compared to 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 for Ragi indicate that ragi roots accumulated Ni and Cr strongly (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, Pb, and Pb remained higher. Nickel 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, treatment demonstrates selective root sequestration of Ni and Cr, with limited aerial transfer, making it relatively safe for cultivation in contaminated soils.

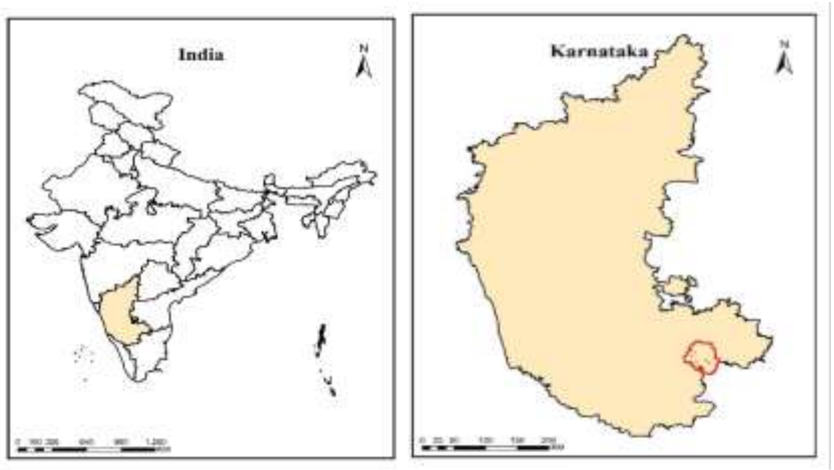
Maize roots showed higher BCF values for Zn, Ni, and Cr (Zn = 41.15; Ni = 20.25; Cr = 107.64 in amended soils), while TF values remained low (Zn = 0.07; Cr = 0.06), confirming root sequestration. Notably, Pb and Cd exhibited TF > 1 (Pb = 2.74 in amended soils; Cd = 1.97 in control soils), indicating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

Hyacinth bean showed higher root and leaf BCF for most of the metals, except for Cr, which was lower under amendments (Table 8). Fruit accumulation (BCF_{fruit}) 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 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 significant food safety concerns. Unlike Napier and maize, which restrict metals to roots, hyacinth bean facilitates systemic distribution, making it unsuitable for food crops in contaminated environments.

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. Figures, Tables, and Schemes



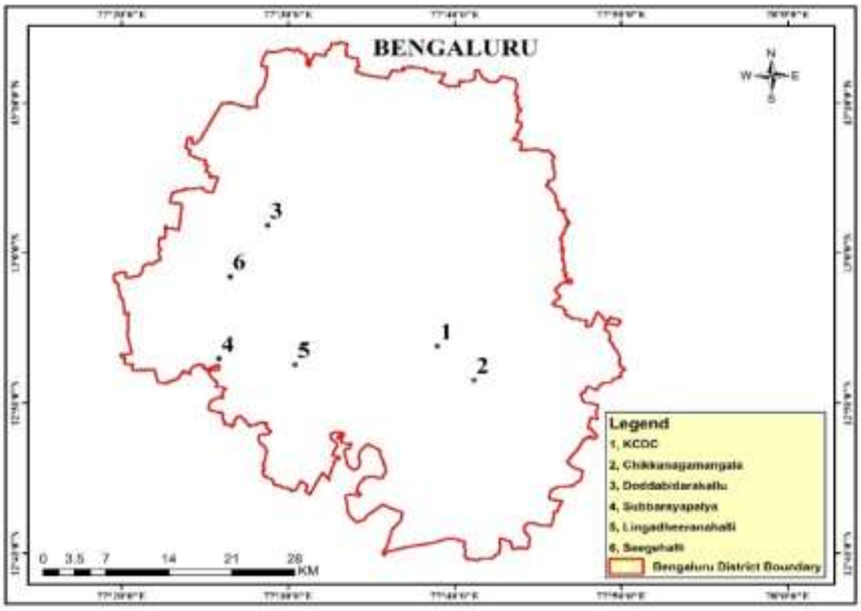


Fig. 1: Compost sampling locations in Bengaluru

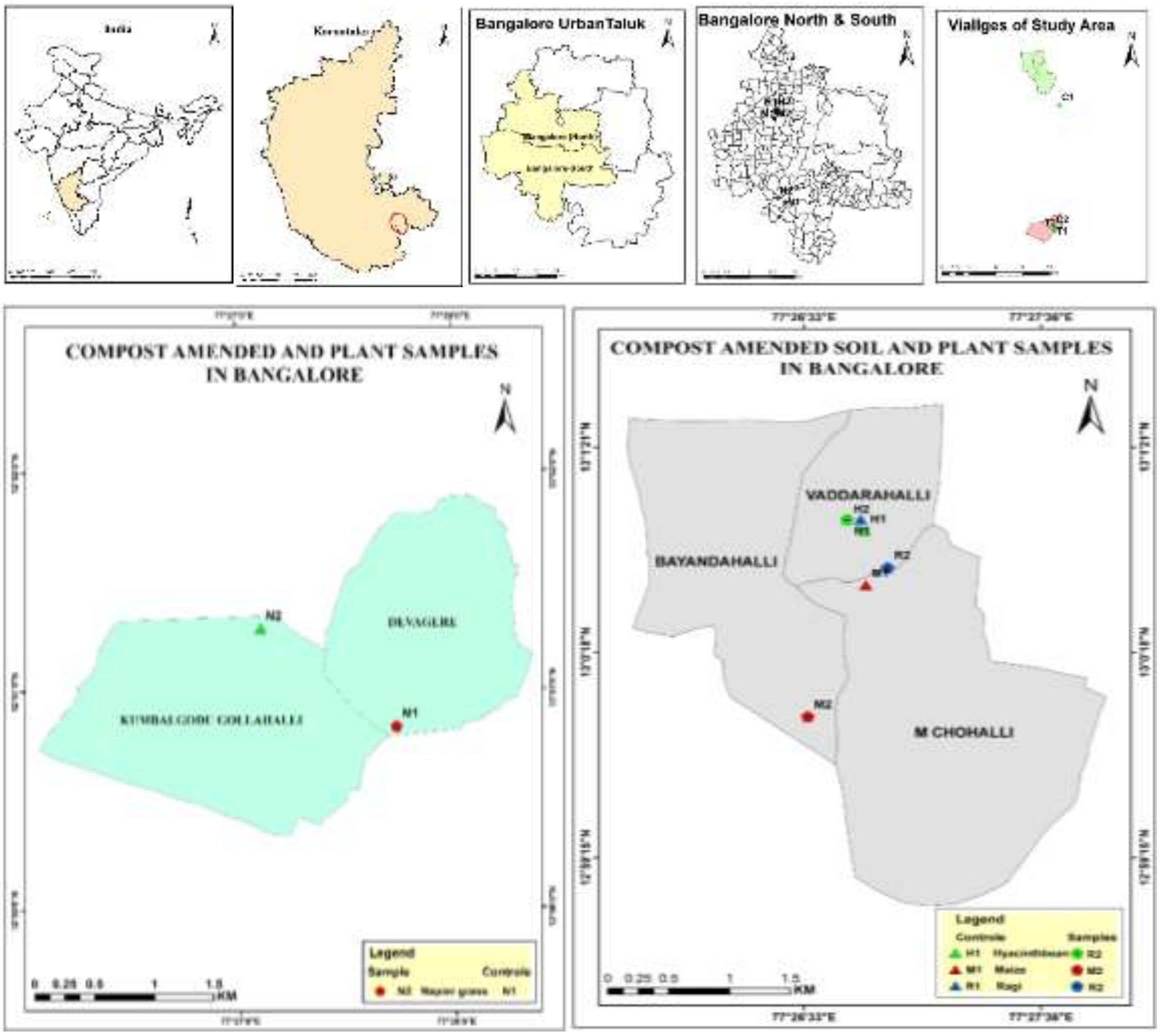


Fig. 2: Compost-amended and non-amended sites in Bengaluru

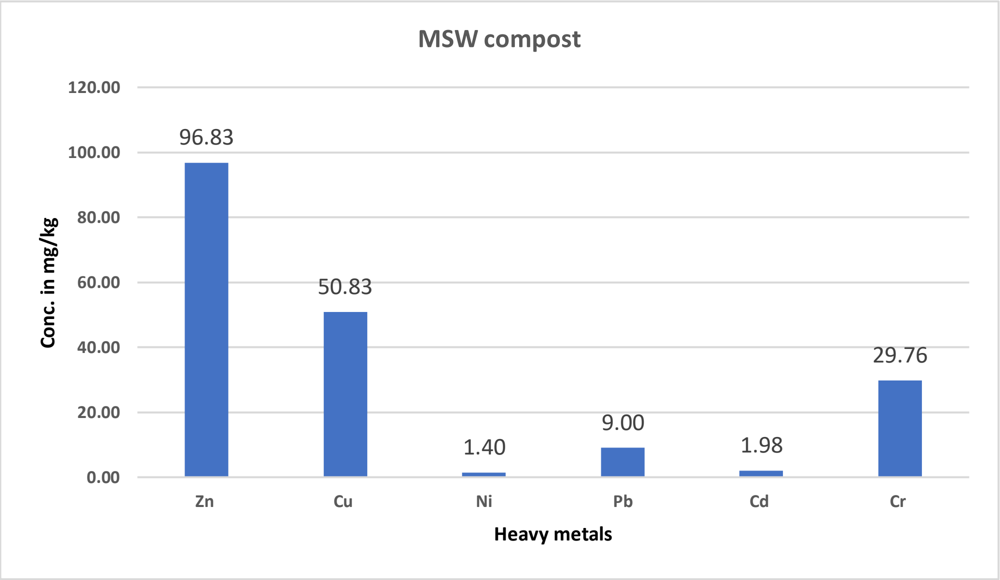


Figure 3: Heavy metal concentration of MSW Compost

Table 1: Physico-chemical properties of Control and Compost-amended Soils

Crop	**Soil parameters**	**Control (Mean ± SD)**	**Amended (Mean ± SD)**	***p* - value**
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
	Org.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
	Org.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
	Org.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
	Org.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

Table 2: Heavy metals in MSW compost

Heavy metal (mg/kg)	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

[*] Fertilizers (Control) Order, 1985; SD – Standard deviation

Table 3: Metal concentrations (mg kg^{-1} d.w.) in the control and the MSW compost-amended soils

Crop	Heavy metals	Control (Mean ± SD)	Amended (Mean ± SD)	p - value	95 % Confidence intervals	FDR (q)	Effect size (d)
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}) in leaves and roots of Napiergrass, Ragi, Maize, and Hyacinth bean

Crop	Plant part	Heavy metals	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
Ma	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	Contrl	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: Bio-concentration factor (BCF) and translocation factor (TF) of Napiergrass

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: Bio-concentration 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

Table 7: Bio-concentration 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: Bio-concentration factor (BCF) and translocation factor (TF) of Hyacinth bean

Heavy	**BCF_{root}**		**BCF_{leaf}**		**BCF_{fruit}**		**TF_{leaf}**		**TF_{fruit}**	
Metal	**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.

3.3. Formatting of Mathematical Components

$$\mathrm{BCF} = \frac{\mathrm{Cparts(root,shoot,leaves,grains)}}{\mathrm{Csoil}} \quad \ldots(1)$$

$$\mathrm{TF} = \frac{\mathrm{Cparts(shoot,leaves,fruit)}}{\mathrm{Croot}} \quad \ldots(2)$$

Where C_{root}, C_{leaf}, $C_{fruit,}$ and C_{soil} represent metal concentrations (mg kg^{-1}, dry weight basis) in roots, leaves, fruit, and soil, respectively.

4. DISCUSSION

Application of municipal solid waste (MSW) compost in agriculture has gained traction as a sustainable resource-recovery strategy; yet 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 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 to 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 and 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; 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 show crop-dependent differences, with significant reductions in some systems Ragi, 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, 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 opined 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, 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 above-ground tissues, as opined by Bose and 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 non-essential 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 due to immobilization within the soil matrix.

A crop-wise comparison further clarified species-specific uptake behavior. Napier grass exhibited higher root metal accumulation but minimal shoot transfer, highlighting its strong stabilization capacity and suitability for fodder cultivation under compost amendment. Ragi and Maize showed regulated uptake of essential micronutrients (Zn and Cu) with controlled translocation, probably because of effective homeostasis and limited risk to edible portions. Although MSW compost application generally reduced soil metal bioavailability, Maize exhibited a 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 safe limits when compared with FAO/WHO permissible limits, Pb (0.75 mg/kg) and Ni (0.54 mg/kg) in hyacinth bean exceeded recommended limits of 0.1 and 0.3 mg/kg, respectively (WHO 1983; Altarawneh 2021), indicating potential dietary risks. 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–TF indices offers strong field-level verification of the heavy-metal limits set under the FCO (FAI 2006). Unlike controlled pot studies that might overestimate metal availability, current field evidence shows that applying MSW compost can enhance soil properties and decrease bioavailable metal fractions; however, metal uptake and translocation vary depending on the crop, as some crops may accumulate metals in their 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.

5. 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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contributed to critical revision and final approval of the manuscript. All authors have read and agreed to the published version of the manuscript.

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