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Effects of Co-composting of Municipal Solid Waste and Pigeon Pea Biochar on Heavy Metal Mobility in Soil and Translocation to Leafy Vegetable Spinach

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Abstract

An experiment was conducted to study the effects of co-composted products of municipal solid waste (MSW) and pigeon pea biochar (PPB) on heavy metal mobility in soil and its uptake by spinach. Application of municipal solid waste biochar co-compost (MSWBC) significantly ($p \le 0.05$) reduced the heavy metal content in spinach leaves and roots compared to municipal solid waste compost (MSWC) amended soil. The percent decrease in spinach leaf following the application of MSWBC-10% PPB compared to MSWC was 20.62%, 28.95%, 36.02%, 41.88%, 41.50%, and 41.23% for Cu, Cd, Pb, Cr, Ni, and Zn, respectively. The dry matter yield of spinach and soil organic carbon (SOC) content in soil amended with MSWBC-10% PPB was significantly increased by 32.75% and 47.73%; and 17.62% and 27.45% relative to control and MSWC amended soil. The study concludes that co-composted product, MSWBC, stabilized heavy metals in MSW, reduced their uptake by spinach and thus making it a viable option for safe disposal of MSW.

Keywords Co-composting · Municipal solid waste · Pigeon pea biochar · Spinach · Heavy metal mobility

Exponential population growth, urbanization and life style changes lead to accumulation of large quantities of municipal solid waste (MSW). Proper utilization and disposal of MSW is a major challenge. Indian cities generate approximately 70 million tonnes (MT) of municipal solid waste (MSW) every year, which upon composting, can supply carbon and most of the essential plant nutrients required for plant growth (Saha et al. 2017). The annual composting potential from MSW in India has been estimated to vary between 5 and 14 MT, depending on the methods of composting, which can provide 120–250 thousand tonnes of major plant nutrients, N, P_2O_5, and K_2O (Saha et al. 2017). Moreover, MSW compost contains huge amount of organic matter which is vital for improving fertility and physical properties as well as biological activities of soils. Indian soils are medium to low in organic matter due to tropical and subtropical climate, intensive tilling of land and removal of crop residues. Therefore frequent external supply of organics is recommended for restoring soil organic matter (SOM) and sustainable crop production (Saha 2002). In this context addition of MSW is useful in enriching SOM. Several authors have reported that the addition of compost made from MSW to soil improves physical, chemical, and biological properties of the soil (Papafilippaki et al. 2015; Weber et al. 2014; Rodriguez-Vila et al. 2016). In addition, composted MSW has other benefits such as the absence of harmful pathogens and volume reduction (40%–50%) (Epstein 1997). However, only approximately 12% of these plant nutrients are being tapped for agricultural use through composting (CPCB 2013).

The major obstacle in the recycling of MSW composts is the significant presence of toxic heavy metals (He et al. 1992). More than 86% of MSW composts prepared in India were found to contain high concentration of heavy metals that exceeded the permissible limits (Saha et al., 2010). When the compost from such MSW is used as manure, some heavy

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metals are subjected to bioaccumulation or biotransfer and may cause risk to human health (kidney damage, neurological damage, blood and bone disorders) via contamination of the food chain through repeated application for crop production (Canet et al. 2000). Therefore, heavy metals in composted MSW and their subsequent release in the soil warrant serious attention before the application of compost made from MSW.

The stabilization of heavy metals through adsorption, complexation, or co-precipitation with amendments has been widely studied in the last decade. Of the numerous amendments used for in situ stabilization of contaminants, organic materials such as composts, biosolids, and manures rich in organic matter have proved to be successful in reducing the mobility of contaminants in multi-metal-polluted soils along with the additional benefit of improving soil fertility through the addition of C and plant nutrients (Clemente and Bernal 2006; Coumar et al. 2016). Recently, biochar has gained significant importance as a soil amendment because of its potential benefits for carbon sequestration in the soil (Lehmann 2007). Biochar refers to carbonaceous residues from incomplete burning of carbon-rich biomass. Moreover, biochar possesses a highly porous structure and contains various functional groups that tends to have strong sorption affinity for organic and inorganic compounds and thus, plays an important role in controlling pollutant levels in the environment. The formation of surface functional groups and adsorption sites during biochar production influences its cation exchange capacity (Liang et al. 2006) and consequently, the capacity of biochar-amended soils to form complexes with metals.

Among the possible methods of waste utilization, mixing of different raw materials during the process of composting, which is known as co-composting, is regarded as the most economical way for the treatment and final disposal of solid waste (Hasanimehr et al. 2011; Yousefi et al. 2012). Previous studies have shown that the use of biochar as an additive material in the composting process improves the quality of the final composted product (Gondek et al. 2018; Sanchez-Monedero et al. 2018). However, there is not much information on the use of soft wood biochar as an additive material in the composting process with MSW and its effects on heavy metal stability, bioavailability, and plant growth. Hence, the present study was designed to evaluate the effect of co-composting of MSW and pigeon pea (soft wood) biochar (PPB) on heavy metal bioavailability and its subsequent effect on uptake and yield of spinach.

Materials and Methods

A greenhouse experiment and laboratory incubation experiments were conducted to evaluate co-composted MSW and PPB material (MSWBC) on heavy metal mobility in soil and their uptake by spinach crops. The PPB was prepared at the Central Institute of Agricultural Engineering (CIAE), Bhopal, using pigeon pea stems as feedstock material. Pigeon pea stems were cut into pieces (10–20 cm), and after sun-drying, the biomass was pyrolysed at 300 °C for 2 h, followed by quenching and subsequent drying in an oven at 105 °C. The PPB was then crushed in a 24-blade Rotar Mill (Model Pulversittee 14) and sieved to obtain a uniform particle size of 53–75 µm. The MSW at partially decomposed condition collected from Vadodara, Gujarat was also processed and sieved through a 1-mm sieve, and a portion was retained for laboratory analysis.

The experimental soil for the green house experiment was collected from the surface (0–15 cm) layer of an agricultural field in the village of Nipaniya Jatkhedi, Bhopal, and was subsequently air dried, ground, and passed through a 2 mm sieve. A representative sample from the sieved soil was analysed for its physicochemical properties using standard methods (Table 1). The experimental soil had a sandy loam texture, pH value of 7.9, and electrical conductivity (EC) of 0.12 dS m^{-1}. The soil had low organic carbon (OC), available nitrogen (N), available phosphorus (P), available potassium (K), and available sulphur (S) content.

Co-composting of MSW along with PPB was carried out under controlled temperature (40^{o}C) and moisture (50% WHC) levels. In the co-composting process, 500 g of MSW in plastic trays were mixed with 2%, 5%, and 10% (w/w basis) of PPB and incubated for 10 weeks with weekly turning using a hand shovel. Similarly 500 g of MSW alone was kept under similar conditions for composting as control. The maturity of MSW-PPB compost was ensured with periodic measurement of CO_2 evolution during decomposition by following the method described by Saha et al. (2010). At the end of the composting period, the matured, co-composted product of MSW–PPB (referred to as municipal solid waste-biochar co-composts, MSWBC-2% PPB, MSWBC-5% PPB, and MSWBC-10% PPB) and MSWC (referred to as municipal solid waste compost, MSWC-0% PPB) was used for the greenhouse experiment. The PPB, MSW, MSWC, and MSWBC materials were analysed for pH, EC, total organic carbon (TOC), and C/N ratio. The content of plant nutrients and potentially toxic heavy metals was analysed after digestion of samples using a hot plate and a di-acid mixture (HNO_3:$HClO_4$, 9:4 v/v). The PPB raw material used for co-composting process had pH of 8.45, total organic carbon (TOC) of 56.25%, total nitrogen (TN) of 1.07% and C/N ratio of 52.57. The MSW raw material had pH, TOC, TN and C/N ratio of 7.08%, 22.52%, 1.29% and 17.46%, respectively. The heavy metal content in the MSW material was 199.1, 8.4, 130.0, 110.5, 62.2 and 434.7 mg kg^{-1} for Cu, Cd, Pb, Cr, Ni and Zn, respectively. Similarly, the heavy metal content in the PPB material was 18.8, 0.2, 0.8, 12.5, 1.2 and 22.5 mg kg^{-1} for Cu, Cd, Pb, Cr, Ni and Zn, respectively.

Table 1 Physicochemical properties of experimental soil

Parameter	Mean ± SD (n = 3)	Method/Reference
pH (soil: water 1:2)	7.90 ± 0.31	Jackson (1973)
EC (soil:water 1:2) (dS m^{-1})	0.12 ± 0.02	Jackson (1973)
Mechanical analysis		International pipette method (Piper 1967)
Sand (%)	73.16 ± 4.54	
Silt (%)	09.30 ± 0.27	
Clay (%)	17.54 ± 1.05	
Textural class	Sandy loam	
Organic carbon (%)	0.49 ± 0.06	Walkley and Black (1934)
Available nitrogen (kg ha^{-1})	167.00 ± 11.34	Subbiah and Asija (1956)
Available phosphorus (kg ha^{-1})	9.34 ± 0.72	Olsen et al. (1954)
Available potassium (kg ha^{-1})	138.90 ± 8.67	Black (1965)
Available sulphur (kg ha^{-1})	7.1 ± 0.95	Chesnin and Yien (1950)
Total heavy metals (DTPA-extractable) (mg kg^{-1})		Lindsay and Norvell (1978)
Cu	61.30 ± 3.19 (9.30 ± 0.46)	
Cd	00.20 ± 0.02 (0.03 ± 0.01)	
Pb	20.87 ± 1.73 (0.34 ± 0.04)	
Cr	24.10 ± 1.60(0.09 ± 0.02)	
Ni	60.83 ± 2.79 (0.60 ± 0.08)	

EC electrical conductivity, *DTPA* diethylene triamine pentaacetic acid. All values in the parenthesis are DTPA−extractable metal content

Pot culture experiments were carried out under greenhouse conditions with spinach as a test crop in a sandy loam soil. Each of the wide-mouthed, glazed pots of 7-kg capacity was filled with 5 kg of processed soil. Treatments were control, MSWC, MSWBC-2% PPB, MSWBC-5% PPB, and MSWBC-10% PPB. In each pot, MSWC, MSWBC-2%, MSWBC-5%, and MSWBC-10% were applied at 5 g kg^{-1} of soil. Potted soils along with MSWC/MSWBC were mixed thoroughly and allowed to equilibrate in moist conditions for one week prior to the sowing of spinach seeds.

Uniform doses of N (30 mg N kg^{-1} soil), P (18 mg P_2O_5 kg^{-1} soil), and K (18 mg K_2O kg^{-1} soil) were supplied in the form of urea, di-ammonium phosphate, and potassium chloride, respectively, to ensure an adequate supply of nutrients. The entire doses of P and K and half of the dose of N were applied before the sowing of seeds, and the other half of the dose of N was added as top-dressing 20 days after sowing. The seeds of spinach (*variety Selection-1*) were treated with Bavistin at 2 g kg^{-1} seed to avoid fungal infection. Ten healthy seeds of spinach were sown in equidistant holes at a depth of 2–3 cm in the potted soil, which were subsequently covered with loose soil. After germination, all seedlings were allowed to grow for 10 days and subsequently thinned out, leaving only five healthy plants in each pot for growing up to the full-grown stage.

At 60 days after sowing, above-ground biomass (leaf) and roots were harvested, separated, washed with distilled water, and air-dried. Roots were washed thoroughly with tap water to remove adhering soil particles, followed by sequential washing with dilute acid (HCl) and distilled water. Air-dried leaf and root samples were then oven-dried at 65 °C until constant weight was attained. Oven-dried plant parts (leaves and root) were ground in a Willey mill and passed through a 2-mm sieve. Homogenized tissue samples were digested in a di-acid mixture containing HNO_3 and $HClO_4$ (9:4 v/v) on a hot plate at 150–175 °C for ~ 2 h until a clear liquid was obtained. Soil samples were collected separately from each pot after the harvest of the spinach crop for analysis. The pH and EC of post-harvest soil samples were measured in suspensions of soil in water (1:2.5 w/v), whereas soil organic carbon (SOC) content was estimated by using the wet oxidation method (Walkley and Black 1934). The bioavailable heavy metal content in soil was extracted by the extractant, DTPA (Lindsay and Norvell 1978).The concentrations of heavy metals in the digested samples (plant, soil, and experimental materials) and of DTPA extractant were determined by using an inductively coupled plasma-optical emission spectrophotometer (Perkin Elmer Optima DV 2100). For quality control during analysis of heavy metals, a reference soil material (ERM-CC 141) from the Institute for

Reference Materials and Measurements, European Commission, Belgium, was used. Standard solutions of Cu, Cd, Pb, Cr, Ni, and Zn were prepared for ICP-OES calibration by serial dilution of 1000 mg L^{-1} of Certipur® (Merck) single-element standard solution.

All measurements are mean values of three replicates. Data were subjected to one-way analysis of variance (ANOVA) using an SPSS version 9.0 statistical package. The mean values were grouped for comparisons based on least significant differences (LSD) among them at a confidence level of $p \leq 0.05$.

Results and discussion

In the present study, MSW and PPB were co-composted to prepare relatively safe products, MSWBCs, to reduce the mobility of toxic heavy metals following the application of the compost to soil. Plant nutrient content and potential toxic heavy metal content in the matured compost after 10 weeks of composting are shown in Table 2. The results indicate that the total content of heavy metals (Cd, Ni, and Zn) in MSWBC (10% PPB) decreased significantly ($p \leq 0.05$) in comparison to MSWC. The MSWC had the highest heavy metal content, whereas MSWBC-10% PPB) had the lowest. This may be due to the dilution effect of PPB addition during co-composting as PPB had very low metal concentrations. These results are consistent with the findings of Hasanimehr et al. (2011) who reported that sawdust addition to sewage sludge during co-composting diluted the heavy metal content, thereby decreasing potentially toxic metal concentrations in the co-composted product. The TOC, C/N ratio, and total K content were significantly ($p \leq 0.05$) highest in MSWBC-10% PPB compared to MSWC, which may be due to the higher content of TOC and K in PPB. The C/N ratio of MSWC was 13.74 as compared to the MSW C/N ratio of 17.46 indicating the decomposition process and compost maturity at the end of composting period. Additionally, the pH of the co-composted products was significantly ($p \leq 0.05$) greater than that of MSWC due to the addition of alkaline element-rich PPB as an additive during co-composting. Apart from the dilution effect, the increased pH and TOC in the co-composted products might play greater roles in reducing heavy metal mobility in soil following its application as a soil amendment. Several authors have reported changes in properties (pH, EC, nutrient content, TOC, C/N ratio, and heavy metal composition) of the final composted product with the use of biochar as an additive in the co-composting process (Gondek et al. 2018; Sanchez-Monedero et al. 2018).

The dry matter yield of spinach leaves and roots after MSWBC application is presented in Table 3. The dry matter yield of spinach leaves and roots varied from 5.13 to 6.81 g pot^{-1} and 0.60 to 0.82 g pot^{-1}, respectively. Application of MSWC significantly increased the dry matter yield of spinach leaves and roots compared to the control ($p \leq 0.05$). The application of the co-composted product, MSWBC (2%, 5%, and 10% PPB), further increased the dry matter yield of spinach leaves and roots. The highest dry matter yield of 6.81 g leaves pot^{-1} was observed in soil amended with MSWBC-10% PPB and was significantly ($p \leq 0.05$) higher than that of the MSWC-treated soil with a percent increase

Table 2 Chemical composition of municipal solid waste compost (MSWC) and municipal solid waste-biochar co-compost (MSWBC)

Co-composted products	Parameters							
	pH	EC (dS m^{-1})	TOC (%)	TN (%)	C/N ratio	TP (%)	TK (%)	TS (%)
MSWC	7.02 ± 0.05^{d}	2.16 ± 0.09^{a}	16.63 ± 0.16^{b}	1.21 ± 0.03^{a}	13.74 ± 0.47^{c}	$0.17 \pm 0.02^{*}$	0.14 ± 0.02^{c}	$0.08 \pm 0.05^{*}$
MSWBC-2% PPB	7.17 ± 0.08^{c}	2.16 ± 0.05^{a}	15.95 ± 0.21^{b}	1.17 ± 0.03^{a}	14.37 ± 0.82^{b}	0.18 ± 0.02	0.18 ± 0.01^{b}	0.08 ± 0.02
MSWBC-5% PPB	7.24 ± 0.08^{b}	2.11 ± 0.04^{a}	16.72 ± 0.32^{b}	1.11 ± 0.01^{b}	14.29 ± 1.01^{bc}	0.18 ± 0.05	0.21 ± 0.01^{ab}	0.07 ± 0.02
MSWBC-10% PPB	7.35 ± 0.05^{a}	2.02 ± 0.07^{b}	19.58 ± 0.40^{a}	1.02 ± 0.03^{c}	19.20 ± 0.47^{a}	0.16 ± 0.03	0.23 ± 0.07^{a}	0.09 ± 0.01

	Total heavy metals (mg kg^{-1})					
	Cu	Cd	Pb	Cr	Ni	Zn
MSWC	199.0 ± 5.33*	8.40 ± 0.78^{a}	130.0 ± 2.51*	110.5 ± 1.26*	62.02 ± 0.83^{a}	434.7 ± 10.51^{a}
MSWBC-2% PPB	197.5 ± 4.07	8.25 ± 0.37^{a}	128.2 ± 2.02	106.3 ± 2.44	60.11 ± 1.01^{a}	426.7 ± 6.22^{a}
MSWBC-5% PPB	191.0 ± 2.94	7.51 ± 0.22^{b}	125.3 ± 1.93	103.9 ± 1.83	59.26 ± 0.67^{a}	415.8 ± 8.82^{a}
MSWBC-10% PPB	182.6 ± 4.64	7.42 ± 0.39^{b}	119.6 ± 2.77	101.0 ± 1.61	54.28 ± 0.87^{b}	386.5 ± 13.51^{b}

MSWC municipal solid waste compost, *MSWBC* municipal solid waste-biochar co-compost, *PPB* pigeon pea biochar, *EC* electrical conductivity, *TOC* total organic carbon, *TN* TN− Total nitrogen, *TP* total phosphorus, *TK* total potassium, *TS* total sulphur

Data represent the mean value ± standard error from three replicates (n = 3). Means followed by a different lowercase letter within a column are significantly different ($p \leq 0.05$). *Represent parameters of non−significant ($p \leq 0.05$) between treatments

Table 3 Effect of municipal solid waste–biochar co-compost on dry matter yield of spinach and nutrient content in leaf

Treatment	Dry matter yield (g pot^{-1})		Nutrient content (%) in leaf			
	Leaf	Root	N	P	K	S
Control	5.13 ± 0.10^{c}	0.60 ± 0.03^{c}	2.26 ± 0.05^{c}	0.23 ± 0.02^{c}	2.95 ± 0.12^{c}	0.65 ± 0.02^{c}
MSWC	5.79 ± 0.09^{b}	0.71 ± 0.04^{b}	2.37 ± 0.06^{c}	0.30 ± 0.02^{b}	3.24 ± 0.10^{bc}	0.85 ± 0.04^{b}
MSWBC–2% PPB	5.78 ± 0.13^{bc}	0.72 ± 0.04^{b}	2.95 ± 0.11^{b}	0.28 ± 0.03^{bc}	3.3 ± 0.14^{bc}	0.78 ± 0.02^{b}
MSWBC–5% PPB	5.83 ± 0.05^{b}	0.78 ± 0.03^{ab}	3.33 ± 0.08^{a}	0.33 ± 0.01^{b}	3.68 ± 0.11^{ab}	0.78 ± 0.05^{b}
MSWBC–10% PPB	6.81 ± 0.10^{a}	0.82 ± 0.01^{a}	3.60 ± 0.09^{a}	0.39 ± 0.02^{a}	4.19 ± 0.12^{a}	0.96 ± 0.03^{a}

MSWC municipal solid waste compost, *MSWBC* municipal solid waste-biochar co-compost, *PPB* pigeon pea biochar

Data represent the mean value ± standard error from three replicates (n = 3). Means followed by a different lowercase letter within a column are significantly different ($p \le 0.05$)

of 17.62%. Similar trends were observed in root dry matter yield with 15.49% increase relative to MSWC application.

Several studies have shown that compost products are generally rich in plant nutrients and organic matter, which stimulates plant growth and yield (Ling et al. 2016; Xie et al. 2014; Srivastava et al. 2016). Researchers have proved that crop yields can be improved by biochar application (Lehmann and Rondon 2006; Blackwell et al. 2009; Coumar et al. 2016a). Results from our pot culture experiments show that the spinach leaf and root dry matter yield were significantly ($p \le 0.05$) increased by the application of MSWC and MSWBC. Approximately 12.87 and 18.33% increase was observed in the dry matter yield of spinach leaves and roots when MSWC was applied; however, in the soil amended with MSWBC-10% PPB, the percent increase rose to 32.75% and 36.67%, respectively, compared to the control treatment. Similar results were reported by Maynard (1995) in vegetable crops in which the application of 11.2 t ha^{-1} of MSWC compost resulted in 58% higher yield compared to the control.

Significant variation in the nutrient content of spinach leaves was observed between the treatments (Table 3). The nutrient content in spinach leaves varied from 2.26% to 3.60% for N, 0.23% to 0.39% for P, 2.95% to 4.19% for K, and 0.65% to 0.96% for S. Application of MSWC significantly increased P and S content in spinach leaves relative to control. Similarly, application of MSWBC also increased the nutrient content of leaves compared to MSWC application; however, significant differences were observed in the soil treated with MSWBC-10% PPB. The highest leaf nutrient content for N, P, K, and S at 3.60%, 0.39%, 4.19%, and 0.96%, respectively, was observed with the application of MSWBC-10% PPB. Many of the early studies on crop growth have also shown that MSW composts could supply essential plant nutrients (Papafilippaki et al. 2015; Terman et al. 1973). Lakhdar et al. (2011) had reported that the application of MSW enhanced plant nutrient (N, P, and K) uptake by the medicinal plant, *Mesembryanthemum edule*, which led to the increase in plant growth when compared to the control.

Application of MSWC and MSWBC significantly affected the heavy metal content in spinach leaves and roots (Table 4). The heavy metal content in spinach leaves varied from 34.23 to 47.33, 0.23 to 0.38, 1.03 to 1.61, 0.80 to 1.60, 2.03 to 3.70, and 21.47 to 36.53 mg kg^{-1} for Cu, Cd, Pb, Cr, Ni, and Zn, respectively. Similarly, the heavy metal content in spinach roots varied from 26.93 to 46.97, 1.51 to 1.69, 2.25 to 3.43, 2.12 to 3.20, 3.10 to 4.57, and 14.40 to 27.03 mg kg^{-1} for Cu, Cd, Pb, Cr, Ni, and Zn, respectively. Thus, the heavy metal content (Cd, Cr, Pb, and Ni) was relatively higher in spinach roots than in the leaves. The application of MSWC increased the heavy metal content (Cu, Cd, Pb, Cr, Ni, and Zn) in spinach leaves and roots compared to the control. Studies conducted by Clemente and Bernal (2006) and Salt et al. (1995) also revealed bioaccumulation and transfer of certain heavy metals to the food chain with the use of MSW compost. The presence of Cd, Co, Mn, Ni, Pb, and Zn in MSW-treated soil was also reported by Ciba et al. (1999).

In contrast to the above results, the application of MSWBC resulted in the reduction of heavy metal content of spinach leaves and roots compared to MSWC-amended soil. Soil amended with MSWBC-10% PPB showed significantly ($p \le 0.05$) lower heavy metal content in leaves and roots of the spinach crop. Compared to MSWC application, significant ($p \le 0.05$) reduction in Cu, Cr, and Ni content in spinach leaves was observed only with the application of MSWBC-10% PPB. However, significant ($p \le 0.05$) reduction in Cd, Pb, and Zn was also recorded in soil amended with MSWBC-5% PPB and MSWBC-10% PPB. The percent decrease in heavy metal content of spinach leaves following the application of MSWBC-10% PPB relative to MSWC was 20.62, 28.95, 36.02, 41.88, 41.50, and 41.23 for Cu, Cd, Pb, Cr, Ni, and Zn, respectively. The percent decrease in heavy metal content of spinach roots was 42.67, 10.65, 34.40, 33.75, 32.17, and 28.71 for Cu, Cd, Pb, Cr, Ni, and Zn, respectively, following the application of MSWBC-10%

Table 4 Effect of municipal solid waste–biochar co-compost on heavy metal content in leaf and root of spinach crop

Treatment	Heavy metal content (mg kg^{-1})					
	Cu	Cd	Pb	Cr	Ni	Zn
Leaf						
Control	34.23 ± 1.96^{b}	0.23 ± 0.03^{c}	1.53 ± 0.02^{b}	0.80 ± 0.06^{b}	2.70 ± 0.12^{c}	28.20 ± 2.08^{c}
MSWC	47.33 ± 1.29^{a}	0.38 ± 0.03^{a}	1.61 ± 0.04^{a}	1.60 ± 0.14^{a}	3.47 ± 0.12^{ab}	36.53 ± 1.72^{a}
MSWBC-2% PPB	45.17 ± 2.48^{a}	0.30 ± 0.03^{b}	1.56 ± 0.02^{ab}	1.55 ± 0.12^{a}	3.70 ± 0.16^{a}	27.73 ± 2.04^{bc}
MSWBC-5% PPB	40.07 ± 2.70^{a}	0.28 ± 0.01^{bc}	1.54 ± 0.02^{b}	1.53 ± 0.09^{a}	2.93 ± 0.19^{bc}	26.03 ± 2.42^{bc}
MSWBC-10% PPB	37.57 ± 1.75^{b}	0.27 ± 0.02^{bc}	1.03 ± 0.05^{c}	0.93 ± 0.09^{b}	2.03 ± 0.13^{d}	21.47 ± 3.57^{b}
Root						
Control	31.57 ± 2.73^{b}	1.60 ± 0.06^{b}	2.42 ± 0.18^{b}	2.30 ± 010^{c}	3.57 ± 0.12^{bc}	14.40 ± 0.35^{d}
MSWC	46.97 ± 1.69^{a}	1.69 ± 0.06^{a}	3.43 ± 0.17^{a}	3.20 ± 0.17^{a}	$4.57 \pm 0.18a$	27.03 ± 0.56^{a}
MSWBC-2% PPB	34.36 ± 3.57^{b}	1.67 ± 0.03^{a}	3.29 ± 0.17^{a}	3.07 ± 0.20^{ab}	4.07 ± 0.19^{ab}	24.77 ± 0.70^{ab}
MSWBC-5% PPB	28.63 ± 2.55^{b}	1.62 ± 0.04^{ab}	2.47 ± 0.23^{b}	2.72 ± 0.12^{ab}	3.73 ± 0.09^{bc}	23.37 ± 0.74^{b}
MSWBC-10% PPB	26.93 ± 3.82^{b}	1.51 ± 0.06^{c}	2.25 ± 0.21^{b}	2.12 ± 0.12^{c}	3.10 ± 0.06^{c}	19.27 ± 0.37^{c}

MSWC municipal solid waste compost, *MSWBC* municipal solid waste-biochar co-compost, *PPB* pigeon pea biochar

Data represent the mean value ± standard error from three replicates (n = 3). Means followed by a different lowercase letter within a column are significantly different ($p \leq 0.05$)

PPB compared to MSWC. This decrease in heavy metal content may be because of reduced release into the soil system due to complex formation of the heavy metals with the stabilized organic matter in PPB or due to their adsorption on the recalcitrant carbon in PPB, which is resistant to microbial degradation. Paré et al. (1998) had suggested complex formation between stabilized organic matter and metals as a possible reason for the restricted mobility of the metals and their availability for plant absorption.

MSWC and MSWBC (2%, 5%, and 10% of PPB) significantly influenced heavy metal uptake by spinach leaves and roots (Fig. 1). The uptake of Cu, Cd, Pb, Cr, Ni, and Zn was highest in the soil amended with MSWC. In contrast, the application of MSWBC-2%, 5%, and 10% levels of PPB resulted in a reduction in heavy metal uptake by the leaves and roots of the spinach crop. Among the MSWBCs, MSWBC-10% of PPB showed significant ($p \leq 0.05$) reduction in heavy metal uptake by spinach leaves and roots compared to the uptake after application of MSWC. These results are consistent with the findings of Papafilippaki et al. (2015) who had found that the application of MSW increased bioavailability of heavy metals such as Cd, Cr, Cu, Pb, Ni, and Zn in soils.

Application of MSWC significantly ($p \leq 0.05$) decreased the soil pH from 8.15 to 8.04 (Table 5). However, soil amended with MSWBC-10% PPB showed a higher pH of 8.19. The addition of both MSWC and MSWBC to the soil substantially increased the soil EC. Similarly, SOC content

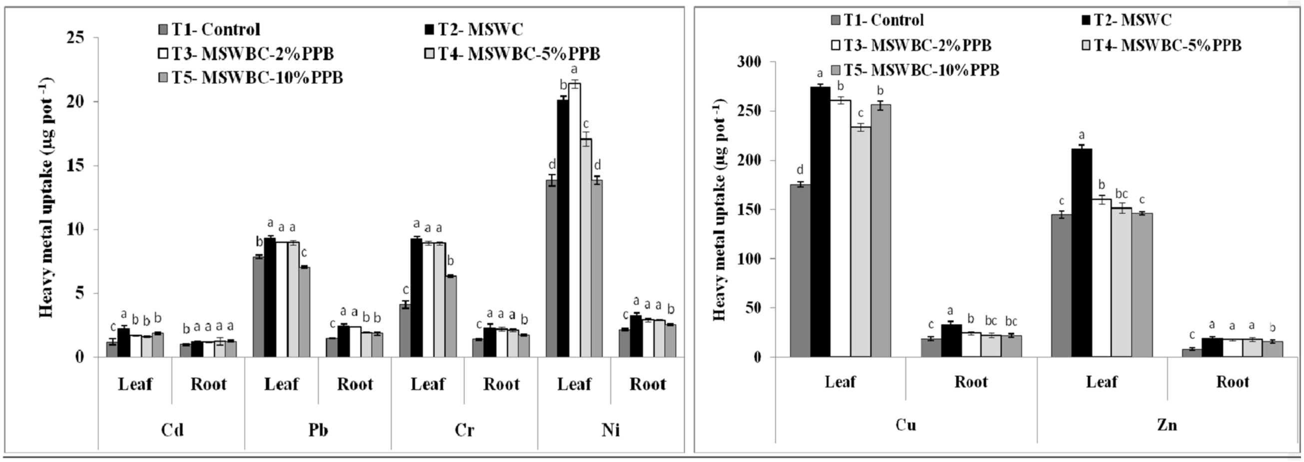

Fig. 1 Effect of municipal solid waste–biochar co-compost on heavy metal uptake by spinach crop

Table 5 Effect of municipal solid waste–biochar co-compost on pH, EC, organic carbon, and available nutrient content of post-harvest soil sample

Treatment	pH	EC (dSm^{-1})	OC (%)	N (kg/ha)	P (kg/ha)	K (kg/ha)	S (kg/ha)
Control	8.15 ± 0.01^{ab}	0.22 ± 0.01^{c}	0.44 ± 0.04^{d}	172.24 ± 2.22^{c}	8.75 ± 0.67^{d}	123.95 ± 4.65^{b}	6.52 ± 0.67^{c}
MSWC	8.04 ± 0.02^{c}	0.24 ± 0.03^{bc}	0.51 ± 0.01^{c}	178.57 ± 2.54^{abc}	9.29 ± 0.61^{c}	132.71 ± 2.56^{a}	6.97 ± 0.63^{b}
MSWBC-2% PPB	8.05 ± 0.06^{c}	0.25 ± 0.01^{bc}	0.58 ± 0.01^{bc}	176.34 ± 2.22^{bc}	9.45 ± 0.74^{bc}	131.34 ± 4.33^{ab}	7.09 ± 0.72^{b}
MSWBC-5% PPB	8.13 ± 0.01^{abc}	0.27 ± 0.01^{ab}	0.61 ± 0.01^{ab}	181.34 ± 3.18^{ab}	9.71 ± 0.88^{b}	134.01 ± 2.63^{a}	7.07 ± 0.74^{b}
MSWBC-10% PPB	8.19 ± 0.03^{a}	0.31 ± 0.02^{a}	0.65 ± 0.02^{a}	182.64 ± 2.18^{a}	10.18 ± 0.88^{a}	137.42 ± 2.48^{a}	7.54 ± 0.69^{a}

MSWC municipal solid waste compost, *MSWBC* municipal solid waste-biochar co-compost, *PPB* pigeon pea biochar

Data represent the mean value ± standard error from three replicates (n = 3). Means followed by a different lowercase letter within a column are significantly different ($p \leq 0.05$)

in the MSWC and MSWBC-amended soil was significantly ($p \leq 0.05$) higher than that of untreated soil (control). The SOC content in the post-harvest soil ranged from 0.44 % to 0.65% with a percent increase of 47.73% compared to the control. Levels of the available nutrients such as N, P, K, and S had also increased from 172.24 to 178.57, 8.75 to 9.29, 123.95 to 132.71, and 6.52 to 6.97 kg ha^{-1}, respectively, in the soil amended with MSWC. Except for available N, significant ($p \leq 0.05$) increase was observed in the levels of plant nutrients in post-harvest soil for the soils amended with MSWC and MSWBC compared to the control. The available nutrient status was found to be highest in the soil amended with MSWBC-10% PPB with values of 182.64 kg ha^{-1} for N, 10.18 kg ha^{-1} for P, 137.42 kg ha^{-1} for K, and 7.54 kg ha^{-1} for S. These results clearly indicate that MSWBC addition resulted in further increase in plant-available nutrients in the soil compared to MSWC application. Several authors have reported similar changes in physicochemical properties of soil and enhanced plant growth with the application of MSW (Papafilippaki et al. 2015; Weber et al. 2014; Rodriguez-Vila et al. 2016).

DTPA-extractable heavy metal concentrations in soil and transfer coefficient values indicate heavy metal mobility in the soil. The DTPA-extractable heavy metal concentrations for Cu, Cd, Pb, Cr, Ni, and Zn varied from 11.0 to 25.24, 0.02 to 0.08, 0.30 to 0.44, 0.15 to 0.38, 0.64 to 0.75, and 0.80 to 1.36 mg kg^{-1}, respectively. In addition to DTPA-extractable heavy metals, transfer coefficients for all of the heavy metals were calculated as the ratio of the concentration of a metal in a plant to the total concentration of the metal in the soil. A higher transfer coefficient indicates a greater mobility of metal from the soil into the plant. The transfer coefficient values varied from 0.23 to 0.40, 1.50 to 2.27, 0.05 to 0.07, 0.03 to 0.05, 0.04 to 0.06, and 1.04 to 1.65 for Cu, Cd, Pb, Cr, Ni, and Zn, respectively. These values indicate that the mobility of Cd from the soil to the plant was higher than that of Zn, Cu, Pb, Ni, and Cr. In other studies, the transfer coefficient value for Cd was confirmed to be higher than those for other heavy metals (Bergmann 1992; Coumar et al. 2016a).

Soil amended with MSWC showed significant ($p \leq 0.05$) increase in DTPA-extractable content and transfer coefficient values compared to the control (Table 6; Fig. 2). However, DTPA-extractable heavy metals and transfer coefficients were more significantly ($p \leq 0.05$) reduced following the application of MSWBC-10% PPB than after MSWC application. The percent reduction in DTPA-extractable content in soil amended with MSWBC-10% PPB was 56.42%, 75.00%, 27.27%, 60.53%, 14.67%, and 21.32% for Cu, Cd, Pb, Cr, Ni, and Zn, respectively, compared to MSWC amended soil. Cuevas et al. (2000) had reported that concentrations

Table 6 Effect of municipal solid waste–biochar co-compost on DTPA-extractable heavy metal content in soil

Treatment	DTPA-extractable heavy metal content in soil (mg kg^{-1})					
	Cu	Cd	Pb	Cr	Ni	Zn
Control	14.04 ± 1.28^{e}	0.02 ± 0.02^{b}	0.30 ± 0.01^{b}	0.18 ± 0.01^{b}	0.64 ± 0.01^{b}	0.80 ± 0.03^{c}
MSWC	25.24 ± 1.17^{a}	0.08 ± 0.02^{a}	0.44 ± 0.02^{a}	0.38 ± 0.01^{a}	0.75 ± 0.02^{a}	1.36 ± 0.08^{a}
MSWBC-2% PPB	22.17 ± 1.01^{b}	0.06 ± 0.01^{ab}	0.44 ± 0.02^{a}	0.21 ± 0.02^{ab}	0.73 ± 0.01^{a}	1.19 ± 0.04^{ab}
MSWBC-5% PPB	18.08 ± 1.07^{c}	0.05 ± 0.02^{ab}	0.43 ± 0.01^{a}	0.21 ± 0.01^{ab}	0.70 ± 0.01^{ab}	1.13 ± 0.04^{b}
MSWBC-10% PPB	11.01 ± 1.84^{d}	0.03 ± 0.02^{b}	0.32 ± 0.01^{b}	0.15 ± 0.02^{b}	0.64 ± 0.02^{b}	1.07 ± 0.09^{b}

MSWC municipal solid waste compost, *MSWBC* municipal solid waste-biochar co-compost, *PPB* pigeon pea biochar

Data represent the mean value ± standard error from three replicates (n = 3). Means followed by a different lowercase letter within a column are significantly different ($p \leq 0.05$)

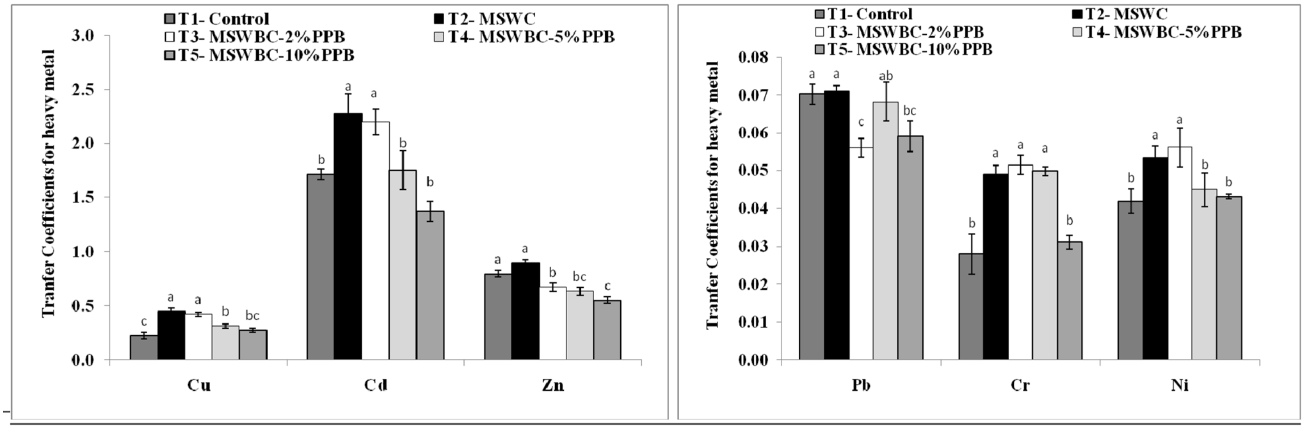

Fig. 2 Effect of municipal solid waste-biochar co-compost on transfer coefficients of heavy metals

of all heavy metals were higher following the application of MSW with significant ($p \leq 0.05$) differences noted only for Zn, Pb, and Cu. Papafilippaki et al. (2015) observed that MSW increased the bioavailability of trace elements, whereas Fang and Wong (1999) reported that co-composting of sewage sludge and lime lowered extractable copper, manganese, zinc, and nickel relative to unlimed sewage sludge compost. Thus, stabilization of heavy metals in MSW during co-composting with PPB as evidenced by the reduction in DTPA-extractable heavy metal content might be due to the processes of co-precipitation, adsorption, and binding of heavy metals with the biochar. Moreover, formation of clay-organic matter-metal complexes due to alkaline pH and surface organic functional groups of bio char following the application of MSWBC compost in soil probably resulted in further reduction in the DTPA-extractable metal concentrations in the soil.

Our study reveals that MSWC is rich in plant nutrients and improves soil fertility, thus stimulating spinach growth. However, it contains appreciable amounts of toxic metals, which increased the heavy metal content in the soil and its availability to spinach crops. In the present study, the use of soft wood (pigeon pea) biochar as an additive during the process of co-composting with MSW improved the quality of the co-composted product, MSWBC. Application of MSWBC-10% PPB in soil significantly reduced the DTPA-extractable heavy metal content by 14.7% (Ni) to 62.5% (Cd) and reduced heavy metal mobility (transfer coefficient values) from the soil to the plant system. Thus, this study concludes that co-composting of MSW with 10% PPB is a viable option for the safe disposal of MSW as soil amendment without affecting soil quality and crop yield.

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