



RESEARCH

Biochar Co-composting: A Strategy for Improving Compost Quality

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ABSTRACT

Use of biochar as a raw material in compost mixture has demonstrated numerous benefits during the composting process and in the end product. Changes in quality parameters in compost produced by co-composting raw materials with poultry litter (PL) and PL biochar (PLB) were studied. PLB was prepared by co-pyrolyzing PL with (5% w/w) and without (0% w/w) Eppawala Rock Phosphate (ERP). Thus, four types of composts were produced: compost without biochar or PL (C), co-compost with 10% (w/w) PL (CC_{PL}), co-compost with 10% (w/w) PLB (CC_{PLB}), and co-compost with 10% (w/w) PLB co-pyrolyzed with ERP (CC_{PLB-ERP}). Composts were made using the closed heap method. Composts were characterized for physical and chemical parameters using standard laboratory methods in SLS1635. Incorporation of PLB and PLB-ERP significantly increased the total phosphorus content in composts by approximately three-fold compared to C and CC_{PL}. Co-composting with biochar enhanced the extractable potassium concentration by 261-325% although the total K concentration did not significantly increase. Incorporation of PLB and PLB-ERP also increasing the total Ca by 209-219% and Mg content by 84-93% ($p < 0.05$). There was no significant variation in Fe, Cu, Mn and Zn contents across compost types. Compared to CC_{PL}, a significant reduction in total nitrogen content was observed in CC_{PLB} and CC_{PLB-ERP}. The addition of ERP led to an increase in total AS content in CC_{PLB-ERP}, but within the maximum permissible levels. Notably, biochar application reduced total Pb concentration, while Cd and Cr concentrations showed no significant differences. When considering quality parameters holistically, incorporation of PLB or PLB-ERP during the composting process enhances the quality of the compost produced, except for electrical conductivity (EC).

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INTRODUCTION

Soil fertility depletion and declining agricultural productivity are major challenges in tropical agricultural systems, primarily due to the reduction of soil organic matter and nutrient imbalances. Sustainable soil management strategies must prioritize the maintenance of adequate organic matter levels and promote efficient biological nutrient cycling to enhance long-term soil productivity. Application of composts could solve some of these issues but needs to be applied in large quantities repeatedly because of their low nutritive values and faster decomposition in hot and humid tropical environments. According to standards of the Sri Lanka Standards Institute, the minimum N, P₂O₅, and K₂O contents should be only 1, 0.5, and 0.5% (w/w), respectively (SLSI, 2019). Evidence shows that the application of biochar can play a significant role in improving soil organic carbon, water holding capacity, soil aeration, increasing soil base saturation, nutrient retention and availability, decreasing the need fertilizers and nutrient leaching (Agegnehu *et al.*, 2017).

One of the approaches to the production of biochar-based soil amendment is co-composting, which involves adding biochar to raw material before composting. This allows for obtaining a compost-biochar product with new and specific properties, called co-composted biochar (COMBI) (Rombel *et al.*, 2022). Based on current findings, the co-composting process has several benefits including shorter composting time, reduced rates of greenhouse gas emissions, reduced ammonia losses, the ability to serve as a bulking agent for compost, and reduced odor (Camps and Tomlinson, 2015). Co-composting was found to modify biochar structure and pores which increased micro pores in the biochar resulting in a larger surface area and increased surface absorption capacity (Antonangelo *et al.*, 2021). Moreover, application of biochars during composting causes changes in the surface functional groups consisting of increasing the number of negatively charged groups, i.e., acid and oxygenated groups (e.g.,

carboxyl, lactone, or phenolic) (Hua *et al.*, 2009; Khan *et al.*, 2016). Such changes on the biochars surface promotes the immobilization of nutrients and prevents their loss during composting (Antonangelo *et al.*, 2021). Co-composting also increases CEC of biochar materials, which leads to better immobilization of nutrients by biochars. During co-composting, biochars also get enriched with easily available sources of N and C; improving its nutritive value (Antonangelo *et al.*, 2021). Moreover, a study by Wang *et al.* (2019) shows that co-composting with biochar facilitates the natural oxidation (aging) of biochars, which contributes to more effective soil fertilization due to the retention of nutrients. Thus, co-composted biochar also prevents the leaching of nutrients into the environment. However, there is a paucity of published information related to COMBI using locally available materials.

The poultry industry has grown significantly after 1977 with economic reforms in Sri Lanka. The poultry population has increased exponentially from 6.3 million to 35.5 million in 2024 (Department of Animal Production and Health, 2024). This expansion of the poultry industry in Sri Lanka, is leading to, the production of substantial amounts of poultry litter, a nutrient-rich organic residue containing considerable quantities of organic carbon and plant available nutrients. Although poultry litter has agronomic value, its improper handling and disposal can pose risks to environmental and human health, including nutrient leaching, water contamination, greenhouse gas emissions, and the proliferation of antibiotic-resistant microorganisms (Maheepala and Jayasinghe, 2019). These concerns have heightened interest in sustainable waste management strategies, particularly those that can transform poultry litter into value-added soil amendments (Maheepala and Jayasinghe, 2019). Pyrolysis is increasingly recognized as an effective approach for stabilizing organic waste while generating biochar with beneficial soil-ameliorating properties. However, biochar typically contains limited quantities of readily available phosphorus and potassium,

restricting its direct use as a fertilizer. Previous studies have shown that co-pyrolyzing biochar with exogenous mineral sources can enhance its nutrient value (Zhao *et al.*, 2016). For example, Dissanayake *et al.* (2018) observed that incorporation of ERP during the pyrolysis process increased the phosphorus availability in Rice Husk Biochar (RHB) by three-fold. Despite this potential, there is a lack of comprehensive research on the physicochemical properties of poultry litter biochar and poultry litter biochar co-pyrolyzed with ERP, as well as how these properties evolve during co-composting with locally available organic materials. Hence, the objective of this study was to develop a better-quality compost by co-composting commonly used raw materials with PLB and characterize its physicochemical properties.

MATERIALS AND METHODS

Poultry litter (PL) was collected from a commercial layer farm and used as the feedstock for biochar production. The raw PL was air-dried for 2–3 days to reduce the moisture content to approximately 10–15% (dry basis) prior to pyrolysis. Poultry litter biochar (PLB) was produced using a double-chamber pyrolyzer designed and developed by the Department of Agricultural Engineering, Faculty of Agriculture, University of Peradeniya (Illankoon *et al.*, 2023). Co-pyrolysis of PL and 5% ERP (w/w) was done using the same pyrolyzer (PLB-ERP). Three sets (replicates) of biochars were made from each feedstock (i.e., PL and PL+ERP) and characterized for their chemical properties. Subsamples from poultry litter feedstock and each biochar sample were sieved through a 2 mm sieve before analysis.

Characterization of biochar samples

The pH and electrical conductivity (EC) were measured according to Singh *et al.* (2017) in 1:10 (m/v) biochar: distilled water suspension. The sample was shaken for 1 h in an orbital shaker and the pH was measured using an EUTECH pH 700 pH meter and EC were measured using a HACH HQ14d Conductivity meter. The modified

dry-ashing method suggested by Enders *et al.* (2012) was followed for the digestion of biochar samples. Samples were ashed in ceramic crucibles for 8 h at 500 °C in a muffle furnace (BIOBASE MX8-12T) and 5.0 mL of 70% concentrated HNO₃ was added to each crucible. The contents were transferred to digestion tubes and heated on the digestion block (Hanon SH420F Graphite Digester) at 120°C until dry. Tubes were allowed to cool and another 1.0 mL HNO₃ (70%) and 4.0 mL of H₂O₂ (30%) were added to each sample and the samples were allowed to dry in the digestion block at 120°C. After cooling, the residue was solubilized in hot distilled water, filtered and used for analysis. Vanadomolybdate colorimetric method (Stewart, 1989) was followed for total phosphorus (TP) determination using a Peak Instruments, C-7100 UV/vis spectrophotometer. Total potassium (TK) was measured using a flame photometer (Sherwood M410). Nutrient elements such as total calcium (TCa), total magnesium (TMg), total iron (TFe), total manganese (TMn), total copper (TCu), total zinc (TZn) and trace elements such as total lead (TPb), total chromium (TCr), total arsenic (TAs) and total cadmium (TCd) were determined using an axially viewed ICP trace analyzer emission spectrometer (Thermo Scientific iCAP 7000 Series). Total carbon% (TC) and total nitrogen as N% (TN) were determined using a CHN analyzer (Perkin Elmer 2400 Series II CHNS Analyzer).

Co-composting process

Composting was carried out by incorporating cattle manure, green leaves of *Gliricidia sepium* and plant dry materials (paddy straw and banana stem) in 1:1:1 ratio with or without biochar. In alignment with Antonangelo *et al.* (2021), who suggested an optimal biochar loading rate between 10–15% because of potential desiccation due to excessive aeration with higher rates (20–27%), a 10% biochar loading rate was selected for this study. Four types of composts were produced: Control - compost without biochar or PL (C), co-compost with 10% (w/w) PL (C_{PL}), co-compost with 10% (w/w) poultry litter biochar (CC_{PLB}), and co-compost with 10%

(w/w) poultry litter biochar co-pyrolyzed with 5% ERP (CC_{PLB-ERP}). The closed heap method recommended by the Department of Agriculture was followed for the composting and mixtures were turned at monthly intervals (Department of Agriculture, 2021). Three sets of compost heaps were prepared for each treatment and maintained as three replicates. After 4 months, the composting process was completed and samples were taken for analysis.

Chemical analysis

Samples were drawn from each compost replicate after air-drying and sieved using a 2 mm sieve, for analysis. Composts were characterized for physical and chemical parameters specified in SLS 1635 using methods specified therein (SLSI, 2019). pH and electrical conductivity (EC) were determined in 1:5 sample: water (w/v) suspension using pH meter and EC meter. Total carbon% (TC) and total nitrogen as N% (TN) were determined using a CHN analyzer (Perkin Elmer 2400 Series II CHNS Analyzer).

Dry ashing followed by acid digestion method described in Enders et al. (2012) was followed for the extraction of total elements. Mehlich-3 (M3) extraction was followed to measure the extractable element contents. Phosphorus content as P₂O₅% (P) in the extracts was determined using the spectrophotometer (Peak Instruments, C-7100 UV/vis) and potassium content as K₂O% (K) was measured using the flame photometer (Sherwood M410). Other nutrient contents such as Ca, Mg, Fe, Cu, Zn, Mn and heavy metals As, Cd, Pb, Cr were measured using the ICP-OES (Thermo Scientific iCAP 7000 Series). Sand contents of compost samples were measured according to standard procedures as a SLSI standard requirement.

Statistical analysis

After the exploratory data analysis, one-way ANOVA on each measured parameter was conducted using the GLM procedure in the Statistical Analysis Software (SAS) to determine statistically significant

differences among the means of different treatments. Mean comparisons were done using Duncan's Multiple Range Test at a $p < 0.05$ probability level.

RESULTS AND DISCUSSION

Biochar yield

The poultry litter biochar and co-pyrolyzed poultry litter biochar with ERP yields were around 58–60%. Biochar yield and its physical and chemical properties depend largely on pyrolysis conditions as well as the composition of the feedstock biomass (Enders et al., 2012). Katuwal et al. (2022) reported a biochar yield range of 37.5–52.8% when PL was contained in oxygen free containers and heated in a furnace at different temperatures. The batch pyrolysis reactor used in this study comprised a two-chamber configuration: an outer cylinder for energy generation and the other for biochar pyrolyzation. Illankoon et al. (2023) observed an average biochar yield of 49% in a pyrolyzer of a similar type when paddy husk was used as the raw material and at temperatures ranging between 400 and 600 °C. Generally, biochar yield decreases with increasing pyrolysis temperature and heating rate. Factors such as the quality of the feedstock material and a slower heating rate may have contributed to the comparatively higher biochar yields, we observed in this study.

Basic properties of biochar

The pH values increased significantly in biochar compared to raw poultry litter, and values for all materials indicated alkalinity (Table 1). Higher pH in biochar compared to that of PL could be due to the removal of acidic functional groups and the enrichment of salts of alkali and alkaline earth elements during carbonization (Singh et al., 2017). Electrical conductivity (EC) decreased in biochar (8.44 dS/m) compared to raw poultry litter (8.59 dS/m), and the addition of ERP further significantly reduced EC (3.92 dS/m). The lower EC in PL-ERP co-pyrolyzed biochar may be due to changes in the composition of free cations in the biochar, resulting from the formation of stable

Table 1. Mean $\pm$ Standard deviation of some basic physicochemical properties and total nutrient contents of poultry litter and biochar samples

Parameter†	PL	PLB	PLB-ERP	P value
pH (1:10)	9.02 ^b $\pm$ 0.04	10.54 ^a $\pm$ 0.33	10.42 ^a $\pm$ 0.02	0.0015
EC (dS/m)	8.59 ^a $\pm$ 0.07	8.44 ^a $\pm$ 0.01	3.92 ^b $\pm$ 0.04	<0.0001
Sand%*	13.60 ^b $\pm$ 1.27	18.57 ^a $\pm$ 0.33	18.76 ^a $\pm$ 1.52	0.0182
Total C% (TC)*	29.26 ^a $\pm$ 4.44	27.95 ^a $\pm$ 3.17	24.27 ^a $\pm$ 2.23	0.2774
C:N*	7.92 ^c $\pm$ 1.15	20.33 ^b $\pm$ 0.77	23.97 ^a $\pm$ 2.19	0.0002
Total N% (TN)*	3.77 ^a $\pm$ 1.11	1.37 ^b $\pm$ 0.13	1.02 ^b $\pm$ 0.12	0.0028
Total P as P ₂ O ₅ % (TP)*	4.28 ^c $\pm$ 0.09	6.2 ^b $\pm$ 0.14	8.23 ^a $\pm$ 0.15	<0.0001
Total K as K ₂ O% (TK)*	2.32 ^b $\pm$ 0.06	4.16 ^a $\pm$ 0.02	2.47 ^b $\pm$ 0.33	0.0009
Total Ca as CaO%*	2.64 ^c $\pm$ 0.12	5.68 ^b $\pm$ 0.31	6.32 ^a $\pm$ 0.26	0.0002
Total Mg as MgO%*	0.57 ^b $\pm$ 0.25	1.40 ^a $\pm$ 0.22	1.02 ^{ab} $\pm$ 0.17	0.0406
Total Fe%*	0.23 ^b $\pm$ 0.01	0.25 ^b $\pm$ 0.03	0.44 ^a $\pm$ 0.03	0.0118
Total Mn (mg/kg) *	288.90 ^c $\pm$ 3.60	353.51 ^b $\pm$ 15.88	471.79 ^a $\pm$ 27.78	0.0014
Total Zn (mg/kg) *	163.70 ^a $\pm$ 19.82	208.88 ^a $\pm$ 31.23	207.39 ^a $\pm$ 16.61	0.0672
Total Cu (mg/kg) *	14.20 ^c $\pm$ 0.87	23.74 ^b $\pm$ 1.44	36.73 ^a $\pm$ 4.46	0.0027

† PL: Poultry Litter, PLB: Poultry Litter Biochar, PLB-ERP: Co-pyrolyzed Poultry Litter Biochar, Numbers with the same letter across a row are not significantly different at $p < 0.05$, * By dry weight basis

mineral complexes. Dissanayake *et al.* (2018) also reported a slight reduction in EC when RHB was co-pyrolyzed with ERP compared to RHB without ERP.

The total C content decreased from 29% in the initial poultry litter to 28% in PLB and 24% in the PLB-ERP, reflecting carbon loss during the pyrolysis process although they were not statistically different. A similar trend was reported by Katuwal *et al.* (2022), who observed a significant reduction in total C from 46.3% in raw litter to 37.74–44.49% in biochar. However, Cantrell *et al.* (2012) reported that pyrolysis of animal manure at 350 °C resulted in a significant increase in carbon content compared to the raw feedstocks. They also observed that increasing the pyrolysis temperature beyond 350 °C, has slightly reduced the carbon content of the resulting biochar, with an average value of 48.8 $\pm$ 5.00 wt.%. Song and Guo (2012) have also observed a reduction in C content in PLB while the ash content increases, as the peak pyrolysis temperature increases from 300 to 600 °C. Comparatively low C contents in PLBs made in this study could be due to low C in the PL and high ash content resulting from to high pyrolysis temperature.

Results indicated that the total N content decreased significantly ($p < 0.05$) from 3.77% in raw poultry litter to 1.37% in PLB and 1.02% in PLB-ERP (Table 1). Song and Guo (2012) reported that about 20 to 98% of N in PL can be lost when the pyrolysis temperature increased from 300 to 600 °C. Total P₂O₅ content increased in both biochar relative to raw poultry litter (4.28%). Conversion of poultry litter into biochar increased total P₂O₅ by approximately 1.5-fold in PLB and 1.9-fold in PLB-ERP. The total K₂O content increased markedly in PLB compared to both raw poultry litter and PLB-ERP, indicating that pyrolysis enhanced K₂O concentration by approximately 80% relative to the feedstock. In contrast, co-pyrolysis with Eppawala rock phosphate (ERP) resulted in a significant reduction in total K₂O content compared to PLB alone. Additionally, potassium losses through volatilization under ERP-amended pyrolysis conditions could not be excluded, especially when the temperature increased beyond 500 °C (Teixeira *et al.*, 2015; Tumbure *et al.*, 2020). However, contrary to the present findings, Dissanayake *et al.* (2018) reported an increase in total K content in rice husk biochar with ERP addition and with

increasing pyrolysis temperature up to 650°C.

Total CaO and MgO contents increased by two-fold following pyrolysis. Pyrolysis also resulted in the enrichment of micronutrients (Fe, Mn and Cu) relative to raw poultry litter. Except for Zn, all other micronutrients increased significantly with ERP addition compared to PLB alone. A similar trend was reported by Sikder and Joardar (2019), who observed a slight increase in total Fe concentration in poultry litter biochar relative to the raw litter. Numerous studies have demonstrated that pyrolysis generally concentrates mineral elements and heavy metals in biochar because carbon-based elements vaporize and non-combustible mineral elements are left behind in the residue mass (Cantrell *et al.*, 2012; Hadroug *et al.*, 2019).

Potentially toxic trace elements

Total Pb and Cr concentrations increased significantly with pyrolysis (Table 2). Total Cd concentration did not vary among different raw materials used for co-compost production. In contrast, total As content in PLB-ERP increased by 2.4-fold when compared to that of PLB, likely attributable to the incorporation of high-As-containing ERP. Katuwal *et al.* (2022) reported that total As content in poultry litter biochar varied between 0.78–1.27 mg/kg and there was no effect of pyrolysis temperature on the content. As concentrations in PLB were comparable to values reported by them.

Compost yield

Compost yield (w/w) was evaluated based on the proportion of final compost relative to the initial raw materials (Figure 1). Compost yields varied among compost mixtures and highest yield was in the CC_{PLB-ERP} (46.9%), followed by CC_{PLB} (46.0%). Compost mixtures without biochar, i.e., C and CC_{PL}, resulted in lower yields, 34.3% and 34.1%, respectively. The increased yield in biochar-added treatments was attributed to biochar acting as a bulking agent thereby increasing the yields of co-compost.

Basic properties in different composts

All composts showed slightly alkaline pH values except CC_{PL} which had a neutral pH (Table 3). However, the pH values of all types of composts were not significantly different ($p>0.05$). Rong *et al.* (2019) composted poultry manure and corn leaf (2:1 ratio), with and without wheat stalk and rice husk biochar, and observed that biochar-amended compost mixtures had higher pH value than controls. They attributed the high pH in co-composted biochar to the acid-neutralizing ability of biochar and larger specific surface area that absorbs more alkaline NH₃. No significant difference among composts we made could be due to the already high pH of the materials used (Table 1).

Sand content in compost samples varied from 16.3 to 19.6% and sand in commercially purchased poultry litter and cow dung could have contributed to high sand contents in the composts. There was no significant variation in sand content among treatments and the values were aligned with the maximum allowable sand content of the Sri Lanka Standard for compost made from raw materials of agricultural origin (SLSI, 2019). Electrical conductivity was similar in all the treatments, however co-composted treatments recorded slightly higher values compared to SLSI standard for EC (<4.0 dS/m in 1:5 suspension), probably due to high basic cation contents in PL, PLB and PLB-ERP. Total carbon (C) content was similar among compost types (Table 3). Several studies however concluded that co-composting with biochar increases the total C contents in the composts (Theeba *et al.*, 2016; Agegnehu *et al.*, 2016; Nain *et al.*, 2022). These studies had used C-rich biochar types for co-composting resulting in increased C contents in resultant composts. In our study the TC values of PLB were very low (Table 1) hence, the C contents did not increase in CC_{PLB} and CC_{PLB-ERP} significantly.

C:N ratios of C and C_{PL} were significantly lower compared to composts made with biochar, which were within the SLSI standards (10 – 25). The lower C:N ratio also

Table 2. Potentially toxic trace elements in poultry litter and biochar samples

Parameter†	PL	PLB	PLB-ERP	P value
Total As (mg/kg)	0.64 ^b ±0.11	1.13 ^b ±0.21	3.87 ^a ±0.60	0.0011
Total Cd (mg/kg)	0.12 ^a ±0.02	0.20 ^a ±0.04	0.23 ^a ±0.07	0.1058
Total Pb (mg/kg)	0.90 ^c ±0.01	1.33 ^b ±0.23	2.13 ^a ±0.14	0.0065
Total Cr (mg/kg)	3.53 ^b ±0.23	6.56 ^a ±0.77	7.77 ^a ±1.13	0.0153

† PL: Poultry Litter, PLB: Poultry Litter Biochar, PLB-ERP: Co-pyrolyzed Poultry Litter Biochar Numbers with the same letter across a row are not significantly different at $p = 0.05$.

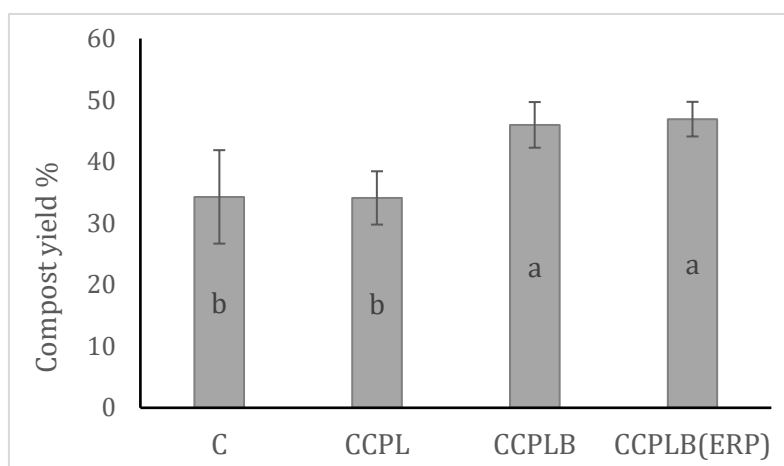


Figure 1. Compost yield in different compost mixtures Compost (C), Co-composted poultry litter (CC_{PL}), co-composted PL biochar (CC_{PLB}) and co-composted co-pyrolyzed PL biochar (CC_{PLB-ERP}). Bars having same lowercase letters are not significantly different at $P < 0.05$. Error bars on each bar represent the $\pm$ SE ($n=3$).

indicated their vulnerability to faster decomposition once applied to soil. The C:N ratio is commonly used as an indicator of compost maturity and stability. However, Oviedo-Ocana *et al.* (2022) noted that this ratio is more closely related to the initial substrate than to maturity.

Total nutrient contents

A significantly high total N content was observed in CC_{PL} with the incorporation of PL (Table 3). However, when co-composted with PLB and PLB-ERP, a significant increase in N content was not observed. This is contrary to Antonangelo *et al.* (2021), who reported that biochar amended compost usually shows higher total nitrogen (N) content than compost without biochar. Theeba *et al.* (2016) found that the N in compost was significantly preserved in rice

husk biochar incorporated composts mainly during the thermophilic phase as compared to control. Steiner *et al.* (2010) reported a similar finding, where the addition of biochar (10–20%) in compost significantly reduced the losses of N by 7.7–23.2% compared to the treatment without treatment. Although the above studies showed nitrogen preservation in co-composts with biochar, the lack of significant increase in total N in CC_{PLB} and CC_{PLB-ERP} in our study could be due to the low biochar rates added in composting.

Marked differences were observed in total phosphate concentrations among the four composts (Table 3). Biochar application as a raw material for composting significantly increased the total P₂O₅ content, in CC_{PLB} by 208% and CC_{PLB-ERP} by 270% when compared to the control (C).

Table 3. Mean± Standard deviation of some basic physiochemical properties and total nutrient contents of different compost samples and respective SLSI standard (SLSI, 2019)

Parameter†	C	CC _{PL}	CC _{PLB}	CC _{PLB-ERP}	p value	SLSI
pH (1:5)	7.23 ^a ±0.09	6.91 ^a ±0.20	7.39 ^a ±0.67	7.82 ^a ±0.31	0.0809	6.5–8.5
EC (dS/m) (1:5)	3.76 ^a ±1.51	5.66 ^a ±0.94	4.27 ^a ±1.05	4.75 ^a ±1.64	0.1553	<4.0
Sand%	19.58 ^a ±1.12	16.82 ^a ±2.61	16.31 ^a ±4.68	16.67 ^a ±0.23	0.4934	<20
Total C%	17.72 ^a ±2.72	20.21 ^a ±1.90	21.21 ^a ±4.80	22.19 ^a ±2.42	0.3306	-
C:N	9.98 ^b ±1.07	8.84 ^b ±0.23	12.64 ^a ±0.54	12.58 ^a ±0.60	0.0021	10-25
Total N%	1.77 ^b ±0.11	2.29 ^a ±0.21	1.69 ^b ±0.42	1.76 ^b ±0.16	0.0297	>1.0
Total P as P ₂ O ₅ %	0.83 ^c ±0.08	1.59 ^b ±0.34	2.55 ^a ±0.39	3.06 ^a ±0.28	0.0003	> 0.5
Total K as K ₂ O%	1.20 ^a ±0.20	1.72 ^a ±0.40	1.59 ^a ±0.31	1.77 ^a ±0.29	0.0684	> 1.0
Total Ca as CaO%	1.03 ^b ±0.09	1.69 ^b ±0.75	3.19 ^a ±0.43	3.29 ^a ±0.22	0.0035	> 0.7
Total Mg as MgO%	0.33 ^b ±0.01	0.44 ^b ±0.07	0.64 ^a ±0.09	0.61 ^a ±0.01	0.0033	> 0.5
Total Fe%	1.56 ^a ±0.31	1.28 ^a ±0.11	1.26 ^a ±0.51	1.18 ^a ±0.16	0.2698	-
Total Mn (mg/kg)	665.0 ^a ±72.6	597.4 ^a ±58.1	584.7 ^a ±80.5	575.6 ^a ±66.5	0.1399	-
Total Zn (mg/kg)	120.4 ^a ±13.9	166.0 ^a ±47.7	140.1 ^a ±20.9	181.3 ^a ±47.3	0.3278	-
Total Cu (mg/kg) *	46.98 ^a ±2.27	43.20 ^a ±8.90	38.99 ^a ±5.84	36.10 ^a ±4.63	0.2583	-

† C: compost, CC_{PL}: Co-composted poultry litter, CC_{PLB}: Co-composted PL biochar, CC_{PLB-ERP}: Co-composted co-pyrolyzed PL biochar; EC: Electrical Conductivity. Numbers with the same letter across a row are not significantly different at $p = 0.05$

Total K₂O content was not increased with incorporating poultry litter and poultry improved its retention in biochar due to their negatively charged surfaces.

Total CaO and Total MgO contents were significantly increased in biochar applied composts, CC_{PLB} and CC_{PLB-ERP}. Application of PLB and PLB-ERP enhanced the total CaO content by 210% and 219% respectively when compared to the control (C). Similarly, the total MgO content in CC_{PLB} and CC_{PLB-ERP} also indicated a 94% and 85% increase, respectively, when compared to the control (C). This could be due to the capacity of the biochar surface has the capacity to retain cations on its negatively charged surfaces in addition to high Ca and Mg contents in PL, PLB and PLB-ERP. No significant differences were observed among the compost treatments for the total micronutrient contents (Fe, Mn, Zn, and Cu). Rombel *et al.* (2022) reported that due to the diversity of functional groups on the surface of biochars, they can absorb various nutrient ions, including nitrate, ammonium, potassium, manganese and phosphate and change their availability in composts that contain biochar.

Extractable nutrient contents

Mehlich-3 Extractable P and K contents were significantly increased in biochar applied composts (Table 4). Co-composting with PLBs increased the proportion of M3 extractable P and K contents almost by two-fold when compared to co-composting with PL. This could be due to the higher extractable P and K contents in PLB and PLB-ERP compared to that of PL (data not presented) and/or faster mineralization of labile organic matter during the composting process in biochar incorporated composts (Ravindran *et al.*, 2022; Parra-Orobio *et al.*, 2023). Although extractable Fe content was decreased in biochar applied treatments, extractable Mn and Zn contents were increased with biochar application. Therefore, PLB and PLB-ERP incorporation as a raw material for co-composting improved the available nutrients of the compost. However, contradictory observations were made elsewhere. According to Agegnehu *et al.* (2016) there was not much variation in extractable nutrients K, Ca, Mg in compost (1.62, 4.15, 2.38 cmol₍₊₎/kg) compared to co-composted biochar (1.74, 4.15, 2.30 cmol₍₊₎/kg). They had used low nutrient containing willow wood biochar in composting while we had used nutrient rich PLB.

Table 4. Mean±Standard deviation of Mehlich-3 extractable (M3) macro and micro nutrient contents in different compost samples. Values within the parenthesis denotes the extractable nutrient as a percentage of total nutrient.

Parameter†	C	CC _{PL}	CC _{PLB}	CC _{PLB-ERP}	p value
M3-P as P ₂ O ₅ %*	0.08 ^b ±0.02 (9.6)	0.14 ^b ±0.02 (8.8)	0.29 ^a ±0.02 (11.4)	0.31 ^a ±0.07 (10.1)	0.0008
M3-K as K ₂ O%*	0.16 ^c ±0.01 (13.3)	0.32 ^b ±0.02 (18.6)	0.58 ^a ±0.11 (36.5)	0.68 ^a ±0.10 (38.4)	0.0006
M3-Ca%*	0.36 ^c ±0.01 (35.0)	0.47 ^{bc} ±0.14 (27.8)	0.59 ^{ab} ±0.03 (18.5)	0.61 ^a ±0.05 (18.5)	0.0100
M3-Mg%*	0.13 ^a ±0.03 (39.4)	0.19 ^a ±0.09 (43.2)	0.20 ^a ±0.01 (31.3)	0.22 ^a ±0.02 (36.1)	0.1283
M3-Fe (mg/kg)*	165.52 ^b ±7.37 (10.6)	188.07 ^a ±5.56 (14.7)	132.80 ^c ±0.85 (10.5)	115.83 ^d ±6.36 (9.8)	<0.000 1
M3-Mn (mg/kg)*	78.33 ^b ±3.89 (11.8)	50.23 ^c ±3.39 (8.4)	105.70 ^a ±4.81 (18.1)	118.50 ^a ±12.12 (20.6)	<0.000 1
M3-Zn (mg/kg)*	36.78 ^b ±2.11 (30.5)	62.68 ^a ±9.59 (37.8)	52.14 ^a ±3.71 (37.2)	58.56 ^a ±1.73 (32.3)	0.0079
M3-Cu (mg/kg)*	2.22 ^a ±0.28 (4.7)	1.81 ^a ±0.38 (4.2)	2.05 ^a ±0.23 (5.3)	1.99 ^a ±0.66 (5.5)	0.7806

† C: compost, CC_{PL}: Co-composted poultry litter, CC_{PLB}: Co-composted PL biochar, CC_{PLB-ERP}: Co-composted co-pyrolyzed PL biochar
Numbers with the same letter across a row are not significantly different at $p = 0.05$ * on dry weight basis

Table 5. Potentially toxic trace elements in different compost samples as against the respective SLSI standard

Parameter†	C	CC _{PL}	CC _{PLB}	CC _{PLB-ERP}	p value	SLSI 2019
Total As (mg/kg)*	0.93 ^b ±0.18	0.90 ^b ±0.17	0.79 ^b ±0.35	1.43 ^a ±0.14	0.0135	max 3
Total Cd (mg/kg)*	0.57 ^a ±0.06	0.51 ^a ±0.15	0.47 ^a ±0.11	0.46 ^a ±0.09	0.3399	max 3
Total Pb (mg/kg)*	15.86 ^a ±0.90	14.47 ^a ±4.49	9.33 ^b ±0.40	9.27 ^b ±1.00 22.79 ^a ±3.1	0.0269 0.2300	max 50 max 50
Total Cr (mg/kg)*	31.51 ^a ±4.84	25.17 ^a ±2.29	23.19 ^a ±9.04	9		

† C: compost, CC_{PL}: Co-composted poultry litter, CC_{PLB}: Co-composted PL biochar, CC_{PLB-ERP}: Co-composted co-pyrolyzed PL biochar
Numbers with the same letter across a row are not significantly different at $p = 0.05$, * On dry weight basis

Potentially toxic trace elements

All the tested toxic elements were within the maximum permissible level according to the SLSI, 2019 standards. Total Cd and Cr concentrations showed no variations among different composts (Table 5). Similar trends were observed by Casini *et al.* (2021) for Cr, who reported that compost digestate with biochar application showed less Cr levels (6 mg/kg) compared to without biochar (20 mg/kg). However, total As content was significantly higher in the CC_{PLB-ERP} treatment, likely due to high As content in ERP, which was indicated by the PLB-ERP as well (Table 2).

In contrast, total Pb content was significantly reduced in the biochar-amended treatments (CC_{PLB} and CC_{PLB-ERP}). Agegnehu *et al.* (2017) elaborated that biochar has affinity to certain heavy metals such as Zn, Cu, Ni, Pb, and As due to its surface physicochemical properties that promote physical sorption, complex formation, precipitation, ion exchange, and electrostatic sorption.

The findings demonstrated that converting poultry litter into biochar and incorporating it in to the composting process could significantly improve the properties of compost. All co-composts made in this study

had higher EC values than the SLSI standards, requiring some formulation changes in future studies. The increased concentrations of P, K, Ca and Mg indicated the PLB can serve as an effective nutrient-rich amendment for compost production. This approach also enhanced compost yield, thereby improving resource use efficiency and providing a potential solution for direct disposal of waste generated in poultry farming. The results suggested that PLB can be utilized as a sustainable strategy to recycle nutrients and reduce dependence on inorganic P and K fertilizers.

CONCLUSIONS

Conversion of PL into biochar has significantly reduced the total N content but increased the total P, K, Ca, Mg, Mn, Zn and Cu contents. Co-pyrolysis of PL with ERP has further increased C:N ratio, total P, Ca, Fe, Mn, Cu, and As contents. Co-composting with PLBs (with or without ERP) could increase the compost yield (36% w/w). Compost made without co-composting has complied with SLSI standards except for C:N ratio and total Mg content. Incorporation of PLBs can increase total phosphorus content in composts by approximately 2–3-fold compared to the compost produced without PL and PLB. However, ERP incorporation did not significantly increase the total P content in compost. Additionally, applying PLB and PLB-ERP can enhance the total calcium and magnesium contents in composts but reduces total nitrogen contents due to loss of N in PL during the pyrolysis process. Concentration of all the heavy metals is within the permissible levels of SLSI standards for all composts made from raw materials of agricultural origin. The results suggested that the application of poultry litter biochar (10% w/w as a raw material) during composting can enhance the quality of the compost considering total P, Ca and Mg and exchangeable P, K, Mg. However, some modifications to the tested compost formulations are needed to reduce the EC in all co-composts below the maximum permissible level of 4 dS/m in SLSI standards. Future research should also assess the effect of biochar addition with different rates and biomasses to further

improve the quality of the composts produced, monitor the greenhouse gas emissions after their soil application, nitrogen dynamics and changes in microbial community in soil.

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DECLARATION OF COMPETING INTEREST

The authors declare that there are no competing interests.

DATA AVAILABILITY STATEMENT

The data presented in this study are available upon request from the corresponding author.

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