

Effectiveness of co-composted biochar on soil acidity and maize growth in acidic soil of Bangladesh

Al-Mushabber Asif^{1§}, Farhana Rahman^{1§}, Jackson Nokh Nokh², Tanja Mimmo^{3,4}, M. Abdulaha-Al Baquy^{1,3*}

¹Department of Soil Science, Hajee Mohammad Danesh Science and Technology University, Dinajpur, 5200, Bangladesh

²College of Life Science and Oceanography, Shenzhen University, Shenzhen, 518060, PR China

³Competence Centre for Plant Health, Free University of Bolzano, Bolzano, 39100, Italy

⁴Faculty of Agricultural, Environmental and Food Sciences, Free University of Bolzano, Bolzano, 39100, Italy

[§] These authors contributed equally * Correspondence: mabaquy@hstu.ac.bd

Abstract

Biochar has attracted enormous interest in enhancing agricultural productivity in acidic soils but its high cost limits widespread adoption. Thus, new amendments such as co-composted biochar (COMBI) are gaining the spotlight, however, the effect of COMBI on plant growth, nutrient uptake, and the mechanism for ameliorating soil acidity remains unclear. This study aimed to investigate the efficacy of COMBI compared to locally available amendments in improving soil properties, nutrient uptake, and maize growth in acidic soil. A pot study was established in a net house with six treatments: control, compost, ash, biochar, poultry litter, and COMBI, applied at 10% (w/w) in triplicate, and replicated in the field experiment. The results showed that the application of amendments increased soil pH and decreased exchangeable acidity. COMBI showed a significant ameliorating effect on soil acidity, increasing soil pH by 1.53 units compared to the control. The effect of COMBI on soil cation exchange capacity (CEC) and base cations was significantly larger compared to the control and other treatments ($p < 0.05$). Also, the application of amendments enhanced the uptake of N, P, K, Ca, and Mg by maize and thus promoted maize plant height, shoot, root, and total dry weight in the pot study. On the nutrient uptake potential of maize, COMBI showed the most significant effect compared to all other treatments. This was translated to a significant increase in total dry biomass (186%) after 40 days of maize growth for COMBI ($p < 0.05$), followed by biochar (89%), poultry litter (50%), compost (47%), and ash (41%). Similar to the pot study, the application of amendments enhanced nutrient uptake and maize growth in the field, and the application of COMBI significantly increased shoot dry weight by 54% after 60 days of maize growth ($p < 0.05$), followed by biochar (38%), compost (21%), poultry litter (15%), and ash (6%). Correlation analyses revealed strong positive relationships between improved soil properties such as pH, organic matter and CEC, and plant growth parameters, particularly nutrient uptake. Therefore, COMBI is a promising alternative for acid soil amelioration and crop growth promotion.

Keywords: Soil health, acidification, composted biochar, soil pH, exchangeable acidity, plant nutrients

1. Introduction

Plant essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) are often limited in low-fertile acidic soils and thereby hamper crop production. In Bangladesh, mineral fertilizers are widely used to maintain soil fertility and crop production in acidic soils. Global attention has grown regarding the unsustainable use of mineral fertilizers, as natural P reserves may be depleted within 50–100 years (Cordell et al., 2009). Despite high demand, nutrient use efficiency in crop plants is only 15–20% due to fixation or leaching of nutrients and promoting eutrophication process (Zhang et al., 2019; Othman et al., 2018). Moreover, improper management of biowastes from agriculture, livestock, and domestic sources further contributes to soil pollution. Converting these biowastes into compost offers a sustainable solution (Nkoa, 2014).

Biochar, a carbon-rich byproduct of biomass pyrolysis, has emerged as a promising soil amendment due to its high porosity and nutrient retention capacity (Lehmann and Joseph, 2015). Nutrient enrichment of biochar through adsorption or organic coating can enhance its effectiveness, allowing for slow nutrient release and improved plant uptake (Li et al., 2020). Co-composted biochar (COMBI) represents a synergistic approach combining the benefits of compost and biochar; however, its impact on nutrient availability in low-fertile acidic soils remains underexplored (Antonangelo et al., 2021; El-Naggar et al., 2019).

Highlighting the interest in adopting COMBI for sustainable agriculture, it is essential to find out how nutrient cycling is affected in low-fertility soil and their associated effects related to nutrient uptake by plants due to changing soil environment after composted biochar application. This study, therefore, aimed to evaluate the effects of co-composted biochar on nutrient availability, retention, and uptake by maize (*Zea mays*) in low-fertile acidic soils. Specifically, the objectives were: (1) to investigate the impact of co-composted biochar on soil P availability in low-fertility soil, (2) to observe the soil P retention under varied organic carbon (C) inputs, and finally, and (3) to determine the P uptake by maize plants in low-fertility soil after the incorporation of co-composted biochar.

2. Materials and methods

This study was conducted at the research field of Department of Soil Science, Hajee Mohammad Danesh Science and Technology University, Bangladesh. Soil was collected from the uppermost layer of the field (0–15 cm) for pot study.

The same site was considered for field study. Following collection, the samples were air-dried and passed through a 1-mm sieve. Biochar was prepared from rice husk using a biochar kiln at 400 °C for a period of 3 h. Compost, poultry litter and ash were collected at the locally available market. To prepare the co-composted biochar (COMBI), compost, ash, poultry litter and biochar were mixed thoroughly in equal proportions of 1:1:1:1. For pot study at net house, the 4.0 kg of soil was placed in each separate plastic pot (6.0 L). A basal dose of fertilizers was applied in each pot @ 66 g, 44 g, and 34 g per pot as urea, triple super phosphate and muriate of potash, respectively. The trial encompassed 6 treatments: (a) control (no amendment), compost, ash, biochar, poultry litter, and COMBI. The treatments were employed to each pot at 10% (w/w). Three replications of the treatments were established in a completely randomized design. The uniform five maize germinated seeds were placed in each pot with maintaining 70% of the water holding capacity. After 40 days of maize growth, shoots and roots of the plants were harvested. Plant height was measured using a scale with an error of ± 0.1 cm. The collected samples were subjected to a thorough rinsing using distilled water, followed by oven dry for 2 h at 105 °C and then at 80 °C until a stable weight was achieved. The plant shoots were ground using a grinding apparatus and thereafter preserved for future examination. After crop harvest, soil samples were collected for further analysis.

A field study was established with the same treatments as pot study. The size of the experimental plot was 1 m x 1 m for each treatment. There was 30 cm distance from each plot and block. During the field preparation, a basal dose of urea, triple super phosphate and muriate of potash was applied @ 66 g, 44 g, and 34 g per plot, respectively. The 15 germinated seeds were transferred to each plot and harvested at 60 days of crop growth. The height of the plants was measured using a measuring scale. The collected plant samples were processed as mentioned above as pot study for further analysis.

The pH measurement was conducted using a glass electrode pH meter, with a 1:25 (w/v) ratio (Pansu and Gautheyrou, 2006). The electrical conductivity was measured using an electrical conductivity meter. Soil organic matter was measured by Walkley and Black method and CEC was determined using the ammonium acetate method at pH 7.0. The CEC was measured by the ammonium acetate method at pH 7.0 (Pansu and Gautheyrou, 2006). The Ca^{2+} and Mg^{2+} were measured by using atomic absorption spectrophotometer. The K^+ and Na^+ were measured by using flame photometer. The nutrient contents of plant samples were analyzed using an Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES) technique (Gao et al, 2016).

Statistical analyses and graphs were prepared using SPSS (v22.0, USA) and OriginPro (v2018, USA). Data were presented as mean $\pm$ standard deviation ($n = 3$). Differences and interactions among treatments were evaluated using ANOVA under a multivariate general linear model.

3. Results

3.1 Effect of amendments on plant and soil properties: Pot study

Significant differences were observed in maize growth parameters across treatments (Table 1). The COMBI treatment showed the highest plant height (95.57 cm pot⁻¹) and total dry biomass (16.37 g pot⁻¹), which were significantly higher than all other treatments ($p < 0.05$). Biochar also enhanced growth, with plant height and biomass of 84.50 cm and 10.81 g pot⁻¹, respectively, outperforming compost, ash, and poultry litter. The control showed the lowest values (56.28 cm and 5.71 g pot⁻¹). Similarly, COMBI yielded the highest shoot (13.61 g pot⁻¹) and root (2.76 g pot⁻¹) dry weights, followed by biochar (8.66 and 2.15 g pot⁻¹), while the control remained lowest. Nutrient uptake by maize also varied significantly among treatments. COMBI recorded the highest uptake of N (507.59 mg pot⁻¹), P (66.69 mg pot⁻¹), K (489.06 mg pot⁻¹), Ca (80.42 mg pot⁻¹), and Mg (33.49 mg pot⁻¹). Biochar also improved K and Mg uptake, whereas compost, ash, and poultry litter resulted in moderate increases compared with the control.

Soil properties also responded positively to the amendments. The highest soil pH was observed under biochar (6.52) and COMBI (6.44), both significantly greater than the control (4.91). COMBI further increased soil organic matter (2.06%) and CEC (9.82 cmol kg⁻¹), followed by biochar and compost, while the control recorded the lowest values. COMBI also showed the highest exchangeable cations, including Ca (7.18 cmol kg⁻¹), Mg (3.73 cmol kg⁻¹), K (2.07 cmol kg⁻¹), and a slight increase in Na (0.49 cmol kg⁻¹). Compost and biochar provided moderate improvements, whereas the control exhibited the poorest soil quality. Overall, COMBI consistently outperformed all other amendments in enhancing maize growth, nutrient uptake, and post-harvest soil fertility.

Table 1: Effect of different soil amendments on plant growth parameters and nutrient uptake by maize plants in pot study. The data were presented as means $\pm$ SE and means sharing dissimilar letters in a column are statistically significant and similar letters are non-significant ($p < 0.05$).

Treatments	Plant height (cm pot ⁻¹)	Shoot dry weight (g pot ⁻¹)	Root dry weight (g pot ⁻¹)	Total dry biomass (g pot ⁻¹)	N	Nutrient uptake by maize plant (mg pot ⁻¹)			
						P	K	Ca	Mg
Control	56.28 d	4.47 d	1.24 d	5.71 d	158.68 d	14.74 c	146.06 c	29.99 d	15.14 c
Compost	79.09 bc	6.98 c	1.46 cd	8.44 c	253.02 c	31.99 b	263.64 b	39.15 c	18.64 c
Ash	73.48 c	6.75 c	1.35 cd	8.10 c	245.94 c	32.72 b	259.00 b	38.40 c	18.88 c
Biochar	84.50 b	8.66 b	2.15 b	10.81 b	318.75 b	28.82 b	313.39 b	64.80 b	26.79 b
Poultry Litter	71.22 c	7.08 c	1.49 c	8.57 c	270.57 c	34.19 b	290.26 b	38.57 c	17.02 c
COMBI	95.57 a	13.61 a	2.76 a	16.37 a	507.59 a	66.69 a	489.06 a	80.42 a	33.49 a

Table 2: Effect of different amendments on soil properties after maize crop harvest for pot study. The data were presented as means $\pm$ SE and means sharing dissimilar letters in a column are statistically significant and similar letters are non-significant ($p < 0.05$).

Treatments	pH	Δ pH	Exchangeable acidity	OM	CEC	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺
				%			cmol kg ⁻¹		
Control	4.91 d	-	31.4 a	0.80 c	4.33 d	5.43 c	2.17 d	0.37 d	0.43 b
Compost	6.19 b	1.28	14.18 d	1.79 a	6.16 c	6.40 b	3.73 a	1.81 ab	0.52 b
Ash	5.73 c	0.82	22.37 b	0.93 c	4.70 d	5.61 c	2.33 cd	1.02 c	0.40 b
Biochar	6.52 a	1.61	9.19 e	1.88 a	7.59 b	5.36 cd	3.07 ab	0.92 c	0.68 a
Poultry Litter	6.26 ab	1.35	16.96 c	1.34 b	7.04 b	4.76 d	2.93 bc	1.62 b	0.43 b
COMBI	6.44 ab	1.53	11.93 d	2.06 a	9.82 a	7.18 a	3.73 a	2.07 a	0.49 b

(OM= Organic matter, EC=Electrical conductivity, CEC= Cation exchange capacity, Ca=Calcium, Mg=Magnesium, K= Potassium, Na= Sodium)

Table 3: Effect of different soil amendments on plant growth parameters and nutrient uptake by maize plants in field study. The data were presented as means $\pm$ SE and means sharing dissimilar letters in a column are statistically significant and similar letters are non-significant ($p < 0.05$).

Treatments	Plant height (cm)	Shoot dry weight (g)	N	P	K	Ca	Mg
					g pot ⁻¹		
Control	111.55 d	52.52 e	1470.41 e	311.73 c	1138.73 c	68.40 e	278.38 e
Compost	132.11 c	63.55 c	1763.17 c	398.16 b	1608.90 b	93.16 c	360.16 c
Ash	129.00 c	55.65 de	1571.16 de	338.69 bc	1245.42 c	75.54 de	302.10 de
Biochar	141.67 b	72.71 b	2095.80 b	489.35 a	2398.73 a	113.89 b	416.87 b
Poultry Litter	134.89 bc	60.70 cd	1705.98 cd	373.82 bc	1599.02 b	82.99 cd	331.37 cd
COMBI	154.21 a	81.17 a	2320.64 a	468.05 a	2435.29 a	127.15 a	457.40 a

The data were presented as means $\pm$ SE and means sharing dissimilar letters in a column are statistically significant and similar letters are non-significant ($p < 0.05$).

Table 4: Effect of different amendments on soil properties after maize crop harvest for field study. The data were presented as means $\pm$ SE and means sharing dissimilar letters in a column are statistically significant and similar letters are non-significant ($p < 0.05$).

Treatments	pH	Δ pH	OM	CEC	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺
			%	cmol kg ⁻¹	cmol kg ⁻¹			
Control	5.05 d	-	0.75 b	4.25 d	1.97 b	2.13 c	0.60 b	0.48 a
Compost	5.70 b	0.65	1.10 b	6.42 ab	2.32 ab	3.73 a	1.33 a	0.45 a
Ash	5.40 c	0.35	0.79 b	4.83 cd	1.83 b	2.27 c	1.05 ab	0.42 a
Biochar	6.10 a	1.05	1.01 ab	6.95 a	2.30 ab	2.67 b	1.00 ab	0.48 a
Poultry Litter	5.72 b	0.67	0.88 ab	6.50 ab	2.20 ab	2.37 bc	0.98 ab	0.47 a
COMBI	5.96 a	0.91	1.03 ab	7.51 a	2.50 a	3.73 a	1.20 ab	0.42 a

The data were presented as means $\pm$ SE and means sharing dissimilar letters in a column are statistically significant and similar letters are non-significant ($p < 0.05$).

3.2 Effect of amendments on plant and soil properties: Field study

Significant differences in maize growth were observed across treatments in the field study (Table 3). The COMBI treatment showed the highest plant height (154.21 cm) and the greatest shoot dry weight (81.17 g), significantly higher than all other treatments ($p < 0.05$). Biochar also enhanced growth, with plant height and shoot dry weight of 141.67 cm and 72.71 g, respectively, outperforming compost, poultry litter, and ash. The control exhibited the lowest values (111.55 cm and 52.52 g). Nutrient uptake also varied significantly among treatments. COMBI showed the highest N (2320.64 mg pot⁻¹), P (468.05 mg pot⁻¹), K (2435.29 mg pot⁻¹), Ca (127.15 mg pot⁻¹), and Mg (457.40 mg pot⁻¹) uptake, followed closely by biochar. Compost, poultry litter, and ash provided moderate improvements, while the control consistently showed the lowest uptake across all nutrients. Overall, COMBI demonstrated superior performance in promoting plant growth and nutrient acquisition, followed by biochar, underscoring the effectiveness of these amendments in field conditions.

Soil properties after maize harvest also showed significant differences among treatments (Table 4). Biochar and COMBI recorded the highest soil pH values (6.10 and 5.96), significantly greater than the control (5.05). COMBI and compost enhanced soil organic matter (1.03% and 1.10%) and CEC (7.51 and 6.42 cmol kg⁻¹), followed by biochar and poultry litter, while ash showed the least improvement. COMBI achieved the highest exchangeable Ca (2.50 cmol kg⁻¹), Mg (3.73 cmol kg⁻¹), and K (1.20 cmol kg⁻¹), with compost also showing strong performance. Exchangeable Na levels remained statistically similar across treatments (0.42–0.48 cmol kg⁻¹). Overall, COMBI consistently improved soil fertility indicators, followed by biochar and compost, whereas the control exhibited the poorest soil conditions, highlighting the critical role of soil amendments in enhancing productivity and soil health under field conditions.

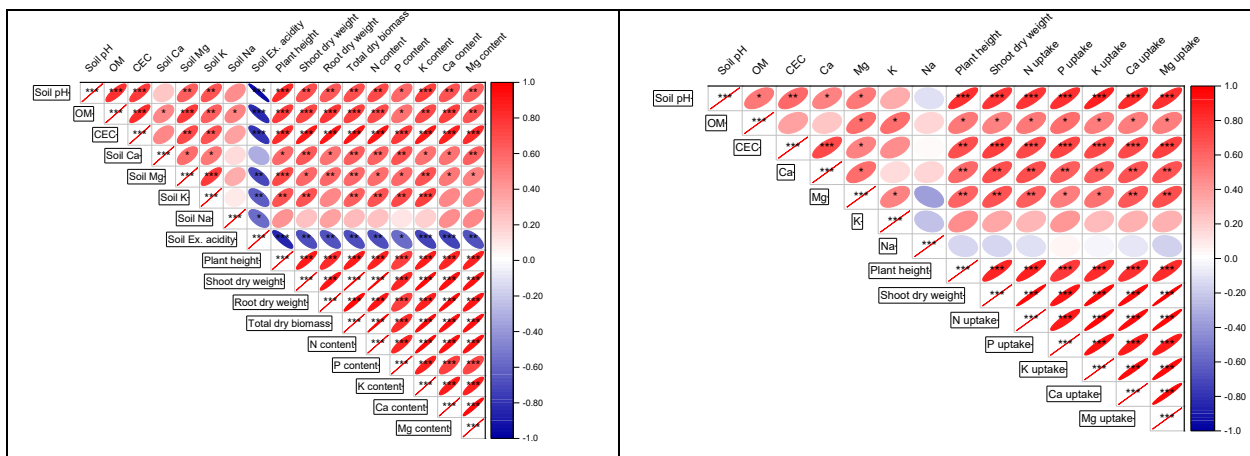


Fig 1. Correlation of soil properties and plant growth parameters (left side: pot study, right side: field study)

3.3 Correlation of soil properties and plant growth parameters

Correlation analysis revealed strong positive relationships between soil properties and plant growth parameters in both pot and field studies (Fig. 1). Soil pH, organic matter, and CEC were significantly correlated ($p < 0.001$) with nutrient uptake (N, P, K, Ca, Mg) and plant growth indicators (height, shoot, and total dry biomass). Organic matter and CEC positively influenced nutrient availability and plant productivity, while exchangeable acidity showed negative correlations with soil fertility traits. Overall, the results highlight that soil amendments improved soil chemical properties, which in turn enhanced nutrient uptake and maize growth performance.

4. Conclusion

The study revealed that soil amendments significantly improved soil properties, plant growth, and nutrient uptake in both pot and field experiments. Among the treatments, COMBI showed the greatest enhancement in soil pH, organic matter, CEC, and nutrient availability (Ca, Mg, K), leading to superior plant height, biomass, and nutrient uptake (N, P, K, Ca, Mg). Biochar and compost also improved soil fertility and plant growth, while poultry litter and ash had moderate effects. The control recorded the lowest values across all parameters. Strong positive correlations between soil properties and plant performance highlight that COMBI is the most effective amendment for improving soil fertility and productivity in nutrient-depleted acidic soils.

Acknowledgement

This research was financially supported by the International Foundation for Science (IFS), Sweden (Grant No. C-6633-1) which is gratefully acknowledged.

References

- Antonangelo, J.A., Sun, X., Zhang, H., 2021. The roles of co-composted biochar (COMBI) in improving soil quality, crop productivity, and toxic metal amelioration. *Journal of Environmental Management* 277, 111443.
- Cordell, D., Drangert, J.-O., White, S., 2009. The story of phosphorus: Global food security and food for thought. *Global Environmental Change* 19, 292–305.
- El-Naggar, A., Lee, S.S., Rinklebe, J., Farooq, M., Song, H., Sarmah, A.K., Zimmerman, A.R., Ahmad, M., Shaheen, S.M., Ok, Y.S., 2019. Biochar application to low fertility soils: A review of current status, and future prospects. *Geoderma* 337, 536–554.
- Gao S, Hoffman-Krull K, Bidwell A L and DeLuca T H. 2016. Locally produced wood biochar increases nutrient retention and availability in agricultural soils of the San Juan Islands, USA. *Agriculture, Ecosystems & Environment*. 233: 43–54.
- Lehmann, J., Joseph, S., 2015. Biochar for environmental management, Biochar for Environmental Management. Routledge.
- Li, H., Li, Y., Xu, Y., Lu, X., 2020. Biochar phosphorus fertilizer effects on soil phosphorus availability. *Chemosphere* 244, 125471.
- Nkoa, R., 2014. Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: A review. *Agronomy for Sustainable Development* 34, 473–492.
- Othman, A., Dumitrescu, E., Andreescu, D., Andreescu, S., 2018. Nanoporous sorbents for the removal and recovery of phosphorus from eutrophic waters: sustainability challenges and solutions. *ACS Sustainable Chemistry & Engineering* 6, 12542–12561.
- Pansu M, & Gautheyrou J. 2006. Handbook of soil analysis: Mineralogical, organic and inorganic methods. In Handbook of Soil Analysis: Mineralogical, Organic and Inorganic Methods. Springer Berlin Heidelberg.
- Zhang, W., Tang, X., Feng, X., Wang, E., Li, H., Shen, J., Zhang, F., 2019. Management strategies to optimize soil phosphorus utilization and alleviate environmental risk in China. *Journal of Environmental Quality* 48, 1167–1175.