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Biochar Effects on Carbon and Nitrogen Dynamics During Co-Composting of Poultry Manure With Carbonized and Uncarbonized Organic Materials in Sub-Saharan Africa

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ABSTRACT

Background: Carbonized organic matter (biochar) and compost are both beneficial soil amendments and particularly meaningful for the restoration of degraded soils. Application of biochar adds stable carbon (C) but only little nitrogen (N) to the soil. Compost is rich in C and N, but losses of these elements during composting are large, and C stability is relatively low. The addition of biochar during composting has been reported to decrease N losses, accelerate the composting process, increase cation exchange capacity (CEC), and increase water-holding capacity compared to composting without biochar. However, C and N dynamics during biochar co-composting vary enormously depending on feedstock quality.

Aims: Therefore, the aims of this study were to find out if biochar addition will reduce C and N losses during composting of organic materials in a field trial in Sub-Saharan Africa or not.

Methods: Six compost treatments, among them three compost mixtures with biochars made from rice husks (cRH), corn cobs (cCC) and wood (cWO) or their un-carbonized feedstocks (RH, CC, and WO), were co-composted with poultry manure (15 vol-%) and rice straw (60 vol-%) in randomly allocated 1 m^3 compost bins.

Results: After composting, biochar treatments had lower or similar C losses, lower contents of dissolved organic carbon (DOC), higher C decomposition rates, and higher or similar pH-values compared with their non-biochar treatments. Biochars that were stored in mesh bags during composting increased in DOC and effective CEC and decreased in surface area. Biochar retained N through accumulation and sorption of ammonium nitrogen (NH_4-N). Microbial biomass and nitrate nitrogen (NO_3-N) were similar among all treatments.

Conclusions: Overall, biochar positively affected C and N retention and compost quality.

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1 | Introduction

Global challenges such as climate change, low agricultural productivity, droughts, and deteriorating ecosystem services are closely linked to soil properties especially soil organic carbon (Lal et al. 2007). Soils in Sub-Saharan Africa (SSA) are naturally low in soil organic carbon (SOC) and nutrients, and they are often further degraded by unsustainable land management practices. Maintaining and increasing SOC are important to enhance structural stability, water-holding capacity (WHC), and cation exchange capacity (CEC) of soils which play a crucial role in increasing the resilience of those ecosystems.

In agricultural systems, organic material is usually added to the soil in the form of organic fertilizers (e.g., manure, compost) or fresh crop residues, which leads to a certain build-up of soil organic C. However, these organic C sources are generally turned over by soil microorganisms relatively quickly because they provide readily available substrates and often have high nutrient contents that increase microbial decomposition. To enhance the stability of the added organic material and improve the C-storage of the soils, the transformation of fresh organic matter to biochar and their subsequent field application might be an appropriate method to enhance soil quality. Biochar is pyrolyzed organic matter that has received vast scientific attention due to its high potential for C sequestration, nutrient retention, increasing CEC, WHC, liming potential, reducing soil bulk density, reducing nitrous oxide (N_2O), and methane (CH_4) emissions (Singh et al. 2010). However, biochar is commonly poor in nutrients, especially nitrogen (N), but rich in stable C (Singh et al. 2010). Thus, the combination of biochar as a more stable C-source with a nutrient-rich material like compost might increase the C-pool in soil and enhance soil fertility due to a more efficient microbial C-turnover. Thus, there could be a synergy by combining both products in particular when mixing both materials already during the composting process (Schulz et al. 2013; Steiner et al. 2011; Steiner et al. 2015). Biochar co-composting has been reported to decrease C (Czekała et al. 2016; Manka'abusi et al. 2018) and N loses (Hua et al. 2009; Kammann et al. 2015; Steiner et al. 2010), increase NH_4 sorption (Steiner et al. 2010) to accelerate the composting process (Dias et al. 2010; Steiner et al. 2011), decrease N_2O (Manka'abusi et al. 2018; Wang et al. 2013) and CH_4 (Chowdhury et al. 2014) emissions, and increase WHC (Prost et al. 2013) compared with composting without biochar. Further, high temperatures during composting are supposed to benefit the abiotic oxidation of biochar surfaces which leads to an increased surface reactivity and sorption capacity compared to fresh biochars and biochars which are field aged at ambient temperatures (Joseph et al. 2010; Wiedner et al. 2015). Therefore, biochar-composts have been seen as a synergic soil amendment that can improve soil quality and increase crop production (Khan et al. 2023). However, the high diversity of feedstocks makes general conclusions on biochar co-composting effects difficult. It is not clear to which degree (if at all) composting and ecosystems respond to these promising biochar effects. Further, knowledge gaps exist regarding mechanisms, such as C stabilization (Prost et al. 2013; Wiedner et al. 2015) or N retention (Kammann et al. 2015) during composting.

In SSA, residues from agricultural production, such as rice husks, corn cobs, and rice straw or saw dust, are abundantly available with only a few alternative uses. For direct field application, their C/N ratios are too wide. Poultry manure is an available and often even cost-free N-rich material and is usually used as fertilizer for direct field application. Its use for co-composting with N poor biochar has the potential to increase the overall N use efficiency.

Therefore, the aim of the present study is to test the effects of biochar co-composting on C and N dynamics during composting of locally available feedstocks in SSA.

2 | Materials and Methods

2.1 | Experimental Setup

The co-composting trial was conducted in Tamale, northern Ghana. The basic mixture of the treatments consisted of poultry manure (15 vol-%; 68.7 kg m^{-2}) and rice straw (60 vol-%; 75.4 kg m^{-2}). This mixture was co-composted with six amendments (25 vol-%) of either biochar made from rice husks (cRH), corn cobs (cCC) and wood (cWO), or their fresh feedstocks (RH, CC, and WO). Treatments masses on dry weight basis ranged from 51.2 kg m^{-2} (WO) to 148.9 kg m^{-2} (cWO; Table 1). Three replicates of each treatment were allocated to 1 m^3 compost bins in a completely randomized block design. The bins were sealed at the bottom and the sides to prevent leaching and covered with polyethylene sheets to hold off rain. Total composting time was 34 days. The compost mixtures were turned and thoroughly mixed in an adjacent empty bin every 3 days for the first 21 days and every day for the remaining time. After the initial mixing, moisture contents were monitored at each sampling and were kept constant at 60% w/w by adding water to the mixtures (Figure 1).

To study changes of biochar properties during the composting process, 15 g of biochar (not washed, not sieved before) was filled into mesh bags (14 × 12 cm) with a mesh size of 100 µm. Four mesh bags were buried in each biochar treatment at 3/4 of the filling height. Two mesh bags were removed for analyses after 17 days, and the other two after 34 days. Before turning the compost, mesh bags were removed to avoid damages.

Biochar from corn cobs and rice husks was produced by slow pyrolysis at around 450°C in a locally produced kiln under low oxygen conditions (Table 1). Wood was charred according to the usual local practice with a traditional earth mound technique. The wood char was collected in the form of abundantly available leftovers of small particle size at a local charcoal trading site. Under these open-air storage conditions, wood char had contact with soil particles, dust, and nutrients as indicated by scanning electron microscopy and energy-dispersive X-ray spectroscopy (data not shown).

2.2 | Sampling and Analysis

Samples of all compost additives were collected. During composting, temperatures were recorded daily at four positions inside the compost piles. Further samples were collected after 4, 17, 27, and 34 days of composting. For each sampling event, five subsamples were taken at 3/4 filling height in each compost bin. All samples

TABLE 1 | Initial properties of co-composted additives of an experiment conducted in Tamale, northern Ghana.

Additive	Mass ($kg\ m^{-2}$)	C		N		C/N	pH	Relative to biochar mass			Relative to C stocks in compost		
		($g\ kg^{-1}$)	($kg\ m^{-2}$)	($g\ kg^{-1}$)	($kg\ m^{-2}$)			Volatile matter (%)	Ash (%)	Fixed C (%)	Biochar (%)	Fixed C (%)	Volatile matter (%)
Rice husk char	76.6	442.6	33.9	7.5	0.6	59.1	7.2	25.7	50.1	24.2	36.4	8.8	9.4
Corn cob char	76.2	798.1	60.8	8.9	0.7	89.9	8.7	20.7	19.6	59.7	50.6	28.7	9.9
Wood char	148.9	451.8	67.3	5.5	0.8	81.9	7.3	30.3	30.1	39.0	53.2	27.9	21.7
Fresh rice husks	116.6	437.4	51.0	11.4	1.3	38.5	5.2						
Fresh corn cobs	54.5	481.1	26.2	4.0	0.2	119.0	4.8						
Wood	51.2	478.7	24.5	2.1	0.1	232.6	8.3						
Rice straw	75.4	409.5	30.9	6.9	0.5	59.4	7.2						
Poultry manure	68.7	412.9	28.4	42.0	2.9	9.8	6.8						

were immediately dried at 40°C prior to laboratory analysis. Moisture contents were determined, and samples were shredded to <2 mm for subsequent analysis. Total C and total N were analyzed by dry combustion (Vario EL Elementar Analysesysteme GmbH, Hanau, Germany) after grinding the dried samples. The pH was determined with a glass electrode (WTW 192, Ingold) in 0.01 M $CaCl_2$ (1:25 w/v). WHC (mL g^{-1}) was determined by measuring the volume of water needed to saturate 10 g of the sample. Bulk density was measured as compost mass per volume. Total C and N were reported as stocks (g kg^{-1} or kg m^{-2}) by multiplication of C and N contents with compost mass (bulk density multiplied with filling height; Table 1). All results were reported based on oven-dried material at 105°C.

As a second group of analysis, 34-day-old compost samples were incubated for another 37 days at 30°C in a Respicond IV apparatus (Nordgren Innovations AB, Bygdeå, Sweden). In contrast to field conditions, during laboratory incubation, temperature was constant. Keeping temperature constant avoided temperature-sensitive reactions and allowed comparison of material-based treatment effects. The 34-day samples reflected the state of properties before field application. For the incubation studies, sub-sample of 3 g each were taken from the final compost samples and adjusted to 60% WHC. These sub-samples were incubated in 250 mL polyethylene beakers. The carbon dioxide (CO_2) evolution was recorded hourly by measuring the changes of the electrical conductivity of 10 mL 0.6 M potassium hydroxide (KOH) solution placed inside the beakers. The apparent respiration equilibrium which evolved over time was considered basal respiration. Total N loss during incubation was calculated by multiplication of the N contents (mean before and after incubation) with weight loss.

Microbial biomass C (C_{mic}) and N (N_{mic}) were determined by the chloroform fumigation extraction method (Vance et al. 1987). A total of 1.2 g of incubated moist compost was fumigated at room temperature with ethanol-free trichloromethane ($CHCl_3$) for 24 h in a desiccator. The fumigated sample and non-fumigated controls were extracted with 24 mL of 0.05 M K_2SO_4 by 30 min horizontal shaking and subsequent filtration (Whatman GF/A filters). The supernatant was subject to C and N determination with the Dimatoc 2000 analyzer. C_{mic} or N_{mic} were calculated as difference between total C or total N extracted from fumigated and non-fumigated treatments, divided by 0.45 for C_{mic} (Vance et al. 1987) and 0.54 for N_{mic} (Brookes et al. 1985).

The metabolic quotient (qCO_2) was calculated as ratio of basal respiration (microbial activity) over the last 10 h of incubation and microbial biomass to describe the CO_2-C produced per unit C_{mic} and time (Anderson and Domsch 1990). As such, the higher qCO_2, the more C is channeled into the energy metabolism and the lower the efficiency of microbial biomass C formation. Further, the C_{mic}/C and N_{mic}/total N ratios were calculated to describe the C and N availability for microorganisms, respectively.

As labile C and N fractions, DOC and total soluble nitrogen (TSN) were determined according to Ghani et al. (2003) in water at 20°C room temperature (DOC_{20} and TSN_{20}, respectively) and after heating for 16 h in a water bath at 80°C (DOC_{80} and TSN_{80}, respectively). For DOC_{20} and TSN_{20}, cold water procedure was used where a mixture of 1.2 g of compost and 24 mL H_2O were shaken for 30 min prior to centrifugation. Then, the supernatant

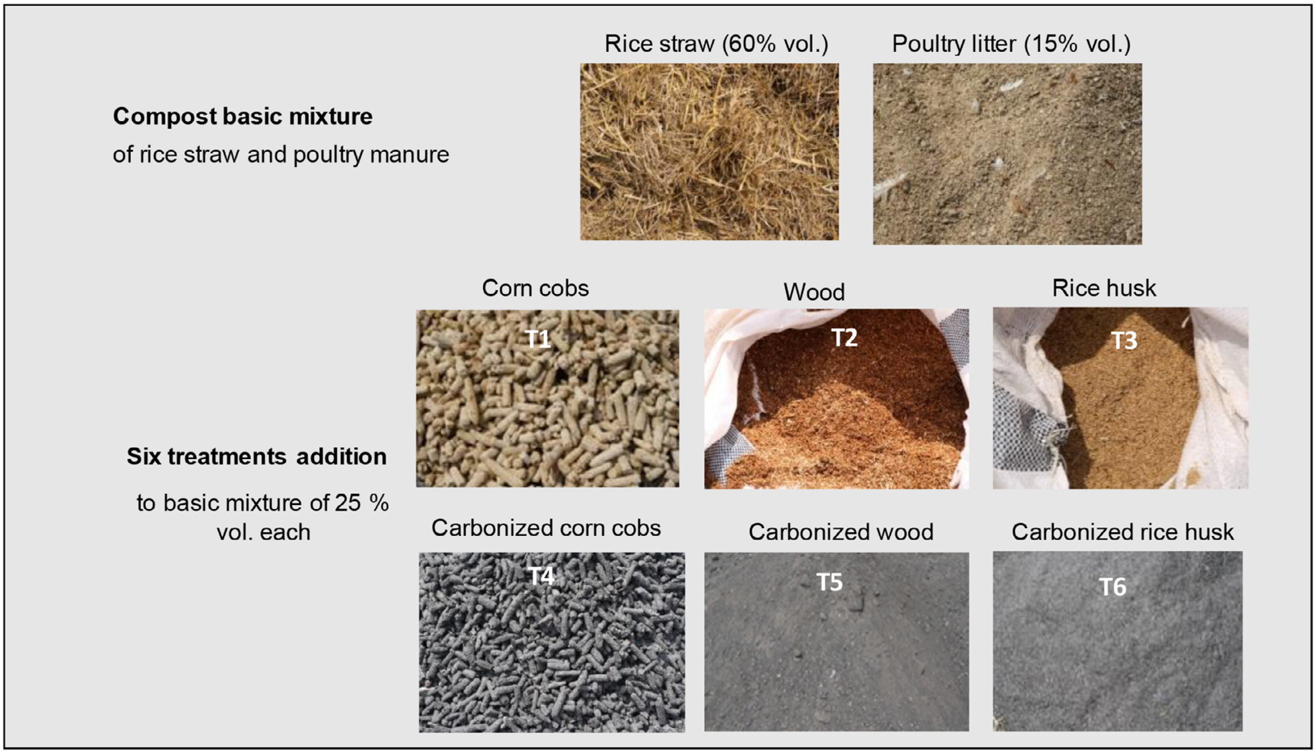

FIGURE 1 | Flow diagram showing basic mixture and treatment additions and their respective volumes.

was passed through a 0.45-µm filter (Whatman GF/A), and DOC_{20} and TSN_{20} were analyzed with a Dimatoc 2000 automatic analyzer (Dimatec, Essen, Germany). Subsequently, 24 mL H_2O was added to the filtrates to determine DOC_{80} and TSN_{80} after heating and further processing according to the outlined cold water procedure.

NH_4-N and NO_3-N were extracted with 0.01 M K_2SO_4. After filtration (0.45 µm) and colorification, NH_4-N and NO_3-N were measured photometrically. Light absorption at the specific wavelengths was measured with a UV/VIS spectrophotometer (Pharo 300 Spectroquant; Merck GmbH, Darmstadt, Germany). NH_4-N sorption isotherms were established by adding 50 mL of eight NH_4Cl solutions adjusted to 0, 1, 5, 10, 20, 40, 70, 100 mg N L^{-1} at a pH of 7 to 1 g of incubated compost samples. Two drops of ethanol-free chloroform were added to avoid microbial N transformations during shaking. After shaking for 24 h and filtration at 0.45 µm, solutions were measured photogrammetrically. N-concentrations were selected in appropriate ranges, and the duration of shaking was adjusted to reach apparent equilibrium conditions as concluded in pre-trials. Lastly, incubated samples were also analyzed for total C and total N.

The biochars in the mesh bags were analyzed for DOC_{20}, DOC_{80}, TSN_{20}, TSN_{80}, total C, and total N according to the outlined methods. Before analysis, fresh biochars were sieved to >100 µm, to be in the same size fraction as the mesh bag biochars. No washing was conducted before analysis. Further, exchangeable cations Al^{3+}, Ca^{2+}, Mg^{2+}, K^+, Na^+ were determined according to the Hexamincobalt method (DIN EN ISO 23470). Fifty milliliters of 0.0166 M hexamincobalt-chloride was added to 1.25 g of biochar. After shaking for 1 h and filtration, cations were measured by ICP-OES (Ciros CCD; Spectro Analytical Instruments GmbH, Kleve, Germany). Effective CEC was calculated as sum of the exchangeable cations, accounting for their valence. Further, specific surface area was measured with the N_2–Brunauer–Emmett–Teller method (Brunauer et al. 1938).

Dynamics of C and N losses (% of initial stocks) during composting in field were modeled by first-order exponential decay functions:

$$C_{loss} \text{ or } N_{loss} = Y_0 + a \cdot e^{-kt}, \quad (1)$$

with k as the rate constant for C or N loss (% of initial C or N stocks) over time (t; days), Y_0 as a fitted equilibrium (% of initial C or N stocks), and a as the difference between C or N loss at day 0 and Y_0. The determined functions represent two pools, one labile pool which was subject to loss and one more stable pool which is the remaining compost material. Functions were fitted with SigmaPlot (Version 10; Systat Software, Inc., San Jose, California, USA).

2.3 | Statistics

Normal distribution of residuals was checked with the Kolmogorov–Smirnov test and visually assessed with qq-plots. Where necessary, data were log or square root transformed prior to statistical analysis (Tables 2 and 3). To account for the multi-factorial design, mixed model analyses (proc mixed) with main factors (biochar, feedstock) and interactions between them were conducted with SAS University edition (Version 3.5; SAS Institute Inc., Cary, NC, USA). Significances ($p \leq 0.05$* and

TABLE 2 | Total C, total N, compost volume, pH, and water-holding capacity (WHC) at day 34.

Treatment	Total C (%)	Total C (kg m^{-2})	C loss rate[a] (% day^{-1})	Total N (%)	Total N (kg m^{-2})	N loss rate[a] (% day^{-1})	C/N	Volume (m^3)	pH	WHC (L kg^{-1})
Rice husk	33.8 ± 2.1	31.2 ± 8.3	0.05 ± 0.04	1.9 ± 0.1	1.8 ± 0.4	0.065 ± 0.057	19.0 ± 0.6	0.41	7.2 ± 0.2	1.3 ± 0.17
Corn cob	37.3 ± 0.9	32.1 ± 0.8	0.04 ± 0.01	2.8 ± 0.1	2.4 ± 0.1	0.240 ± 0.073	28.4 ± 0.6	0.30	7.9 ± 0.1	1.64 ± 0.14
Wood	37.8 ± 0.4	20.6 ± 9.4	0.07 ± 0.01	2.1 ± 0.4	1.1 ± 0.3	0.117 ± 0.017	21.0 ± 3.3	0.33	8.0 ± 0.1	1.90 ± 0.22
Rice husk char	38.5 ± 0.5	36.7 ± 3.4	0.09 ± 0.01	2.1 ± 0.0	2.0 ± 0.1	0.108 ± 0.077	20.5 ± 0.4	0.32	7.9 ± 0.1	0.99 ± 0.03
Corn cob char	54.9 ± 0.7	39.4 ± 0.5	0.05 ± 0.03	2.1 ± 0.1	1.5 ± 0.1	0.069 ± 0.030	20.6 ± 1.2	0.30	8.3 ± 0.1	1.11 ± 0.05
Wood char	43.3 ± 0.8	73.3 ± 7.7	0.11 ± 0.02	1.4 ± 0.0	2.3 ± 0.2	0.152 ± 0.040	13.7 ± 0.2	0.39	7.8 ± 0.1	0.82 ± 0.02
Mixed model *p* values[b]										
Transformation	None	None	None	None	Log	None	Log		None	Log
Biochar	<0.0001	<0.0001	0.0783	0.0001	0.0968	0.4682	<0.0001		0.0007	<0.0001
Feedstock	<0.0001	0.0053	0.0068	<0.0001	0.1172	0.9362	0.0002		<0.0001	0.0388
Biochar × Feedstock	<0.0001	<0.0001	0.0144	0.0007	0.0001	0.0648	<0.0001		0.0004	0.0004
Biochar vs. non-biochar LSD comparison										
Rice	0.000	0.262	0.0220	0.2661	0.3202	0.126	0.958		<0.0001	0.000
Corn	<0.0001	0.142	0.4070	0.0001	0.0029	0.003	<0.0001		0.005	0.000
Wood	0.000	<0.0001	0.0447	0.0002	0.0001	0.171	<0.0001		0.082	<0.0001

Note: Significances are given for effects and interactions as well as for least square means of pairwise feedstock (biochar vs. non-biochar) comparisons (means ± SD; $n = 3$).

[a] C or N loss rates (k) were fitted to the C or N loss data (relative to initial C or N stocks) by the function loss $= Y_0 + a \times e^{-k*t}$, with Y_0 being the minimum value to which the function heads, $Y_0 + a$ being the relative initial C or N stocks (ca. 100%) and t being days of composting. The functions are plotted in Figure 3.

[b] Mixed model formulation: y = Block + Biochar + Feedstock + Biochar × Feedstock. Block had no significant effects.

TABLE 3 | C fractions after laboratory incubation.

Treatment	DOC_{20} ($g\ kg^{-1}$)	DOC_{80} ($g\ kg^{-1}$)	Cumulative respiration ($g\ kg^{-1}$ C)	Basal respiration ($mg\ CO_2$-C $kg^{-1}\ h^{-1}$)	C_{mic} ($g\ kg^{-1}$)	qCO_2 ($mg\ CO_2\ g^{-1}\ C_{mic}\ h^{-1}$)	C_{mic}/C ($g\ kg^{-1}$)
Rice husk	6.2 ± 2.2	9.2 ± 0.5	70.6 ± 10.4	1.00 ± 0.69	2.63 ± 0.48	0.56 ± 0.25	7.3 ± 1.6
Corn cob	7.3 ± 0.8	20.2 ± 2.0	155.5 ± 16.0	2.35 ± 0.63	13.07 ± 3.65	0.19 ± 0.07	34.1 ± 10.1
Wood	8.9 ± 8.0	8.1 ± 1.5	81.9 ± 12.7	1.82 ± 0.55	1.86 ± 0.58	1.08 ± 0.63	4.7 ± 1.6
Rice husk char	3.4 ± 0.9	5.4 ± 1.0	33.9 ± 4.1	0.32 ± 0.02	5.18 ± 1.66	0.07 ± 0.03	13.5 ± 4.5
Corn cob char	5.8 ± 1.1	6.3 ± 0.6	20.8 ± 2.3	0.40 ± 0.10	7.72 ± 1.05	0.05 ± 0.01	13.1 ± 1.6
Wood char	1.5 ± 1.2	2.3 ± 0.5	13.8 ± 1.4	0.17 ± 0.03	2.02 ± 0.18	0.09 ± 0.02	4.4 ± 0.6
Mixed model *p* values[a]							
Transformation	None	None	Log	None	Log	Log	Log
Biochar	0.0009	<0.0001	<0.0001	<0.0001	0.58	<0.0001	0.4949
Feedstock	0.0015	<0.0001	0.0001	0.0792	0.0002	0.0176	0.0005
Biochar × Feedstock	0.3889	<0.0001	<0.0001	0.1375	0.0395	0.1363	0.0135
Biochar vs. non-biochar LSD comparison							
Rice	0.010	0.003	<0.0001	0.048	0.044	0.000	0.069
Corn	0.117	<0.0001	<0.0001	0.000	0.072	0.008	0.007
Wood	0.009	0.000	<0.0001	0.001	0.726	0.001	0.919

Note: Significances are given for effects and interactions as well as for least square means of pairwise feedstock (biochar vs. non-biochar) comparisons (means ± SD; $n = 3$).

[a] Mixed model formulation: Y = Block + Biochar + Feedstock + Biochar × Feedstock. Block had no significant effects.

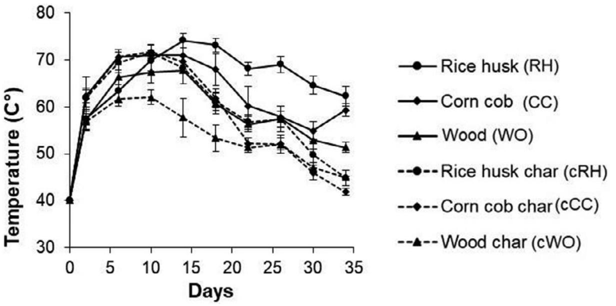

FIGURE 2 | Change of temperatures of compost treatments over time in a field experiment conducted in Tamale, northern Ghana. Means ± SD represent 4 days with four measurements each day.

$p \leq 0.005$**) of differences between treatments were determined by comparing least square means.

Relations between the parameters determined after laboratory incubation were explored by a principal component analysis (PCA) with a varimax rotation and Kaiser normalization by SPSS (Version 22.0; IBM Corporation, Armonk, NY, USA) after z-transformation of all variables. Variables with a measure of sampling accuracy of <0.5 in the anti-image correlation matrix were removed from the PCA. Data are given as means ± standard deviations. Figures and calculations were prepared with Excel 2010 (Microsoft Corporation, Redmond, WA, USA).

3 | Results

3.1 | Composting Tempeartures

All six compost treatements had a sharp increase in temperature in the first days (Figure 2). Peak temperatures were reached after about 10 days, except for RH which reached peak tempearture after about 14 days. Peak temperatures were higher in RH (74 ± 2°C) compared with cRH (71 ± 1°C) and higher in CC (68 ± 3°C) compared with cCC (62 ± 2°C) but similar in WO (72 ± 2°C) and cWO (72 ± 1°C) treatments. After 2 weeks, a cooling phase initiated slowly. At the end of the experiment, biochar treatments had lower temperatures (42–45°C) compared with non-biochar treatments (51–62°C). Temperature at day 34 correlated with basal respiration ($r = 0.63$, $p < 0.05$).

3.2 | Total C

Initially, C contents (g kg^{-1}) were similar in biochar (45 ± 5%) and non-biochar treatments (42 ± 1%; Table 1). Taking the total compost mass into account, C stocks (kg m^{-2}) varied initially, with 1.4 times higher C stocks in cCC compared with the CC treatment. C stocks were 1.5 times higher for cWO than WO but lower C stocks for cRH than RH (0.8 times; Table 1).

C stocks declined exponentially over time (Figure 3a). After composting (at day 34), biochar treatments had significantly higher C contents (46 ± 8%) compared with non-biochar treatments (36 ± 2%; Table 2). However, mass variations masked treatment effects on C contents. Hence, total C stocks (kg m^{-2}) were on average higher in all biochar compared with non-biochar treatments. The largest difference was between WO and cWO (3.6 times) while a non-significant differences on a pairwise feedstock comparison was observed for rice husks and corn cobs which both had 1.2 times higher C stocks with biochar (Table 2). WO and RH had significantly higher C losses (71 ± 11% and 42 ± 6 %, respectively) compared with their counterparts, cWO (42 ± 6%) and cRH (61 ± 4%). However, C loss was not significantly different between CC (62 ± 1%) and cCC (67 ± 0.4%) at day 34 (Figure 3a). The initial contribution of biochar to the total C stocks was 36% for cRH, 51% for cCC, and 53% for cWO (Table 1). Hence, for cRH, at least 18% of the added biochar C must have been decomposed because C losses after composting were higher than the sum of initial poultry manure and rice straw C stocks.

C loss rates (derived from an exponential decay function fitted to relative C loss over time; Figure 3a, Table 2) were 1.6 ± 0.2 times higher in biochar treatments compared with non-biochar treatments (average over pairwise feedstock comparisons), though the difference between CC and cCC was not significant (Table 2). In addition, biochar treatments tend to flatten out at higher relative C stocks than their non-biochar counterparts in the fitted relative C loss functions.

3.3 | Total N

Initially, N contents were similar among all treatments with 1.2 ± 0.04% for biochar and 1.2 ± 0.1% for non-biochar treatments (Table 1). In line with C, total N stocks declined exponentially over time (Figure 3b). At the end of composting, N contents were higher in non-biochar (2.3 ± 0.5%) compared with biochar treatments (1.8 ± 0.4%; Table 4). After accounting for mass losses, N losses (relative to initial N stocks) were significantly higher in RH (63 ± 9%) compared with cRH (51 ± 4%) and in WO (69 ± 9%) compared with cWO (45 ± 6%; Figure 3b). In contrast, cCC had a significantly higher N loss (64 ± 2%) than CC with an overall lowest N loss (Figure 3b). CC had the highest N loss rate (fitted to relative N loss over time), while all other treatments were not significantly different in N loss rates (Table 4).

C/N ratios were higher for biochar than non-biochar treatments throughout composting. Initial C/N ratios ranged from 38.5 to 232.6 (for non-biochar feedstock) and 59.1 to 89.9 (for biochar feedstock; Table 1). After composting, C/N ratios of non-biochar treatments ranged from 19 to 28 and those of biochar treatments ranged from 13 to 20 (Table 2). C/N ratio linearly declined over time. At day 34, CC had the overall lowest C/N ratio (13.1) with less than half of the C/N ratio compared with cCC, corresponding to its low N loss (Table 2).

3.4 | C and N Fractions After Incubation

After incubation, DOC$_{20}$ contents were lower for all biochar (by 61%) compared with non-biochar treatments (Table 3). DOC$_{80}$ was significantly lower (by 37%) for all biochar compared with non-biochar treatments. The highest DOC$_{80}$ contents were observed in the CC treatment. DOC$_{80}$ slightly dominated total DOC (sum of DOC$_{20}$ and DOC$_{80}$) with a proportion of 56 ± 6%, except for CC which had 2.8 times higher contents of DOC$_{80}$ than DOC$_{20}$ (Table 3).

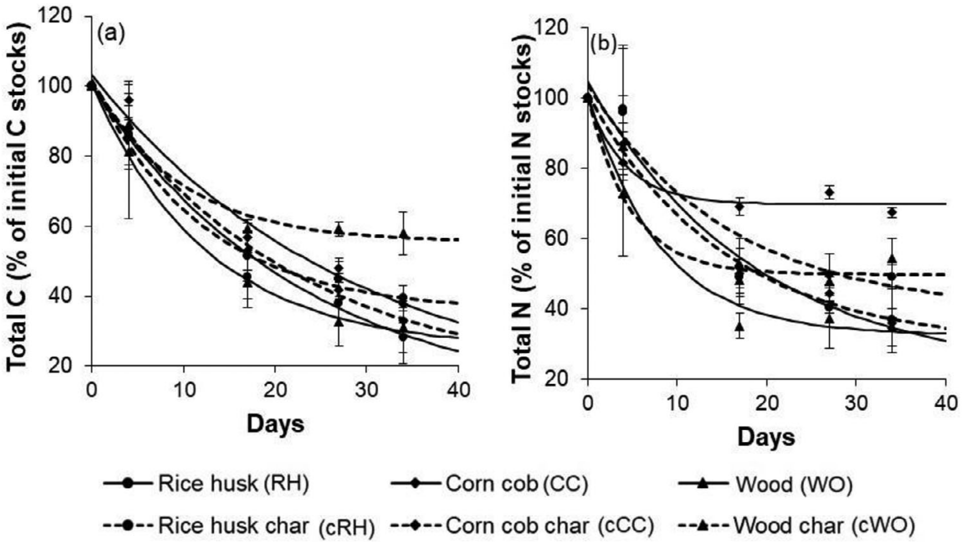

FIGURE 3 | Change of total C (a) and total N (b) relative to initial stocks (kg m^{-2}) of compost treatments over time in a field experiment conducted in Tamale, northern Ghana. Initial stocks (at day 0) are calculated values based on the compost mass and C and N contents of the raw materials and were normalized to 100%. Exponential first order functions were fitted. Means ± SD; *n* =3.

The patterns of TSN fractions were similar to those of DOC (Table 4). TSN_{80} was 3.6 times higher than DOC_{80} but the relative differences among the treatments were almost identical for the two parameters (r = 0.99**). TSN_{80} contents were significantly lower in biochar treatments compared with non-biochar treatments (by 37%), while for TSN_{20}, biochar was only significantly lower than non-biochar pair for wood. In line with DOC_{80}, CC had the highest TSN_{80} contents. TSN_{80} slightly dominated total TSN (sum of TSN_{20} and TSN_{80}) with a proportion of 58 ± 9%, except for CC which had 3.3 times higher contents of TSN_{80} than TSN_{20} (Table 4).

Cumulative CO_2-C respiration (normalized to total C contents after incubation) during incubation was significantly higher (5.2 ± 2.8 times) in non-biochar treatments compared with biochar treatments (average over pairwise feedstock comparisons) with CC having by far the highest respiration (Table 4). Basal CO_2-C respiration (normalized to total C contents after incubation) of incubated samples was significantly higher (6.5 ± 3.8 times) for all non-biochar than their biochar counterparts (average over pairwise feedstock comparisons; Table 4). CC had the overall highest basal respiration. Basal respiration correlated with temperature at day 34 (r = 0.65**).

In line with cumulative respiration, N loss during incubation (normalized to total N contents after incubation) was 2.5 ± 0.7 times higher in non-biochar compared with biochar treatments (Table 4). C/N ratio remained largely unchanged during incubation for all treatments.

C_{mic} (Table 3) and N_{mic} (Table 4) correlated strongly (r = 0.95**) with a C_{mic}/N_{mic} ratio of 12.2. However, there were no significant differences between the biochar and non-biochar pairs, except for CC which had the highest C_{mic} and N_{mic} contents (1.7 and 1.4 times higher than cCC, respectively). C_{mic} per unit total C was similar for all treatment pairs except for CC which had the overall highest ratio (Table 4). In case of CC, C_{mic} represented 3.4% of total C. The metabolic quotient (qCO_2) was 8.2 ± 4.5 times higher in non-biochar compared with biochar treatments (average over pairwise comparison), with the lowest difference for the corn cob pair with only a 3.7 times higher basal respiration per unit C_{mic} for CC (Table 4).

N_{min} fractions were normalized to total N contents after incubation prior to comparison (Table 4). K_2SO_4 soluble NH_4-N was significantly higher (4.9 ± 2.9 times) in biochar compared with non-biochar treatments (Table 4). Adsorption of NH_4-N (at 1 mg NH_4-N L^{-1} equilibrium solution; derived from a linear fit of adsorbed against soluble NH_4-N; Figure 4) was significantly higher (3.3 ± 1.1 times) for biochar than non-biochar treatments (average over pairwise feedstock comparisons; Table 4). Similarly, the proportion of NH_4-N in the equilibrium solution from adsorbed NH_4-N was lower for biochar (from 12 ± 1% for cWO to 20 ± 5% for cCC) compared with non-biochar treatments (from 27 ± 19% for WO to 97 ± 31% for RH).

NO_3-N contents did not significantly differ between treatments (Table 4). A larger proportion (78 ± 18%.) of the N_{min} was in the form of NH_4-N. CC had the overall lowest NO_3-N (0.11 ± 0.04 mg kg^{-1}N) and NH_4-N contents (0.13 ± 0.01 mg kg^{-1} N). The proportion of N_{min} to total N contents ranged from <0.01 to 0.04% (cWO), N_{mic} ranged from 1.1% (cWO) to 3.8% (CC), and total TSN ranged from 0.8% (cWO) to 10.6% (CC; Table 4).

The PCA yielded significant relations between the parameters after laboratory incubation (Figure S1). The first factor of the PCA explained 69% of the total variance. It represented the positive correlations between cumulative respiration, basal respiration, DOC_{80}, DOC_{20}, N loss, TSN_{80} as well as the negative correlations of these parameters with the C/N ratio, adsorbed NH_4-N, and soluble NH_4-N. The second factor explained 13% of the total variance and represented C_{mic}, N_{mic}, and the C_{mic}/C ratio. The variables qCO_2, C_{mic}/N_{mic} ratio, TSN_{20}, and NO_3-N were excluded from the PCA because of their weak correlations with the other variables.

TABLE 4 | N fractions after laboratory incubation.

Treatment	**TSN_{20} ($g\ kg^{-1}$)**	**TSN_{80} ($g\ kg^{-1}$)**	**N_{loss} ($g\ kg^{-1}$ N)**	**N_{mic} ($g\ kg^{-1}$)**	**C_{mic}/N_{mic}**	**NH_4-N ($g\ kg^{-1}$ N)**	**NO_3-N ($g\ kg^{-1}$ N)**	**NH_4-N sorption[a] ($mg\ kg^{-1}$ N)**
Rice husk	0.7 ± 0.3	1.3 ± 0.1	68.5 ± 3 1.5	0.34 ± 0.10	7.8 ± 0.9	3.2 ± 1.4	2.2 ± 0.5	7.7 ± 3.3
Corn cob	0.7 ± 0.0	2.5 ± 0.2	142.8 ± 16.1	1.08 ± 0.15	11.9 ± 1.9	1.3 ± 0.1	1.2 ± 0.4	12.5 ± 2.2
Wood	1.2 ± 0.7	1.0 ± 0.3	100.6 ± 2.3	0.14 ± 0.12	18.2 ± 11.1	16.0 ± 12.5	2.5 ± 0.3	28.6 ± 13.7
Rice husk char	0.4 ± 0.1	0.7 ± 0.1	39.1 ± 5.7	0.59 ± 0.25	9.1 ± 1.1	14.5 ± 4.4	1.6 ± 0.6	35.5 ± 3.3
	0.8 ± 0.2	0.8 ± 0.1	46.8 ± 4.6	0.78 ± 0.16	10.0 ± 0.7	10.2 ± 0.7	1.5 ± 0.5	31.6 ± 8.3
W1	0.1 ± 0.1	0.3 ± 0.0	35.4 ± 2.7	0.14 ± 0.00	14.1 ± 1.6	35.8 ± 5.1	2.2 ± 1.2	81.2 ± 7.0
Mixed model *p* values[b]								
Transformation	Log	None	Log	Log	Log	Log	Sqr	Log
Biochar	0.0003	<0.0001	<0.0001	0.4814	0.0347	<0.0001	0.4926	<0.0001
Feedstock	0.013	0.0266	0.0266	0.0012	0.0009	<0.0001	0.0761	0.0005
Biochar × Feedstock	0.0006	0.1199	0.1199	0.2766	0.003	0.1171	0.433	0.1698
Biochar vs. non-biochar LSD comparison								
Rice	0.1001	0.0013	0.0521	0.1873	0.0626	0.0009	0.2534	<0.0001
Corn	0.8814	<0.0001	0.0004	0.3759	0.0129	<0.0001	0.5333	0.0037
Wood	<0.0001	0.0002	0.0011	0.5723	0.0044	0.0139	0.5199	0.0033

Note: Significances are given for effects and interactions as well as for least square means of pairwise feedstock (biochar vs. non-biochar) comparisons (means ± SD; *n* = 3).

[a] Backtransformed mean sorption at 1 mg NH_4-N L^{-1} in equilibrium solution calculated with linear fits from Figure 4.

[b] Mixed model formulation: Y = Block + Biochar + Feedstock + Biochar × Feedstock. Block had no significant effects.

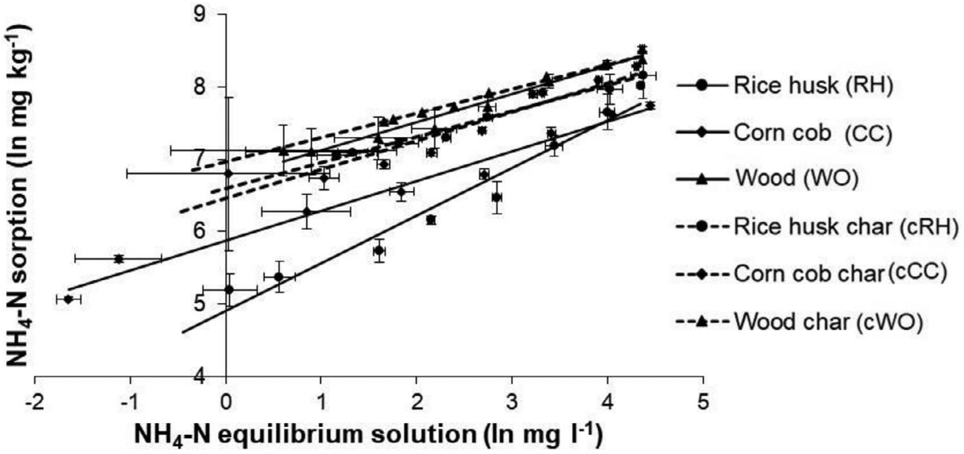

FIGURE 4 | Change of ln transformed NH_4-N sorption and NH_4-N in equilibrium solution with increasing NH_4 inputs after an incubation study in the laboratory. Linear functions were fitted. Means ± SD; $n = 3$.

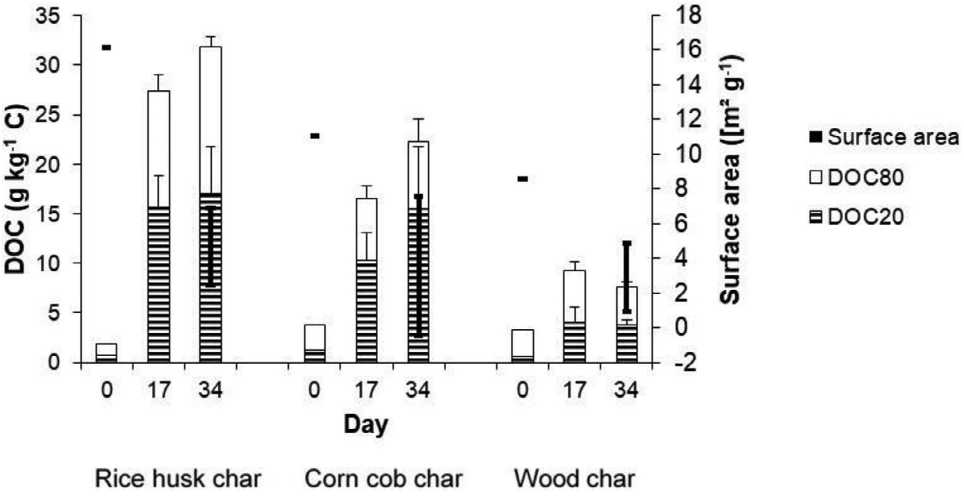

FIGURE 5 | DOC_{20} and DOC_{80} contents and BET surface area (initial and day 34) of rice husk, corn cob, and wood biochar from mesh bags over time in a field experiment in Tamale, northern Ghana. Initial values are means from fresh biochars, and all other dates are means ± SD; $n = 3$.

3.5 | Further Properties

Initial pH values ranged from 6.8 to 7.8. At the end of the composting process, pH increased at similar rates for all treatments by 0.5 units on average over all treatments. After composting, cCC and cRH had significantly higher pH values than their non-biochar feedstocks, while the wood pair had similar values (Table 2).

WHC decreased over time and was significantly higher for non-biochar (1.6 ± 0.3 L kg^{-1}) than biochar treatments (1.0 ± 0.2 L kg^{-1}) at day 34 (Table 2).

3.6 | Mesh Bag Biochar Properties

DOC contents of the mesh bag biochars increased over time (Figure 5). The increase was higher for DOC_{20} than DOC_{80}. Increase for DOC_{20} was 6.1 (wood) to 24.3 (rice husks) times higher, while DOC_{80} was 1.4 (wood) to 12.1 (rice husks) higher than their initial values. Brunauer, Emmett, and Teller (BET) surface areas showed opposite trends with a decline of 3.0 times for wood and 3.5 times for rice husks. The BET theory is commonly used to evaluate the gas adsorption data and generate a specific surface area result expressed in units of area per mass of sample (m^2 g^{-1}). In line with DOC, exchangeable cations increased by 2.3 times for rice husks, 1.3 times for corn cobs, or remained similar for wood (Figure S2).

4 | Discussion

4.1 | Effects of Biochar on C Dynamics

The dynamics of carbon during the composting process was influenced by the proportion and rate of C loss as well as accessibility of the treatment for microorganisms. The proportion of C loss during composting was lower for rice husk and wood biochar treatments compared with their counterpart non-biochar treatments but similar for corn cob. C loss was attributed to two factors. First, the pool size of easily decomposable C declined over time with decreasing supplies of labile C. Such labile C pools were represented by the extracted DOC (Ghani et al. 2003), with DOC_{80} being more active and labile than DOC_{20}, as indicated by higher correlations with C loss during incubation. Second, C stabilization that results from increased formation of stable, non-reactive humus compounds occurs as compost matures and protects C from further decomposition over time. During composting, usually, decomposition is dominant in the initial thermophilic phase, while C stabilization becomes dominant in the subsequent maturation phase (de Bertoldi et al. 1983). However, for many parameters that describe C dynamics, it is challenging to distinguish between effects caused by labile C depletion or C stabilization.

In this study, variations of C loss among treatment were attributed to the following explanation which supports the phenomena of both labile C supplies and C stabilization. First, DOC was lower for biochar than non-biochar treatments after composting and incubation, indicating a comparatively larger labile C pool remaining in the non-biochar treatments. This was consistent with previous studies (Dias et al. 2010; Jindo et al. 2012). Second, cumulative and basal respiration were lower for the biochar treatments compared with non-biochar treatments. This, however, contradicts previous findings in which an increased respiration was rather observed in composts that contained biochar compared with controls without biochar (Czekała et al. 2016; Khan et al. 2014; Steiner et al. 2011). It, therefore, becomes important to specify for which phase (thermophilic or maturation) during composting respiration is reported. However, the stimulation of microbial activity is regarded as one of the main impacts of biochar additions to compost (Steiner et al. 2015). A third reason for the variation in C loss in this study was a lower availability or more rapid depletion of labile substrates in the biochar treatments as reflected by compost temperature, which declined earlier for biochar than non-biochar treatments. Furthermore, higher or similar peak temperatures for non-biochar compared with biochar treatments were attributed to the quantity of easily decomposable C, as suggested by the correlation between temperature and basal respiration. The lack of a temperature increase by biochar addition was similar to the finding of Jindo et al. (2012) but contradicted most other studies, which found higher peak temperatures in biochar than non-biochar treatments due to the stimulation of respiration by biochar (Czekała et al. 2016; Jindo et al. 2012; Steiner et al. 2010; Wei et al. 2014). In this study, basal respiration per unit C_{mic} and time (qCO_2) was lower for biochar than non-biochar treatments, indicating a higher efficiency of microbial biomass C uptake of the remaining C of biochar treatments (Anderson and Domsch 1990). The C_{mic}/N_{mic} ratio (12.2) indicates that microbial biomass consisted of a larger proportion of fungi than bacteria (Cheng et al. 2013). Lastly, as expected, the modeled function had a tendency for relative net C losses to flatten out at higher levels for biochar than non-biochar treatments, thus supporting our initial hypothesis that biochar is much less degradable than the other compost components. To further support the effect of biochar on compost C stabilization, the DOC contents of all biochars in the mesh bags increased over time. A small increase in DOC corroborates other studies where lower C losses were attributed to DOC sorption on biochar surfaces (Prost et al. 2013; Wiedner et al. 2015). Furthermore, the negative correlations between C/N ratio and C loss as well as DOC contents suggested that limited supplies of labile C accounted for C loss patterns.

Microbial C (C_{mic}) was not different for biochar and non-biochar treatments. Some studies have reported an increase in C_{mic} in compost with biochar additions (Khan et al. 2014). However, Jindo, et al. (2012) reported lower C_{mic} with 2% biochar addition to compost compared with non-biochar treatments and related it to variations in labile C. We reasoned that in both Jindo, et al. (2012) and other studies with a similar experimental duration, C_{mic} in non-biochar treatments would likely decline in the course of further decomposition of labile C if the experimental periods were prolonged. Therefore, although we conclude that labile C supplies and degree of C stabilization explained quantities of C loss, further measurements are necessary to confirm the degree of C stabilization and labile C depletion. Contents of both DOC fractions of the corn cob non-biochar treatment (CC) were the largest after composting, indicating the largest remaining labile C pool among all treatments. Moreover, higher C_{mic} per unit total C for the CC treatment indicated a larger C availability for microorganisms compared with the other treatments. This large labile C pool was attributed to the large particle size and high structural stability of the corn cobs. Apparently, the accessibility of C for microorganisms was largely limited to the surface of the particles. It is reasonable to assume that C decomposition of CC will increase beyond C loss of corn cob biochar (cCC) treatment over time which would support the conclusion that all biochar treatments have lower C losses than non-biochar treatments. Notwithstanding, large C losses despite biochar addition have been reported by other studies. For example, Dias et al. (2010) observed a C loss of 70%, despite biochar additions, while a range of C losses between 50% and 70% were reported for manure composting without biochar additions (Bernal et al. 2009).

The temperature curves indicated that the observed timeframe covered largely the thermophilic phase of composting and only the beginning of the maturation phase. Large C losses and a long thermophilic phase in this study were attributed to the optimum conditions for microorganisms, such as high surrounding temperatures (often higher than 30°C), moisture contents between 50% and 60%, high nitrogen supply, sufficient pore volume and oxygen, and frequent compost turning.

Despite the relative stability of C in biochar treatments compared with non-biochar treatments, however, at least 18% of the added corn cob biochar-C was subject to decomposition, which also likely affected the easily decomposable pools of rice husk and wood biochar. Biochar-C losses were attributed to the high volatile matter contents of the used biochars (Table 1). High volatile matter contents and high hydrogen/carbon (H/C) ratios of biochar indicate a large pool of easily decomposable biochar (Enders et al. 2012). Contrarily, biochar with a low H/C ratio was largely recalcitrant in the studies of Prost et al. (2013). The decomposition of biochar's volatile matter during composting could be of advantage because high volatile matter contents may lead to high C/N ratios and potential N immobilization after field application.

With respect to the rate of carbon loss, fitted C decomposition rates (C loss per unit time) were higher for biochar than non-biochar treatments indicating a faster decomposition of biochar treatments. Higher C decomposition rates have been reported by previous studies, next to higher peak CO_2-C emissions in biochar treatments (Dias et al. 2010; Steiner et al. 2010).

4.2 | Biochar Effects on N Retention

N losses were lower for rice husk and wood biochar compared with non-biochar treatments. This was attributed to lower N_2O and NH_3 emissions from cRH and cWO observed by Manka'abusi et al. (2018) from the same experiment. But N loss was higher for cCC compared with CC corresponding to higher NH_3 volatilization from cCC treatments. This N loss was connected to the high pH values and dominantly aerobic conditions (de Bertoldi et al. 1983). After composting, the remaining N can be divided in a labile organic N pool (such as amino sugars, proteins, or amino acids) and a stable organic N pool. In line with DOC, TSN represented labile N pools, as indicated by the correlation with N_{mic} and N loss during incubation. N dynamics are a function of N loss and N retention. In this study, NH_4-N sorption was higher for biochar than non-biochar treatments. This is in line with most other studies (Hua et al. 2009; Khan et al. 2014). For example, Steiner et al. (2010) found a 52% increase of N retention with 20% biochar addition during co-composting with poultry litter compared with the control without biochar. Second, total NH_4-N contents in this study were higher for biochar than non-biochar treatments. Lastly, TSN_{20} and TSN_{80} were lower for biochar than non-biochar treatments. The lower N losses of cRH and cWO compared to their non-biochar counterparts were attributed to N retention by sorption of NH_4-N and soluble NH_4-N. Therefore, low N loss after composting of CC were attributed to the high remaining supply of labile N as well as N_{mic} (although N_{mic} was not significant).

With increasing C/N ratio, N loss and TSN decreased, but total and adsorbed NH_4-N increased, while no correlation was found with N_{mic}. Apparently, not N but labile C supplies limited organic C and N decomposition and led to the accumulation and sorption of NH_4-N instead of its incorporation into microbial biomass.

The lack of correlations with NO_3-N suggested that NO_3-N did not explain variations in N dynamics. However, as suggested by Kammann et al. (2015), NO_3-N may not have been entirely detected by the conventional extraction with K_2SO_4.

4.3 | Biochar as Bulking Agent

Biochar has been suggested as a bulking agent for co-composting to facilitate aeration (Steiner et al. 2010). However, the efficiency of bulking agents depends on their porosity (surface area), particle size, and structural stabiliy to prevent the physical compaction over time (Dias et al. 2010).

With regard to particle size, rice husk biochar and the small charcoal particles were less efficent than the coarser corn cob biochar. Nevertheles, in terms of structure, all biochars were suitable, despite partial decomposition of corn cob biochar. Rice straw, fresh corn cobs, and coarse sawdust are also frequently used as bulking agents. Rice straw provided structural stability and a high pore volume in the first days but also high insulation. In the context of hot climates, insulation that supports hot and long thermophilic phases is of advantage for pathogen removal but of disadvantage for efficient composting (de Bertoldi et al. 1983). In the course of composting, the rice straw structure colapsed, resulting in clumps; thus, its efficiency as bulking agent declined. Further, particles with a small diameter, for example, rice husks, isolate better than coarse particles, for example, corn cobs. The higher and longer lasting high temperature of RH was attributed to isolation effects. With respect to structure, corn cobs were too stable for efficient composting making sieving of the mature compost proportion necessary before field application. Hence, overall, corn cob biochar was the most effective bulking agents of the present study.

4.4 | Biochar Effects on CEC and Surface Area

Increasing effective CEC of mesh bag biochars over time went along with higher NH_4-N sorption of biochar than non-biochar treatments after composting. Increasing CEC of biochars is often attributed to increasing DOC contents over time (Singh et al. 2014; Wiedner et al. 2015). In line with our findings, other studies also found an increase of DOC and CEC of biochar particles (Prost et al. 2013). The high sorption capacity of DOC is well known (Kalbitz and Knappe 1997). However, NH_4-N sorption was lower for DOC rich non-biochar than biochar treatments, indicating that not only DOC but also other factors, such as abiotic oxidation (also known as aging), contributed to the increase of CEC of biochars. Abiotic oxidation may be accelerated under high temperatures such as during composting (Joseph et al. 2010).

Initial surface areas of all biochars were in a range of low activity clays, such as kaolinite (Petersen et al. 1996), thus, very small but in line with the low temperature (400°C) biochars studied by Mukherjee et al. (2011). Over time, surface area declined even further, which was attributed to pore clogging by organic matter (Prost et al. 2013) as indicated by the increase of DOC contents.

4.5 | Biochar Effects on pH

Higher or similar pH values for biochar compared with non-biochar treatments are consistent with previous findings (Zhou et al. 2022). This suggested that the ash fraction of the biochars added basic cations to the composts. The same liming potential of biochars has been reported for soils (Chintala et al. 2014). However, during composting, higher pH values may also lead to higher NH_3 losses. The increase of pH of all treatments over time is a common observation (Wang et al. 2013) and was attributed to the release of exchangeable cations from organic matter in the course of decomposition.

5 | Conclusion

Overall, the combination of carbonized feedstocks such as rice husk, corn cobs, and wood with compost decreases microbial C decomposition during the composting process compared with untreated feedstock additions. Due to increasing sorption capacity of added biochar material, labile DOC and nitrogen in form of

NH_4-N are fixed and consequently saved from microbial degradation and leaching. NH_4-N sorption capacity of the composts increased highest in composts treated with rice husk, followed by wood and corn cob biochars compared with non-biochar-treated composts. Microbial biomass was not enhanced by biochar addition in comparison with the non-biochar control which contradicts other studies which describe microbial biomass increase due to biochar presence. Also, the temperature rise in the biochar-treated compost declined earlier during the whole composting process than in non-biochar controls, potentially caused by less C availability due to sorption to the biochar pores. Nevertheless, the positive effects of biochar addition to compost during co-composting procedure causing NH_4-N-retention and labile C fixation need further investigation to determine the soil and crop response after field application, the magnitude of biochar effects at lower or higher rates of biochar addition as well as biochar effects during co-composting with other feedstocks.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.