

## Reducing Nitrogen Loss during Poultry Litter Composting Using Biochar

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Poultry litter (PL) is a potentially underused fertilizer because it contains appreciable amounts of N, P, K, and micronutrients. However, treatments like composting to reduce potential pathogens, weed seeds, and odor often result in high losses of N through  $\text{NH}_3$  volatilization. Biochar (BC) has been shown to act as an absorber of  $\text{NH}_3$  and water-soluble  $\text{NH}_4^+$  and might therefore reduce losses of N during composting of manure. We produced three PL compost mixtures that consisted of PL without added BC (BC0), PL + 5% BC (BC5), and PL + 20% BC (BC20). The BC was produced from pine chips and used without further modifications. Three replicates of each treatment were placed in nine bioreactors to undergo composting for 42 d. The entire composting experiment was repeated three times in a complete-block design. Moisture content, temperature, pH, mass loss, gas ( $\text{NH}_3$ ,  $\text{CO}_2$ ,  $\text{H}_2\text{S}$ ) emissions, C, and nutrient contents were measured periodically throughout the experiments. Results showed no difference in PL mass loss with BC addition. Moisture content decreased, pH increased significantly, and peak  $\text{CO}_2$  and temperatures were significantly higher with BC20 compared with BC0. These results indicate a faster decomposition of PL if amended with BC. Ammonia concentrations in the emissions were lower by up to 64% if PL was mixed with BC (BC20), and total N losses were reduced by up to 52%. Biochar might be an ideal bulking agent for composting N-rich materials.

**I**N 1997, THE POULTRY INDUSTRY in the United States produced 576,436 Mg of N and 276,932 Mg of P in the form of poultry litter (PL) (Gollehon et al., 2001). This makes PL a potentially important resource of plant nutrients; however, storage and direct land application of untreated PL has disadvantages such as odors, pathogens, or fly breeding material (Kithome et al., 1999).

Direct combustion, pyrolysis (thermochemical conversion without oxygen) (Cantrell et al., 2007; Schnitzer et al., 2007; Tagoe et al., 2008), and composting (Kithome et al., 1999) have been suggested as mechanisms to produce a stabilized PL product (biochar [BC], ash, or compost) that can be used as fertilizer with little or no adverse effects. The disadvantage of these methods is a considerable loss of N. Nitrogen content decreases rapidly with increasing temperature if PL is directly combusted (Faridullah et al., 2008). Gaskin et al. (2008) found that even at relatively low temperatures (400 and 500°C), pyrolysis of PL resulted in large N losses (69 and 76%, respectively). Nitrogen begins to volatilize at 200°C, and alterations in chemical structure during carbonization of biomass have long-term consequences for N availability (Knicker and Skjemstad, 2000). Nitrogen is also lost during composting through  $\text{NH}_3$  volatilization. Ogunwande et al. (2008) found a cumulative N loss to vary between 71 and 88% during composting of PL. This reduces the fertilizer potential and economic value of the product while causing environmental pollution (Kithome et al., 1999).

The high N concentration and low C/N ratio in PL favors  $\text{NH}_3$  volatilization during composting. Attempts have been made to reduce volatilization losses by increasing the C/N ratio or by using adsorbents such as zeolite (Kithome et al., 1999). Adding waste materials with a high C/N ratio can help to immobilize some of the N but may reduce the speed of decomposition. Materials like zeolite have been shown to adsorb  $\text{NH}_3$ , but they are more effective when applied on the surface than when mixed into PL (Kithome et al., 1999). Adsorbed N is not available for crops if the zeolite is not land applied or if the adsorbed N is not plant available.

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**Abbreviations:** BC, biochar; BC0, 0% biochar additions, by weight; BC5, 5% biochar additions, by weight; BC20, 20% biochar additions, by weight; LI, load in (initial sample); LO, load out (final sample); MC, moisture content; PL, poultry litter.

Recent research on BC as a soil amendment has shown beneficial effects on soil fertility apart from its nutrient content (Glaser et al., 2002; Lehmann et al., 2003; Steiner et al., 2007). Biochar (charcoal not used as a fuel) may retain  $\text{NH}_4\text{-N}$ . Steiner et al. (2008) found increased recovery of  $^{15}\text{N}$ -labeled N fertilizer on charcoal-amended soil in comparison to soil without charcoal. The N retained may be plant available because increased plant growth was seen in BC-amended and N-fertilized soil compared with the unamended soil under heavy leaching conditions (Steiner et al., 2007). Lehmann et al. (2003) found decreased  $\text{NH}_4^+$  leaching in soils amended with BC and manure.

Activated C adsorbs  $\text{NH}_3$  (Rodrigues et al., 2007), but it is expensive. Iyobe et al. (2004) showed that woody charcoal produced at  $500^\circ\text{C}$  had a higher capacity for  $\text{NH}_3$  adsorption than the activated C. Biochars generated at low pyrolysis temperatures can also adsorb  $\text{NH}_3$  if acidic functional groups are present on the BC surface or if the BC has a low pH (Kastner et al., 2009).

Although BC has the potential to reduce N losses during composting, its use would add a substantial amount of C. Cereal straw, cotton waste, and wood wastes are most frequently used as bulking agents in manure composting operations. They influence substrate properties such as pore space, moisture adsorption, C/N ratio, and particle density. However, the addition of available C may negatively influence compost stability (Adhikari et al., 2009). Due to its recalcitrance, the use of BC as a bulking agent should not result in the addition of readily available C, and thus its use would not increase the effective C/N ratio.

We hypothesized that co-composting PL with BC might minimize  $\text{NH}_3$  volatilization by adsorbing precursors such as  $\text{NH}_4^+$ , urea, and uric acid without reducing the speed of decomposition and the stability of the final product.

## Materials and Methods

### Materials, Treatments, and Study Design

We obtained PL from a broiler house in North Georgia in May 2008. The litter was stored outside in large covered bins until it was used for the experiments (Run 1 was initiated in June 2008, and Run 3 was completed in January 2009). The C and nutrient content of the PL is summarized in Table 1.

Biochar was produced from pine chips in a large batch reactor at  $400^\circ\text{C}$ . The BC had a C content of  $758.7 \text{ g kg}^{-1}$  and

nutrient contents of  $2.6 \text{ g N kg}^{-1}$ ,  $0.4 \text{ g S kg}^{-1}$ ,  $0.18 \text{ g P kg}^{-1}$ ,  $2.0 \text{ g K kg}^{-1}$ ,  $2.7 \text{ g Ca kg}^{-1}$ , and  $0.5 \text{ g Mg kg}^{-1}$ . Pine chip BC obtained after pyrolysis was used without further modification. Particle size fractionation showed that 82% of the BC was in a particle size range of 1.2 to 16.0 mm. The majority (54%) was found between 4.0 and 9.5 mm.

The experiment was run three times (Run 1, Run 2, and Run 3) in a complete-block design with three replicates per treatment. For each run, three compost mixtures were prepared on a dry weight basis with the fresh weight ranging from 23 to 25 kg: PL (BC0), 95% PL + 5% by weight BC addition (BC5) and 80% PL + 20% by weight BC addition (BC20). Water was added by weight to achieve a gravimetric moisture content (MC) of 60%, and the materials were mixed using a rototiller. Randomization was restricted within each replication of the run so that treatments were uniformly distributed.

Each treatment was placed in a bioreactor to undergo composting for 42 d. The bioreactors were insulated stainless steel vessels with a diameter of 0.4 m and a volume of  $0.06 \text{ m}^3$ . The insulation reduced heat loss, thus mimicking conditions in a large compost pile. A detailed description of the bioreactors is provided in Das et al. (2001) and Das and Tollner (2003). Temperature in the reactors was monitored using two T-type thermocouples at 0.25 and 0.37 m from the surface in each barrel. When the compost temperature exceeded  $65^\circ\text{C}$ , the temperature was controlled by pumping ambient air through the bottom of the vessel at a rate of  $1.7 \text{ m}^3 \text{ h}^{-1}$ . Otherwise, air was introduced every 20 min for 30 s, providing an effective aeration of  $0.04 \text{ m}^3 \text{ h}^{-1}$ . The temperature was recorded daily. The compost was homogenized once a week by mixing the contents of each bioreactor with a shovel in a clean wheelbarrow. At homogenization, the total mass of the compost was measured, and samples were taken for MC and pH.

Moisture content was evaluated by drying a 200-g subsample in an oven at  $105^\circ\text{C}$  for 24 h. Another subsample was dried (at  $105^\circ\text{C}$ ) and stored for nutrient analysis. Carbon dioxide,  $\text{O}_2$ ,  $\text{NH}_3$ , and hydrogen sulfide ( $\text{H}_2\text{S}$ ) were measured daily in the headspace of each barrel by discontinuing aeration to the barrel system for 30 min, withdrawing a gas sample with a gas sample drawing monitor (Eagle; RKI Instruments, Inc., Union City, CA) for 2 min, and recording gas concentrations. The monitor has a maximum variance of  $\pm 5\%$  and a detection range of 0 to  $400 \text{ mL L}^{-1}$ , 0 to  $500 \text{ mL L}^{-1}$ , and 0 to

**Table 1.** Total carbon and nutrient contents in the compost mixes.

| Sampling time | Biochar content    | pH     | C                  | N     | C/N   | S    | P     | K                  | Ca    | Mg    |
|---------------|--------------------|--------|--------------------|-------|-------|------|-------|--------------------|-------|-------|
|               | $\text{g kg}^{-1}$ |        | $\text{g kg}^{-1}$ |       |       |      |       | $\text{g kg}^{-1}$ |       |       |
| LI†           | 0                  | 8.70a‡ | 370.0b             | 35.6a | 10.4b | 5.3a | 16.6a | 35.7a              | 29.1a | 6.0a  |
|               | 50                 | 8.66ab | 374.6b             | 34.9a | 10.8b | 5.3a | 14.8b | 31.2b              | 25.5b | 5.5ab |
|               | 200                | 8.55b  | 458.8a             | 29.6b | 15.7a | 4.1b | 13.9b | 27.7c              | 24.4b | 4.9b  |
| LO            | 0                  | 9.15b  | 296.4c             | 30.4a | 9.8c  | 6.7a | 27.2a | 50.5a              | 47.7a | 11.0a |
|               | 50                 | 9.13b  | 349.7b             | 29.9a | 11.8b | 7.0a | 24.9b | 46.9b              | 43.9a | 10.6a |
|               | 200                | 9.27a  | 426.6a             | 27.5b | 15.6a | 6.5a | 20.3c | 37.2c              | 32.8b | 9.0b  |

† LI, load in (initial sample); LO, load out (final product after 42 d).

‡ Homogenous subgroups are indicated by the same letter (ANOVA; Student-Newman-Keuls post hoc test;  $p < 0.05$ ;  $n = 9$ ).

100  $\mu\text{L L}^{-1}$  for  $\text{O}_2$ ,  $\text{CO}_2$ , and  $\text{H}_2\text{S}$ , respectively. Ammonia was measured with  $\text{NH}_3$  sample tubes (RAE Systems, San Jose, CA) using a hand pump and sample tubes with a range of 5 to 100  $\mu\text{L L}^{-1}$  or 25 to 500  $\mu\text{L L}^{-1}$  (depending on concentration). The colorimetric tubes have a precision of no more than  $\pm 12\%$  and use the following reaction principle:  $3\text{NH}_3 + \text{H}_3\text{PO}_4 \rightarrow (\text{NH}_4)_3\text{PO}_4$  (Gas Detection Tube Data Sheet, www.raesystems.com).

## Total Elemental Analysis and pH Measurements

Chemical analysis (except C, N, and S) were conducted by extracting and digesting 0.5 g of dry material with 10 mL of 15.8 mol  $\text{L}^{-1}$  nitric acid (Method 3050B, USEPA, 1996) in HP500 microwave vessels and a CEM Mars Express microwave digestion system (CEM, Matthews, NC). The extracts were diluted with deionized water, and total elemental concentrations were measured using an inductively coupled plasma atomic emission spectrometer (Model 61E ICP; Thermo Jarrell-Ash, Franklin, MA).

Carbon, H, N, and S were measured simultaneously in finely ground 1-mg samples. Each sample was measured in three replicates by combustion (CHNS-932; LECO, St. Joseph, MI). Sulfamethazine was used as a standard for calibration.

The pH was measured in a 40 mL 1:2 v/v solution of sample in deionized water. The mixture was allowed to equilibrate for 30 min with occasional stirring with a glass rod. The resulting solution was filtered through Whatmann No. 4 filter paper, and pH was measured using an Accumet 50 pH/EC meter (Accumet, Hudson, MA).

## Mass Loss Calculation and Carbon and Nitrogen Balance

The bioreactors were weighed before and after homogenization to determine the weight of the subsamples removed from the compost. Removed sample weights were weekly corrected for decomposition and added to the compost weight recorded. It was assumed that the BC did not undergo significant decomposition during composting; consequently, weight was subtracted from the total compost weight. The BC/PL ratio was calculated from the corrected mass loss every week, which allowed us to determine the C and N balances on the PL component of the mixes.

## Statistical Analysis

Treatment effects were analyzed by general linear model univariate and repeated measures ANOVA in a complete-block design. Homogeneous subsets were separated by the Student-Newman-Keuls test. Statistical analyses and plots were performed using SPSS Statistics 17.0 and SigmaPlot (SPSS Inc., Chicago, IL).

## Results and Discussion

### Composting Process

Values of  $\theta_g$  were not significantly different between the treatments ( $n = 9$ , univariate ANOVA) at load in (LI, initiation of the composting), but the BC5 treatment received too much water by mistake in Run 3 (mean, 66.6% compared with 60%). Run 3 differed also in temperature patterns because the ambient air was considerably colder. The

average temperatures in the building where the barrels were located were 25.3, 22.3, and 15.4°C for Run 1, Run 2, and Run 3, respectively. At load out (LO, last compost sample taken), the  $\theta_g$  of the treatments were significantly different (mean BC20 = 58.4%, BC5 = 61.4%, and BC0 = 63.5%;  $p < 0.01$ ;  $n = 9$ ). The MC increased in the BC0 and BC5 composts but decreased in the BC20 ( $p < 0.05$ ) (Fig. 1) over the course of decomposition. The greatest change in MC in the BC20 occurred during the first week. In the BC20 treatment, the BC may have enhanced compost aeration, leading to a reduced MC. Other studies producing compost in relatively closed barrels found that the amount of water released through microbial activity can exceed the amount lost through evaporation (Viel et al., 1987; Fernandes et al., 1988).

The composting runs had significantly different peak temperatures in the first week (repeated measures  $p < 0.01$ ;  $n = 9$ ). Run 3 had the lowest peak temperature (50.1°C), followed by Run 2 (61.8°C) and Run1 (66.0°C). One reason for this difference might have been cooler ambient temperatures in December than in June (15.4 vs. 25.3°C). In addition, the PL was stored outside, and the initial microbial community was probably influenced by the low temperatures.

The high MC in the BC5 treatment in Run 3 further reduced the peak temperature significantly. Therefore, treatment BC5 was excluded from temperature analysis. The peak temperature reached after initiation of composting (Week 1) was significantly higher ( $p < 0.01$ ) in the 20% BC treatment than in the BC0 barrels (65.1 and 58.2°C, respectively) (Fig. 2). Also, the time to reach the maximum temperature was shorter in the barrels with BC20. The mean temperature during the first week was significantly higher in the BC20 treatment (50.4°C) than in the BC0 treatment (46.8°C; repeated measures,  $p < 0.01$ ;  $n = 9$ ). The difference in peak temperature could have been even greater if the aeration had not been set to limit the maximum temperature at 65°C. This might have caused unequal aeration of the treatments, with implications for gaseous emissions and MC. However,

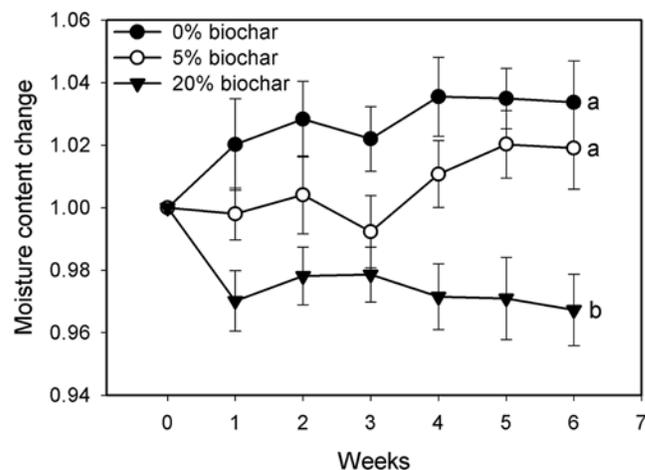


Fig. 1. Normalized weekly changes in moisture content during the composting of poultry litter with and without pine chip biochar amendment (paired samples  $t$  test for the increase and ANOVA and Student-Newman-Keuls comparison; letters indicate significant differences; means and SE;  $n = 9$ ;  $p < 0.05$ ).

the threshold temperature was not reached in Run3, and we could measure equal patterns in moisture and NH<sub>3</sub> reductions. Moreover, the temperatures in Run 2 exceeded 65°C only in two barrels and only on Day 3. Oxygen availability during the composting process is critical (Bertoldi et al., 1983). The BC particles may have decreased bulk density and increased aeration. Peak temperature was also significantly higher in the Week 2 ( $p < 0.05$ ). In Week 3, the BC-amended compost did not differ from that without amendment, but in Week 4, the BC-amended compost had lower peak temperatures (Fig. 2). This indicates a faster initiation of the composting process with BC addition. Hua et al. (2009) did not find differences in peak temperatures when composting sewage sludge with bamboo charcoal, but the highest rate of BC in that study was only 9%, which may have been too low to show a marked impact.

The C content did not differ significantly between Runs 1, 2, and 3 (Table 1). The BC20 treatment had a significantly higher C content than the BC0 and BC5 treatments but had significantly less total N ( $p < 0.01$ ) at LI and LO. Biochar co-composting significantly reduced the nutrient contents of the resultant mixtures primarily due to dilution with the relatively low nutrient content of the BC. This was the case for LI and LO samples except for sulfur (S). The S content was significantly lower in BC20 at LI but not at LO. This indicates reduced losses of S due to gaseous emissions. All observed nutrient concentrations except N increased during the composting process. Total N decreased significantly during composting in BC0 and BC5 but not in BC20 (paired-samples  $t$  test;  $n = 9$ ). This is in contrast to Hua et al. (2009), who found increasing N concentrations in decomposing sludge with a much lower N concentration than the PL used in this study. The C/N ratio did not change significantly during the course of composting, but total C decreased in BC0 and BC5 ( $p < 0.01$ ). The C/N ratio remained below 16 even in the BC20 treatment. At this ratio, N immobilization would not happen even if all the BC C was available (Epstein, 1997).

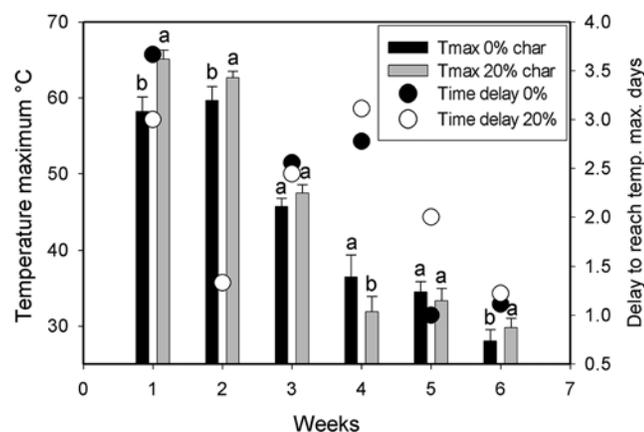


Fig. 2. The influence of pine chip biochar on peak temperatures (Tmax) and the time delay to reach maximum temperature after weekly compost (poultry litter) mixing (ANOVA and Student-Newman-Keuls comparison; letters indicate significant differences; means and SE;  $n = 9$ ;  $p < 0.05$ ).

The initial pH of the compost was slightly but significantly lower (Table 1) when amended with 20% BC at LI. In contrast, the pH of BC20 was significantly higher at LO (Fig. 3). The increased pH in BC20 may be due to faster and more complete decomposition in the BC-amended compost. The pH is known to increase in composts due to the degradation of acids (Gajalakshmi and Abbasi, 2008). An increased retention of NH<sub>4</sub><sup>+</sup> in the BC20 could also have contributed to the pH increase (Kelleher et al., 2002).

No differences could be detected in mass loss. The sensitivity of the scale made small differences difficult to detect. However, the total dry weight (including BC weight) conserved was highest ( $p < 0.01$ ) in BC20, with 76.8% of the original mass remaining, in comparison to 70.2 and 71.8% in BC0 and BC5, respectively. Calculating for PL weight only, the treatments did not differ significantly, and 70.2, 70.3, and 70.9% of PL matter remained in BC0, BC5, and BC20, respectively. Run 3 conserved more PL C than Run 1 and Run 2 (71.7, 53.6, and 54.5%, respectively), and more total DM was conserved in Run 3 (79.9%) in comparison to Run1 (64%) and Run2 (67.5%).

### Gaseous Emissions of Carbon, Nitrogen, and Sulfur

Hydrogen sulfide was present in measurable concentration only during the first 5 d. The concentrations of H<sub>2</sub>S in the headspace of the compost barrels were significantly greater without BC amendments (1.4, 2.0, and 4.8 μL L<sup>-1</sup> for BC20, BC5, and BC0, respectively) (Table 2). This represents a reduction in H<sub>2</sub>S of 58 and 71% for BC5 and BC20, respectively. Calculating for PL mass only, the H<sub>2</sub>S concentration was significantly reduced in BC20 barrels ( $p < 0.05$ ) (Table 2). Again, the reduction may be the result of improved aeration created by BC addition. However, the O<sub>2</sub> demand was very high in the first few days, and O<sub>2</sub> concentrations reached minimum values of 0% after the aeration system was disconnected for measurements.

Ammonia concentrations peaked after each (weekly) mixing of the compost (Fig. 4a). Mean concentrations were significantly ( $p < 0.01$ , repeated measures) reduced in the

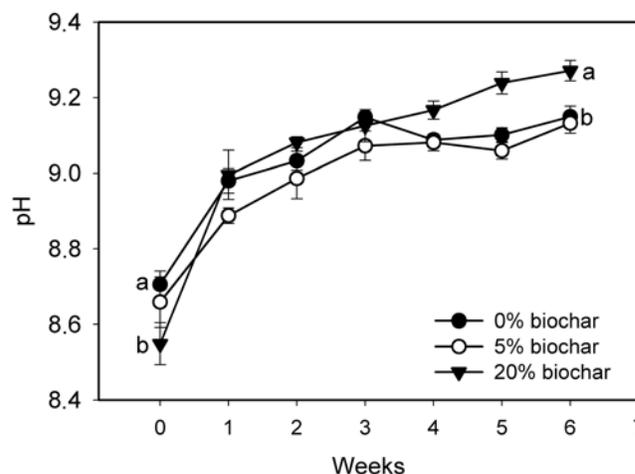


Fig. 3. Changes in pH during the course of poultry litter decomposition (ANOVA and Student-Newman-Keuls comparison at load in and load out; letters indicate significant differences; means and SE;  $n = 9$ ;  $p < 0.05$ ).

**Table 2. Mean headspace concentrations of carbon dioxide, ammonia, and hydrogen sulfide in the composting barrels.**

| Gas                                  | Biochar content<br>g kg <sup>-1</sup> | Run 1 | Run 2   | Run 3 | Mean   |
|--------------------------------------|---------------------------------------|-------|---------|-------|--------|
| CO <sub>2</sub> , mL L <sup>-1</sup> | 0                                     | 32    | 47      |       | 37     |
|                                      | 50                                    | 29    | 43      |       | 35     |
|                                      | 200                                   | 33    | 47      |       | 37     |
| NH <sub>3</sub> , μL L <sup>-1</sup> | 0                                     |       | 162.2a† | 69.2a | 117.4a |
|                                      | 50                                    |       | 149.6a  |       |        |
|                                      | 200                                   |       | 73.5b   | 49.5b | 62.3b  |
| H <sub>2</sub> S, μL L <sup>-1</sup> | 0                                     | 8.9a  | 2.1a    |       | 4.8a   |
|                                      | 50                                    | 3.5b  | 0.5a    |       | 2.0ab  |
|                                      | 200                                   | 1.7b  | 1.1a    |       | 1.4b   |

† Homogenous subgroups are indicated by the same letter (repeated measures ANOVA; Student-Newman-Keuls post hoc test;  $p < 0.05$ ;  $n = 3$ , totals:  $n = 6$ ). Values are corrected for poultry litter mass.

‡ Hydrogen sulfide was only in measureable concentration during the first 5 d. Carbon dioxide and H<sub>2</sub>S were only measured in the first two runs because of a malfunction of the gas analyzer. Ammonia was not measured in the first run.

BC20 treatment. The mean reduction was 58% (47% if corrected for PL mass) and was highest during Run 2, with a reduction of 64% (55% if corrected for PL mass). The emissions of NH<sub>3</sub> from animal manure are influenced by pH, the NH<sub>4</sub><sup>+</sup>-NH<sub>3</sub> equilibrium, and mineralization intensity (Martins and Dewes, 1992). The original (un-composted) biomass used in this study had a pH value above 7, which favors NH<sub>3</sub> losses. During composting, the pH rose to above 9 and was highest in the BC20 treatment. This makes changes in pH unlikely to be the cause of reduction in NH<sub>3</sub> volatilization. Because BC is recalcitrant, we did not effectively change the C/N ratio. Neither mineralization intensity nor temperature decreased with BC amendments. The most likely mechanism by which the losses of NH<sub>3</sub> were reduced might have been NH<sub>4</sub> adsorption by the BC. This has been observed in fertilized soils (Lehmann et al., 2003, Steiner et al., 2008) and in compost (Hua et al., 2009).

Kithome et al. (1999) found the use of adsorbents such as zeolite and coir pith to be most suitable for reducing NH<sub>3</sub> losses during composting of PL. A layer of 38% zeolite placed on the surface of the manure reduced NH<sub>3</sub> losses by 44%, whereas 33% coir placed on the surface reduced the losses by 49%. Low-temperature (400–500°C) BCs are significantly cheaper than activated C because they do not require a costly second activation step. Biochar availability may increase if pyrolysis of biomass is used as an alternative energy source (Bridgwater, 1999). In addition, the NH<sub>3</sub> adsorption capacity can be as high as that of activated C, depending on biomass source and production temperature (Iyobe et al., 2004; Kastner et al., 2009). Consequently, BC may be useful in reducing NH<sub>3</sub> emissions from composting high-N wastes such as animal manures.

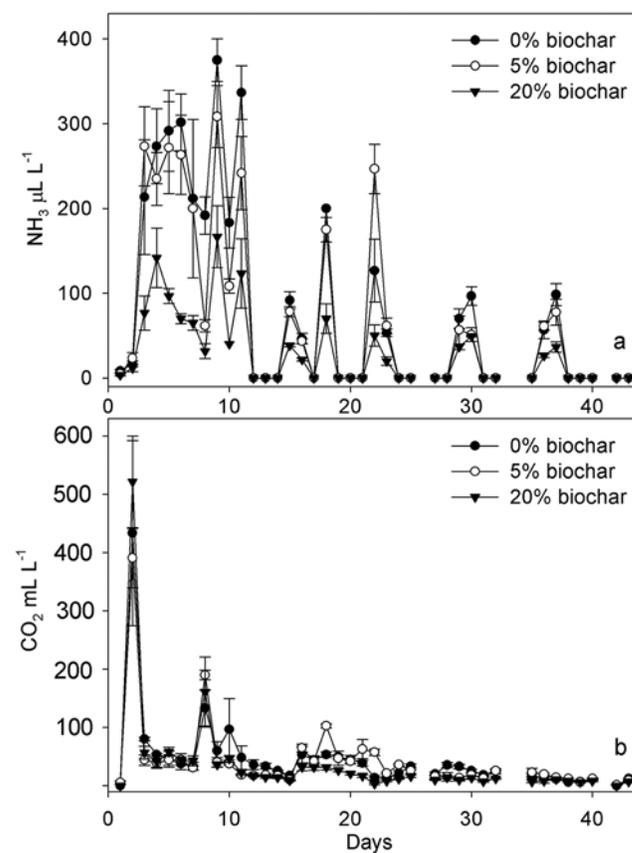
The overall CO<sub>2</sub> concentrations in the barrels did not differ significantly between treatments (Table 2; Fig. 4b). However, the first CO<sub>2</sub> peak was significantly higher in BC20 than in barrels containing BC0 (36.5, 39.9, and 50.5% for BC0, BC5, and BC20, respectively). This might have been limited by the O<sub>2</sub> supply, which was completely consumed. The increased

peak temperatures corroborate the increased CO<sub>2</sub> evolution in compost with BC.

## Carbon and Nitrogen Balance

Carbon originating from PL represented 90.3% in the BC5 and 66.1% in the BC20 treatment. Due to the very low N content of pine chip char, most of the N in the mixtures originated from PL and represented 99.6% in BC5 and to 98.2% in BC20 treatment. More N was retained in BC20 compost than in BC0 compost in Runs 1 and 2. Run 3 did not show significant differences due to lower activity in general. The losses of N were 49.0% in BC0, 47.6% in BC5, and 31.3% in BC20 and were 44.3, 48.4, and 21.2%, correspondingly, in Run 1 and Run 2. In total, the BC20 compost lost significantly less N (26.7%;  $p < 0.01$ ) than the BC0 (39.5%) and BC5 (37.3%) treatments (Fig. 5a).

Ogunwande et al. (2008) recorded N losses in composting ranging from 70.73 to 88.17%, where the lower value was obtained by adding sawdust to increase the C/N ratio to 25:1. Average N losses of 40% were reported by Raviv et al. (2002), which are similar to the losses measured in the current study. Leaching of N did not occur in this study, and NH<sub>3</sub> volatilization is generally the predominant loss of N.



**Fig. 4. Headspace concentration of (a) NH<sub>3</sub> and (b) CO<sub>2</sub> in the barrels over the course of poultry litter composting (Run 2; means and SE;  $n = 3$ ).**

The treatments lost equal amounts of PL C and conserved 56.4, 60.3, and 63.6% in BC0, BC20, and BC5, respectively (Fig. 5b). The total C amounts remaining (not corrected for PL) were in the order BC20 > BC5 > BC0, with 73.8, 67.2, and 56.4% of original C conserved, respectively ( $p < 0.05$ ). This demonstrates the recalcitrant nature of carbonized materials and supports the assumption that BC C remained relatively inert during the composting process.

## Conclusions

Changes in pH and MC along with greater peak temperatures and greater CO<sub>2</sub> respiration in the BC treatments suggest that the composting process was more rapid if PL was amended with BC. More detailed respiration measurements are necessary to delineate differences in decomposition speed. The addition of BC reduced emissions of NH<sub>3</sub>, significantly reducing losses of N, and also reduced H<sub>2</sub>S emissions. Biochar addition during composting did not change the effective C/N ratio because BC C was largely unaffected by microbial decomposition. As a result, mineralization rates of labile C remain high, and the BC component of the compost provides enhanced durability when applied as a soil amendment with important implications for C sequestration. A high mineralization intensity and conservation of N are favorable for composting, in particular for composting N rich manures. Further studies should delineate the N release from charcoal particles and its environmental and agronomic consequences.

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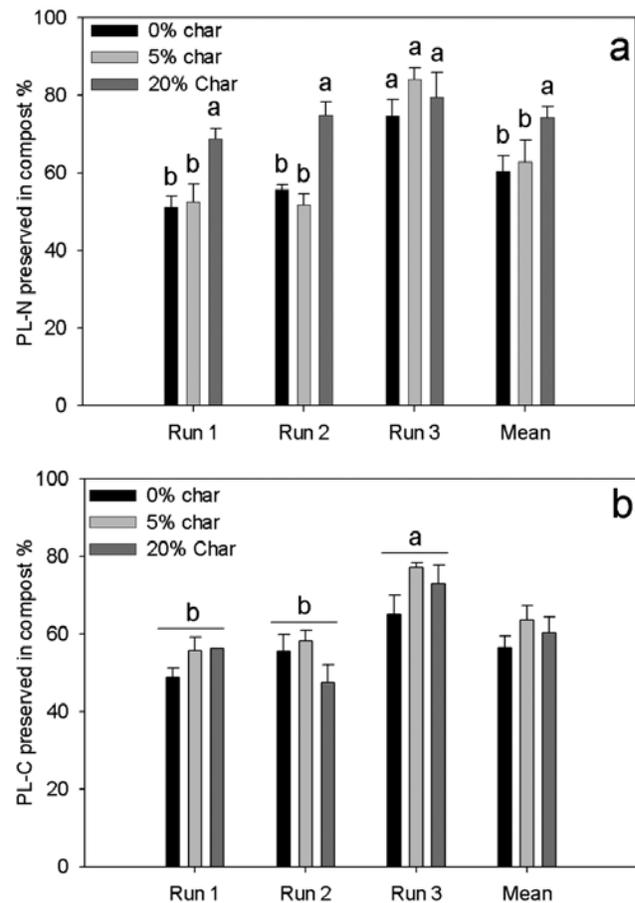


Fig. 5. Losses in (a) poultry litter nitrogen (PL-N) and (b) poultry litter carbon (PL-C) during the course of decomposition. Run 3 is higher due to lower decomposition rates in winter (ANOVA and Student-Newman-Keuls comparison; letters indicate significant differences; means and SE;  $n = 9$ ;  $p < 0.05$ ).

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