The Influence of Biochar Addition on Chicken Manure Composting and Associated Methane and Carbon Dioxide Emissions

Xingyong Jia,[a,b,c] Meng Wang,[a] Wenqiao Yuan,[a,]* Xiaotang Ju,[b] and Baozhu Yang [c]

The effect of biochar addition and turning frequency was examined relative to biochar-chicken manure co-composting and its associated methane (CH_4) and carbon dioxide (CO_2) emissions. The results demonstrated that biochar addition was more effective in accelerating the composting process, which was indicated by a 5.2% increase in peak pile temperature and a 148% increase in peak CO_2 emission with 20% biochar amended-compost, compared with the control that had no biochar. The compost pH increased and moisture content decreased significantly over the whole course of composting with the biochar amendment. The addition of 20% biochar also resulted in a 54.9% decrease in peak CH_4 emission compared with the control. More frequent turning (daily *vs*. every 3 or 7 days) accelerated the composting process and reduced the CH_4 emission.

Keywords: Biochar; Chicken manure; Composting; Turning frequency; CH_4/CO_2 emissions

Contact information: a: Department of Biological and Agricultural Engineering, North Carolina State University. Box 7625, Raleigh, NC, USA, 27695-7625; b: College of Resources and Environmental Sciences, China Agricultural University, Beijing, China, 100193; c: National Engineering Research Center for Information Technology in Agriculture, Beijing, China, 100089;
** Corresponding author: wyuan2@ ncsu.edu*

INTRODUCTION

Composting is one of the most effective technologies for recycling organic wastes in agriculture due to its low cost and rather simple operation. Composting reduces waste mass, destroys weed seeds, provides sufficient sanitation, and produces valuable end products for agriculture (Hubbe *et al.* 2010; Jiang *et al.* 2011; Sun *et al.* 2014). However, the composting of organic wastes has been closely associated with the emissions of greenhouse gases; for example, the principal greenhouse gas methane (CH_4) is generated from composting livestock wastes through the degradation of soluble lipids, carbohydrates, organic acids, and proteins in anaerobic conditions. Methane has a global warming potential 23 times higher than CO_2 (Fukumoto *et al.* 2003; Sun *et al.* 2014).

A potential solution to this global warming challenge is to co-compost animal manure with biochar (Jia *et al.* 2015). Biochar is charcoal produced from biomass *via* pyrolysis or gasification. Biochar has been traditionally used as a soil amendment due to its positive effects on soil nutrient status, microbial community, and soil biota or plant growth (Zhang *et al.* 2012; Clough *et al.* 2013). Recently, the chemical stability of biochar and its slow degradation has attracted interest in using biochar as a carbon sink to reduce greenhouse gas emissions (Lehmann 2007). For example, Liu *et al.* (2011) observed that CH_4 emissions from paddy soil amended with biochar was reduced by 91.2% compared with those without biochar. Karhu *et al.* (2011) showed a decrease in CH_4 emissions in an agricultural soil from southern Finland under birch biochar amendment at 9 ton per hectare.

Similarly, Spokas *et al.* (2009) observed a rate of greater than 20% (w/w) in reduced emission of CO_2 from a silt loam soil amended with wood chip biochar. Liu *et al.* (2011) reported that CO_2 emission was reduced from waterlogged paddy soil amended with bamboo (*Bambuseae* (*spp.*)) and rice straw biochar pyrolyzed at 600 °C. Despite the environmental and agricultural benefits associated with the use of biochar in soil, little is known about the application of biochar to composting and its associated CH_4/CO_2 emissions during the process. The role of biochar in composting is not well understood yet. Limited literature indicated that (1) biochar can be used as a bulking agent. The aeration and structure of compost materials may be improved due to the high porosity and low density of the biochar (Sonoki *et al.* 2011); (2) biochar can hold moisture due to its large porosity and high water holding capacity (Wang *et al.* 2013). Appropriate moisture content is critical to composting; (3) due to its large surface and porosity, biochar may alter and retain microorganisms in composting (Zhang *et al.* 2014).

The objective of this study was to understand the effect of biochar addition on chicken manure composting and its associated CH_4/CO_2 emissions. The effect of biochar was compared to sawdust, a bulking agent widely used in composting. The effects on pH, temperature, moisture content, and CH_4 and CO_2 emissions were evaluated. Turning frequency was used as the primary parameter of aeration, and a temperature control mechanism in an enclosed reactor was also studied.

EXPERIMENTAL

Raw Materials and Characterization

The rice hull biochar used in this study was produced by low temperature gasification in an existing top-lit updraft gasifier.

Table 1. The Main Characteristics of Rice Hull Biochar, Sawdust, and Chicken Manure (based on dry weight and ash free)

<table>
<tr><td colspan="6">Biochar</td></tr>
<tr><td rowspan="2">Surface area (m^2/g)</td><td colspan="5">Elemental analysis</td></tr>
<tr><td>Carbon (%)</td><td>Hydrogen (%)</td><td>Nitrogen (%)</td><td>Sulfur (%)</td><td>Oxygen (%)</td></tr>
<tr><td>183</td><td>28.83 ± 2.7</td><td>0.38 ± 0.002</td><td>0.36 ± 0.0003</td><td>0.083 ± 0.0001</td><td>70.35 ± 1.9</td></tr>
<tr><td rowspan="2">High heating value (MJ/kg)</td><td rowspan="2">pH (1:20 H_2O)</td><td colspan="4">Proximate analysis</td></tr>
<tr><td>Volatile (%)</td><td>Ash (%)</td><td>Fixed Carbon (%)</td><td>Moisture content (%)</td></tr>
<tr><td>10.2±0.28</td><td>10.43 ± 0.65</td><td>5.72 ± 3.85</td><td>66.81 ± 3.22</td><td>23.60 ± 0.99</td><td>2.44 ± 0.08</td></tr>
<tr><td colspan="6">Sawdust</td></tr>
<tr><td>Total C (%)</td><td>Total N (%)</td><td>C/N</td><td colspan="2">Moisture Content (%)</td><td>pH (1:20 H_2O)</td></tr>
<tr><td>37.87 ± 2.60</td><td>0.064 ± 0.004</td><td>592</td><td colspan="2">25.0 ± 3</td><td>7.2 ± 0.9</td></tr>
<tr><td colspan="6">Chicken manure</td></tr>
<tr><td colspan="2">NH_4^+-N (mg kg^{-1})</td><td>NO_3^--N (mg kg^{-1})</td><td colspan="2">Moisture Content (%)</td><td>pH (1:20 H_2O)</td></tr>
<tr><td colspan="2">696.11 ± 15</td><td>174.47 ± 6</td><td colspan="2">22.67 ± 3.2</td><td>8.18 ± 0.8</td></tr>
</table>

The average temperature in the gasifier was approximately 500 °C. and the highest combustion zone temperature was approximately 870 °C (James *et al.* 2016). Pine sawdust was used as the control bulking agent to compare with biochar. Chicken manure was collected from the poultry/chicken unit of the Department of Poultry Science at North Carolina State University (Raleigh, NC, USA) and stored in sealed containers at 4 °C until the initiation of the experiment. The main properties of biochar, sawdust, and chicken manure are shown in Table 1.

Elemental compositions of the biochar were measured using a CHNS/O elemental analyzer (PerkinElmer 2400, Waltham, MA, USA) following the ASTM D5373-02 standard (2003). The volatile matter content of biochar was determined by heating the sample in a muffle oven at 950 ± 20 °C for 7 min; the volatile matter in the sample was calculated using the dry weight loss of the samples following the ASTM D3175-11 standard (2011). In a similar way, the ash content was determined by heating the sample at 575 ± 25 °C for 4 h, and the ash content was calculated based on the dry weight loss of the biomass following the ASTM E1755 standard (1997). Higher heating value was determined with a bomb calorimeter (IKA-Calorimeter C 200, IKA-Werke GmbH and Co. KG, Staufen, Germany) using benzoic acid as the standard according to the ASTM D240 standard (2002). The BET surface area analysis was performed in a surface area analyzer (Autosorb-1C, Quantachrome, Boynton Beach, FL, USA) using isothermal nitrogen sorption according to the ASTM D6556-07 standard (2007). Infrared radiation detection for the determination of total carbon and thermal conductivity detection for the determination of nitrogen were carried out with a Leco TruMac® analyzer (LECO Corporation, St. Joseph, MI, USA) (AOAC 1998).

The Composting Experiment

The complete factorial design included biochar content (0%, 10%, and 20% dry weight basis of the total composting substrate), sawdust content (10%, 20%, and 30% dry weight basis of the total composting substrate), and turning frequency (every 1, 3, and 7 days). The total mass of the substrate (amendment plus chicken manure) in each treatment was 150 g, which was placed in a 500-mL glass bottle. The volume of the compost was in the range of 400 mL to 450 mL depending on the treatment because the biochar and sawdust had different densities. Each treatment was replicated three times, and the experiment was conducted for 43 days in a constant-temperature incubator with the temperature set at 35 ± 0.5 °C. Before composting, water was added to achieve a gravimetric moisture content of 65%, and the materials were thoroughly mixed.

Sampling and Analyses

Methane and carbon dioxide emissions were measured on composting days 1, 2, 3, 4, 5, 6, 7, 8, 14, 15, 21, 22, 28, 29, 35, 36, 42, and 43 according to the following procedures. Prior to sampling, the composting bottles were sealed for 8 h. A 5 mL gas sample in the headspace was extracted using an air-tight syringe, and the gas was analyzed by gas chromatography-mass spectrometry (Shimadzu GCMS- QP2010 system, Shimadzu, Kyoto, Japan). The gas chromatograph was equipped with an Rt-QPLOT™ column (30 m, 0.25 mm ID, 8 µm). The column was programmed to hold at 30 °C for 1 min, ramp at 4 °C/min to 40 °C and then hold at 40 °C for 2 min. The injector temperature was 110 °C, and the injector split ratio was set at 40:1. The flow control mode was linear velocity at 38 cm/s. The interface temperature was 100 °C, and the detector temperature was 200 °C.

Helium was used as the carrier gas. Methane standards of 3% (v/v) and CO_2 standards of 5% (v/v) were used for the calibration of results. Background concentrations of CH_4 and CO_2 were subtracted from the measurements.

On composting days 0, 6, 13, 20, 27, and 41, the pH was measured in a 30 mL 1:10 (m/v) solution sample in deionized water. The mixture was equilibrated for 30 min with occasional stirring with a glass rod, and then the supernatant was analyzed by an Ultra Basic Benchtop pH meter (Denver Instrument, Denver, CO, USA). Moisture content was evaluated by drying 5 g of fresh sample in an oven at 105 °C for 24 h to a constant weight.

The data was subjected to ANOVA analysis using SPSS Version 12.0 software (SPSS Inc., Chicago, Illinois, USA), and differences (p < 0.05) between means were determined using the Duncan-Waller test.

RESULTS AND DISCUSSION

Biochar Effects on Composting Progress

A noticable increase in pH of all treatments was observed at the beginning of the composting, but later the rate of increase became slower (Fig. 1). The initial increase in pH can be explained by the rapid degradation of acids and large amounts of NH_3 emission as soon as the compost was established (Gajalakshmi and Abbasi 2008; Steiner *et al.* 2010). Later, the production of organic acids and the incomplete oxidation of organic matter in the compost balanced the pH value (Liu *et al.* 2011). Figure 1A shows that the greater the amount of biochar added, the higher the observed pH value. Biochar has a characteristic high pH (10.43, as shown in Table 1) due to the ash in biochar containing more basic cations, like Ca^{2+}, Mg^{2+}, K^+, Na^+, *etc*., that had strong H^+ exchange capability in the compost (Uras *et al.* 2012). In addition, the high porosity and high surface area of biochar enabled absorption/adsorption and retention of NH_3 or water-soluble NH_4^+ (Jia *et al.* 2015). The effect of sawdust addition on pH was different from that of biochar, as shown in Fig. 1B. Increasing sawdust addition resulted in a slightly lower pH value, which might be related to larger quantities of CO_2 that were released during the composting process (Fig. 5B). At day 28, the pH slightly decreased for all sawdust treatments, which might be explained by the partial anaerobic regions in the compost due to large particles of sawdust. These particles result in the incomplete oxidation of organic matter and the production of organic acids (Liu *et al.* 2011).

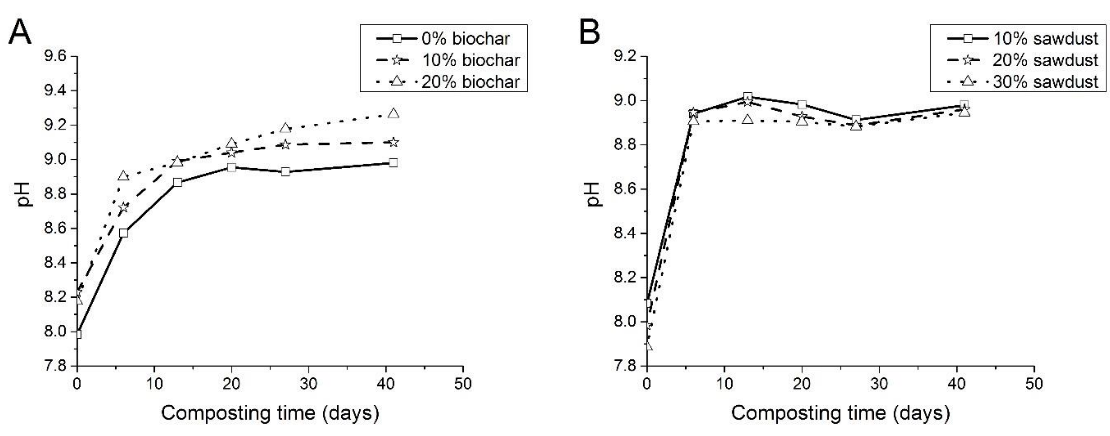

Fig. 1. Changes in pH by the additions of (A) biochar and (B) sawdust during composting

The effects of biochar and sawdust on the temperature profile of the compost are shown in Fig. 2. The peak temperature reached 53 °C to 60 °C on days 5 to 6 in all treatments, and the mesophilic and thermophilic phases appeared in the first two weeks, after which, a downward trend was observed. Significant increases in the peak temperature at the thermophilic stage of composting were observed with biochar addition; 20% biochar addition produced the greatest increase, followed by 10% (Fig. 2A). Compared with the control (no biochar), 20% biochar addition produced a 5.2% increase in the major peak of temperature. This increase happened because the high porosity of the biochar greatly contributed to the O_2 availability in the compost, which benefited the activities of microorganisms that released intensive heat (Fischer and Glaser 2012). Unlike biochar, larger sawdust additions decreased the temperature of the compost (Fig. 2B). This result might be explained by the higher free air space in the sawdust-amended compost, which allowed for greater convective air flow and more heat loss.

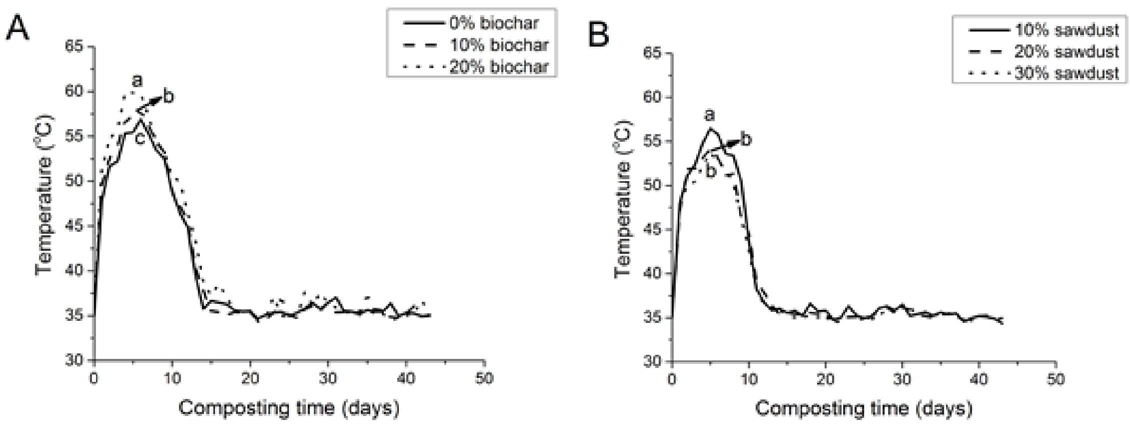

Fig. 2. Changes in compost temperature by the additions of (A) biochar and (B) sawdust. Different letter inserts of a, b, or c on the curves indicate significant differences in peak temperature ($p <$ 0.05).

Moisture content (MC) decreased significantly in the composts over the course of decomposition, especially in the first two weeks (Fig. 3). The greatest decrease in MC was found in the 20% biochar amendment (Fig. 3A).

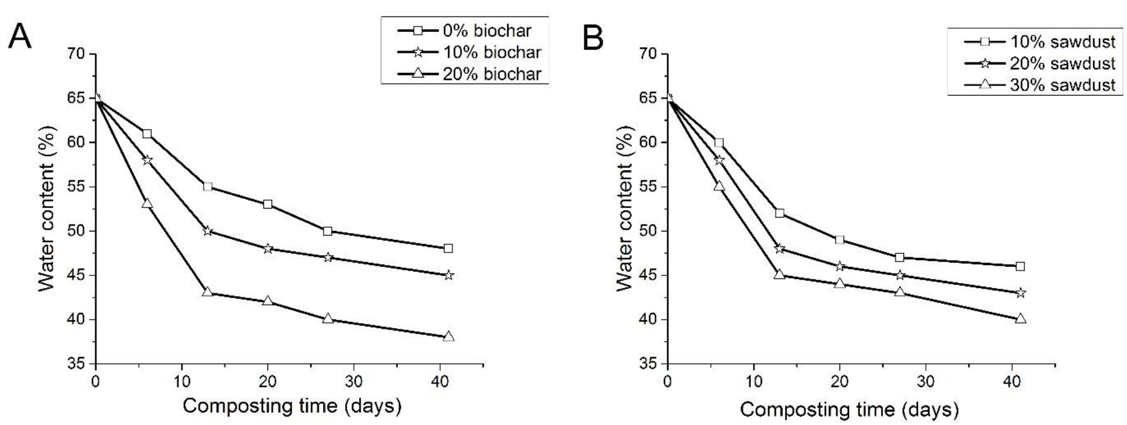

Fig. 3. Changes in compost moisture content by the additions of (A) biochar and (B) sawdust

Biochar may have decreased bulk density and enhanced compost aeration; large amounts of water may be released through microbial activity, which can exceed the amount lost through evaporation (Steiner *et al.* 2010). More sawdust amendments also resulted in a significant decrease in the MC of compost (Fig. 3B). This occurred because the high aeration rate due to the air voids of sawdust could cause intense water evaporation (Kader *et al.* 2007).

Biochar Effects on CH_4 Emission

As can be seen in Fig. 4, the emission of CH_4 started immediately after the mixing of compost in all treatments. The peaks were observed on days 5 to 6, and there were no significant differences during the rest of the composting time. At the early stage of composting, methanogenic microorganisms that are limited to strict anaerobic conditions degrade soluble lipids, carbohydrates, organic acids, and proteins (Fukumoto *et al.* 2003; Jiang *et al.* 2011; Sun *et al.* 2014). However, with a small volume of compost, the length of the period until the anaerobic portions disappeared was short (Fukumoto *et al.* 2003). The emission patterns of CH_4 in the study were similar to previous reports (Fukumoto *et al.* 2003; Sun *et al.* 2014).

As shown in Fig. 4A, when more biochar was added, less CH_4 emission from the compost was detected. Compared with the control (no biochar), 20% biochar addition resulted in a 54.9% reduction in the peak CH_4 emission, indicating that biochar was very effective in reducing CH_4 emissions in chicken manure compost. There are at least three reasons to explain this reduction. The extremely high porosity of the biochar enhanced the supply and distribution of O_2 and restricted the activities of methanogenic microorganisms. Secondly, the high porosity and high surface area of the biochar compared to that of sawdust enabled better absorption/adsorption and retention of CH_4. Finally, the high pH in biochar amendments (Fig. 1A) restricted the activities of methanogens that prefer nearly neutral pH (Kessel and Russel 1996).

Figure 4B shows that less CH_4 emission was detected with increasing amounts of sawdust, which might be explained by the fact that sawdust as a bulking agent can also significantly increase the free air space in the compost, which inhibits the growth of methanogens.

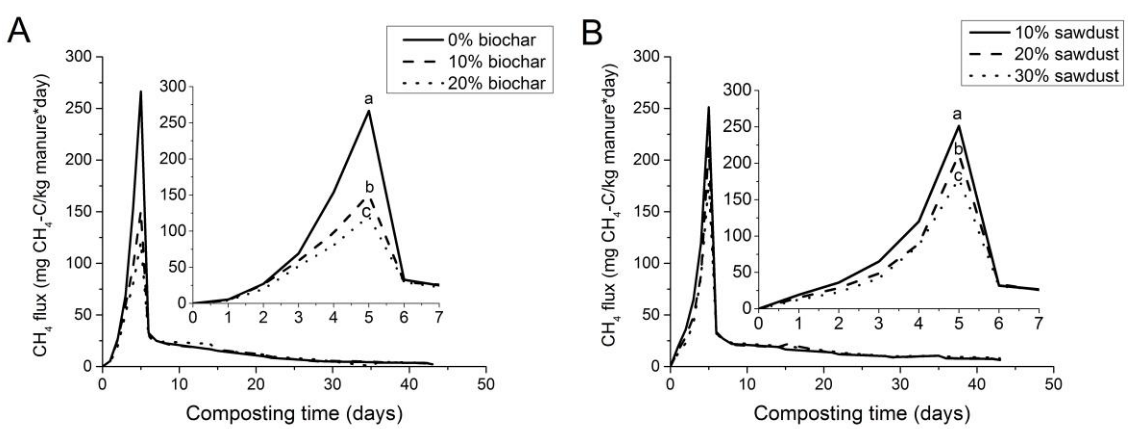

Fig. 4. The effect of biochar (A) and sawdust (B) on CH_4 emission during composting. Different letter inserts of a, b, or c on the curves indicate significant differences in peak CH_4 emission ($p < 0.05$).

Biochar Effects on CO_2 Emission

All treatments had a relatively high CO_2 emission immediately after composting started, and the peaks were observed on days 2 to 3 (Fig. 5). The quick peak for CO_2 emission can be explained by the fast degradation of the total organic carbon (TOC) and mineralization of the organic matters by microbes (Santos *et al.* 2014). Figure 5A shows that biochar addition boosted CO_2 emission. The peak CO_2 was approximately 148% higher in the 20% biochar addition compared with the control. This result suggests that the high porosity of biochar increased the O_2 supply of the compost, which benefits aerobic microorganisms that degrade organic matters to produce CO_2. This is in agreement with Steiner *et al.* (2010), who reported that the CO_2 peak was significantly higher in biochar-amended poultry litter compost. In their study, CO_2 emissions were also considered as an indicator of composting rate, such that a higher the CO_2 concentration reflected stronger microbial activity and faster composting rate. In Fig. 5B, the increase in CO_2 emission with more sawdust addition might be explained by the high TOC content of sawdust (Table 1), which significantly increased the C:N ratio of the compost and provided more carbon sources for microbial growth.

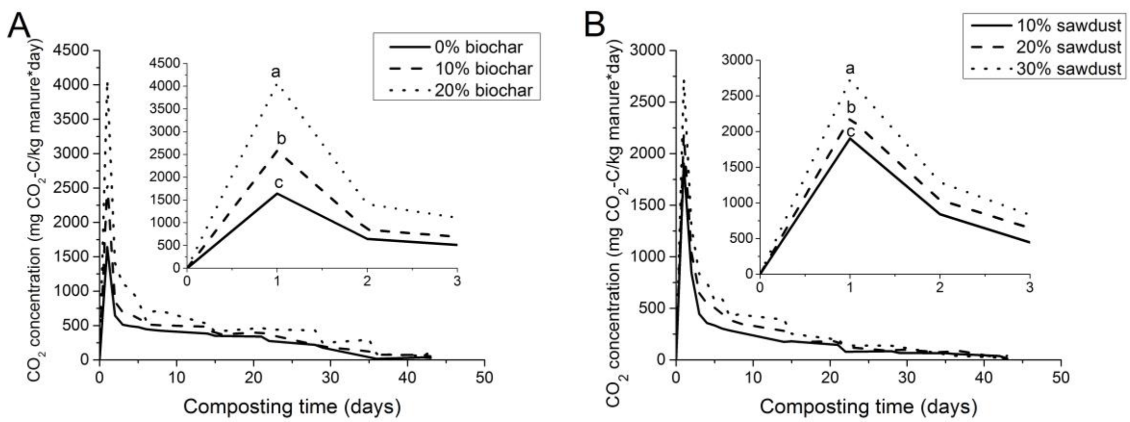

Fig. 5. The effect of biochar (A) and sawdust (B) on CO_2 emission during composting. Different letter inserts of a, b, or c on the curves indicate significant differences in peak CO_2 emission ($p < 0.05$).

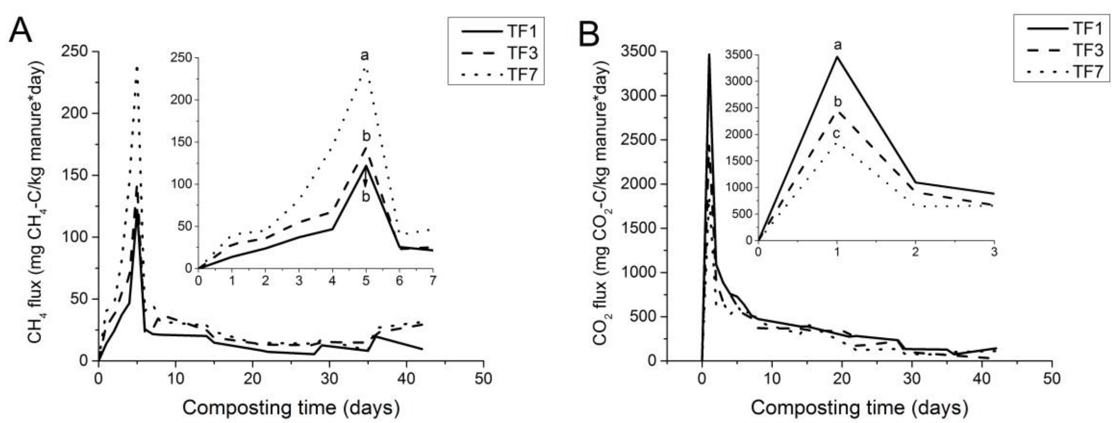

Fig. 6. The effect of turning frequency on the emissions of CH_4 (A) and CO_2 (B) during composting. Significant differences are marked with different letters ($p < 0.05$).

The Effect of Turning Frequency

The influence of turning frequency (TF, every 1, 3, or 7 days, designated as TF1, TF3, and TF7, respectively) on CH_4 and CO_2 emissions is shown in Figs. 6A and 6B, respectively. Less frequent turning (TF7) resulted in more CH_4 emissions compared with TF1 and TF3; less frequent encouraged anaerobic conditions that promoted methanogenic microorganism activity. However, the effect of TF on CO_2 emission was different from that on CH_4 (Fig. 6B). The peak CO_2 emission was much higher at more frequent turning (TF1) than in TF3 or TF7 because O_2 availability from sufficient aeration contributed to aerobic microbial activity for transforming available carbon sources to CO_2.

CONCLUSIONS

1. The addition of biochar to chicken manure composting significantly increased the composting rate compared with the control (no biochar). The high porosity of biochar greatly contributed to the O_2 availability in the compost, which benefited microorganismal degradation of organic matter.
2. Addition of biochar to chicken manure compost resulted in significantly reduced peak CH_4 emissions, but higher peak CO_2 emissions. By enhancing the supply and distribution of O_2 in the compost, biochar restricted the activities of methanogenic microorganisms but boosted aerobic microorganisms. In addition, biochar enabled better absorption/adsorption and retention of CH_4.
3. More frequent turning of the compost accelerated the composting process and reduced CH_4 emission, but CO_2 emission was increased.

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REFERENCES CITED

Association of Official Agricultural Chemists (AOAC) (1998). *Official Methods of Analysis*, 16th Ed., AOAC International, Rockville, MD, USA.

ASTM E1755 (1997). "Standard test method for ash in biomass," ASTM International, West Conshohocken, PA, USA.

ASTM D240 (2002). "Standard test method for heat of combustion of liquid hydrocarbon fuels by bomb calorimeter," ASTM International, West Conshohocken, PA, USA.

ASTM D5373-02 (2003). "Standard test methods for instrumental determination of carbon, hydrogen and nitrogen in laboratory samples of coal and coke," ASTM International, West Conshohocken, PA, USA.

ASTM D6556-07 (2007). "Standard test method for carbon black-total and external surface area by nitrogen adsorption," ASTM International, West Conshohocken, PA, USA.

ASTM D3175-11 (2011). "Standard test method for volatile matter in the analysis sample of coal and coke," ASTM International, West Conshohocken, PA, USA.

Clough, T. J., Condron, L. M., Kammann, C., and Müller, C. (2013). "A review of biochar and soil nitrogen dynamics," *Agronomy* 3, 275-293. DOI: 10.3390/agronomy3020275

El Kader, N. A., Robin, P., Paillat, J. M., and Leterme, P. (2007). "Turning, compacting and the addition of water as factors affecting gaseous emissions in farm manure composting," *Bioresour. Technol.* 98, 2619-2628. DOI: 10.1016/j.biortech.2006.07.035

Fischer, D., and Glaser, B. (2012). "Synergisms between compost and biochar for sustainable soil amelioration," *INTECH Open Access Publisher*, 167-198.

Fukumoto, Y., Osada, T., Hanajima, D., and Haga, K. (2003). "Patterns and quantities of NH_3, N_2O, and CH_4 emissions during swine manure composting without forced aeration-effect of compost pile scale," *Bioresour. Technol.* 89(2), 109-114. DOI: 10.1016/S0960-8524(03)00060-9

Gajalakshmi, S., and Abbasi, S. A. (2008). "Solid waste management by composting: State of the art," *Crit. Rev. Environ. Sci. Technol.* 38(5), 311-400. DOI: 10.1080/10643380701413633

Hubbe, M. A., Nazhad, M., and Sánchez, C. (2010). "Composting as a way to convert cellulosic biomass and organic waste into high-value soil amendments: A review," *BioResources* 5(4), 2808-2854. DOI: 10.15376/biores.5.4.2808-2854

James, A., Yuan, W., Boyette, M., Wang, D., and Kumar, A. (2016). "Characterization of biochar from rice hulls and wood chips produced in a top-lit updraft biomass gasifier," *Transactions of the ASABE* in press.

Jia, X., Yuan, W., and Ju, X. (2015). "Effects of biochar addition on manure composting and associated N_2O emission," *J. Sustain. Bioenerg. Syst.* 5, 56-61. DOI: 10.4236/jsbs.2015.52005

Jiang, T., Schuchardt, F., Li, G., Guo, R., and Zhao, Y. (2011). "Effect of C/N ratio, aeration rate and moisture content on ammonia and greenhouse gas emission during the composting," *J. Environ. Sci.* 23, 1754-1760. DOI: 10.1016/S1001-0742(10)60591-8

Karhu, K., Mattila, T., Bergström, I., and Regina, K. (2011). "Biochar addition to agricultural soil increased CH_4 uptake and water holding capacity-results from a short-term pilot field study," *Agr. Eco. Env.* 140(1), 309-313. DOI: 10.1016/j.agee.2010.12.005

Kessel, J. A. S., and Russell, J. B. (1996). "The effect of pH on ruminal methanogenesis," *FEMS Microbiol. Ecol.* 20(4), 205-210. DOI: 10.1016/0168-6496(96)00030-X

Lehmann, J. (2007). "A handful of carbon," *Nature* 447(7141), 143-144. DOI: 10.1038/447143a

Liu, Y., Yang, M., Wu, Y., Wang, H., Chen, Y., and Wu, W. (2011). "Reducing CH_4 and CO_2 emissions from waterlogged paddy soil with biochar," *J. Soil Sediment* 11(6), 930-939. DOI: 10.1007/s11368-011-0376-x

Santos, A., Bustamante, M. A., Moral, R., and Bernal, M. P. (2014). "Carbon conservation strategy for the management of pig slurry by composting: Initial study of the bulking agent influence," *Mitig. Adapt. Strateg. Glob. Change.*, 1-13. DOI: 10.1007/s11027-014-9593-0

Sonoki, T., Furukawa, T., Mizumoto, H., Jindo, K., Aoyama, M., and Monedero, M.Á.S. (2011). "Impacts of biochar addition on methane and carbon dioxide emissions during composting of cattle manure," Asia Pacific Biochar Conference. DOI not available.

Spokas, K. A., Koskinen, W. C., Baker, J. M., and Reicosky, D. C. (2009). "Impacts of woodchip biochar additions on greenhouse gas production and sorption/degradation of two herbicides in a Minnesota soil," *Chemosphere* 77(4), 574-581. DOI: 10.1016/j.chemosphere.2009.06.053

Steiner, C., Das, K. C., Melear, N., and Lakly, D. (2010). "Reducing nitrogen loss during poultry litter composting using biochar," *J. Environ. Qual.* 39, 1236-1242. DOI: 10.2134/jeq2009.0337

Sun, X. P., Lu, P., Jiang, T., Schuchardt, F., and Li, G. X. (2014). "Influence of bulking agents on CH_4, N_2O, and NH_3 emissions during rapid composting of pig manure from the Chinese Ganqinfen system," *J. Zhejiang Univ. Sci. B.* 15(4), 353-364. DOI: 10.1631/jzus.B13a0271

Uras, Ü., Carrier, M., Hardie, A. G., and Knoetze, J. H. (2012). "Physico-chemical characterization of biochars from vacuum pyrolysis of South African agricultural wastes for application as soil amendments," *J. Anal. Appl.* 98, 207-213. DOI: 10.1016/j.jaap.2012.08.007

Wang, C., Lu, H., Dong, D., Deng, H., Strong, P.J., Wang, H., and Wu, W. (2013). "Insight into the effects of biochar on manure composting: Evidence supporting the relationship between N_2O emission and denitrifying community," *Environ. Sci. and Technol.* 47(13), 7341-7349. DOI: 10.1021/es305293h

Zhang, A., Bian, R., Pan, G., Cui, L., Hussain, Q., Li, L., Zheng, J., Zheng, J., Zhang, X., Han, X. *et al*. (2012). "Effects of biochar amendment on soil quality, crop yield and greenhouse gas emission in a Chinese rice paddy: A field study of 2 consecutive rice growing cycles," *Field Crops Res.* 127, 153-160. DOI: 10.1016/j.fcr.2011.11.020

Zhang, J., Fan, L., Luo, C., Shao, L., and He, P. (2014). "Humification characterization of biochar and its potential as a composting amendment," *J. Environ. Sci.* 26(2), 390-397. DOI: 10.1016/S1001-0742(13)60421-0

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