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Effects of biochar on carbon pool, N mineralization, microbial biomass and microbial respiration from mollisol

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Biochar incorporation as a soil amendment has been shown to enhance soil quality. However, there has been conflicting reports on its short term effects on C and N mineralization and microbial biomass. An incubation experiment was conducted to determine the effects of three different levels (0.5, 1 and 2%) of biochar on carbon mineralization, soil organic carbon, nitrogen mineralization, microbial biomass and total nitrogen from mollisols of two different organic matter (high organic matter soil and low organic matter soil) levels. The experiment consisted of four treatments (Soil, Soil + 0.5% biochar, Soil + 1% biochar and Soil + 2% biochar) and each was replicated three times. Overall, soil respiration rate was reduced by biochar additions over a 100-day period. Two percent biochar application rate showed greatest CO_2-C reduction. Soil respiration in high organic matter soil was higher than low organic matter soil. NO_3^--N level was reduced by biochar addition in both high and low organic matter soils. Control (Soil) of the high organic matter soil showed the highest NO_3^--N (33.79 mg kg^{-1}) and NH_4^+-N (7.23 mg kg^{-1}) values at 70 days. The total nitrogen was increased by biochar additions; 1 and 2% application rates showed the highest total nitrogen values. Biochar additions also increased soil microbial biomass carbon and soil microbial biomass nitrogen of both soils.

Key words: Biochar, C mineralization, N mineralization, microbial biomass.

INTRODUCTION

Biochar is the product of the thermal degradation of organic materials in the absence of air (pyrolysis) and is distinguished from charcoal by its use as soil amendment (Lehmann et al., 2011). It is considered as a carbon-rich organic matter with long residence time up to hundreds of years (Kuzyakov et al., 2009; Lehmann et al., 2015). Biochars made from diverse biomass species (feedstock) are characterized by different morphological and chemical properties but also characteristically differ based on specific pyrolysis conditions (that is, final pyrolysis temperature or peak temperature, rate of charring or ramp rate, and duration of charring time) (Mukherjee and Zimmerman, 2013). Hence biochar properties and the effect on crop production depend

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on feedstock, pyrolysis conditions and soil type (Jeffery et al., 2011). The effect of biochar is said to be strongly connected to the soil properties and the climate but the correlations with crop yield are not completely clear (Cornelissen et al., 2018). Several authors (Agegnehu et al., 2016; Jeffery et al., 2017) have stated that the yield increases are related to an overall improvement of soil qualities. Biochar application is reported to stimulate (Wardle et al., 2008; Luo et al., 2011) or conversely, to suppress (Keith et al., 2011; Zimmerman et al., 2011) the mineralization of native soil organic carbon (SOC); these effects are termed positive and negative priming, respectively (Luo et al., 2011; Keith et al., 2011; Zimmerman et al., 2011). The differing results observed in previous studies may have been due to variations in the proportion of labile C in biochars (Luo et al., 2011), the presence or absence of plant-derived labile organic matter input in soil (Keith et al., 2011), and the degree of biochar ageing in soil (Zimmerman et al., 2011; Cross and Sohi, 2011; Liang et al., 2010).

Soil respiration is a product of several rhizospheric processes, which is root exudation, root respiration, and root turnover, as well as decomposition of litter and bulk soil organic matter from various pools with different characteristic turnover times (Luo et al., 2001). Release of CO_2 from soils due to the production of CO_2 by roots and soil organisms and, to a lesser extent, chemical oxidation of carbon compounds is commonly referred to as soil respiration. Soil surface CO_2 efflux, or soil respiration, is a major component of the biosphere’s carbon cycle which is influenced by the environment change because it may constitute about three-quarters of total ecosystem respiration (Law et al., 2001). Application of biochar has been shown to have a variety of effects on the soil biota which may be associated with its impacts on C and N cycling. Biochar has the capacity to potentially sequester C, and also has agronomic benefits such as improving soil quality, nutrient availability and crop yield (Sohi et al., 2010; Spokas et al., 2012; Schulz and Glaser, 2012). Biochar amendments can alter soil N dynamics (Clough and Condron, 2010), increase soil pH, base saturation, available nutrient content, nutrient retention and CEC (Cation Exchange Capacity) (Tiessen et al., 1994; Glaser et al., 2002; Moreira et al., 2005; Mukherjee and Zimmerman, 2013), and decrease Al toxicity (Glaser et al., 2002).

Many research works (Spokas and Reicosky, 2009; Prayogo et al., 2014) have been done to determine how mineralization of C and N is affected by biochar application but few emphases have been made on testing the effects of different biochar application rates on microbial respiration, nitrogen mineralization, microbial biomass and soil organic carbon pool from mollisol of two different suborders with different organic matter levels. The rate of biochar application on the soil is expected to have serious influence on the impact of biochar on soil processes, including microbial soil respiration and nitrogen mineralization. Therefore, a laboratory incubation method in which soil temperature and moisture regimes could be manipulated was employed. The objective of this study is to determine the effects of low and high biochar application rates on microbial soil respiration, soil organic carbon content, N mineralization as well as microbial biomass from mollisol of two different suborders with varying organic matter levels.

MATERIALS AND METHODS

Soil and biochar

Mollisol consisting of two levels of organic matter, high organic matter and low organic matter, was used for the experiment. The high organic matter soil which is of the Suborder Udolls (Dark colored) was obtained from the Experimental and Practical Basement of Northeast Agricultural University while the low organic matter soil which is of the Suborder Albolls (Light colored and high concentration of sand and silt) was obtained from Northeast Forestry University. The crop planted in the previous season on both soils was maize. The soils were collected randomly at a depth of 0-20 cm, after sieving to < 2 mm and the basic properties determined (Table 1). The biochar which was produced from corn at a pyrolysis temperature of 450°C in an oxygen-restricted environment in a batch system was provided by Jin and Fu Agriculture Co., China and was crushed to pass through 2 mm sieve. The properties of biochar and soils are listed in Table 1.

Incubation procedure and soil respiration

Soil sieved to 2 mm was amended with biochar at different rates, 0.5, 1 and 2% which are equivalent to 10, 20 and 40 t ha^{-1} respectively. For incubation, dry weight soil equivalent to 25 g were placed in air-tight glass jars (0.3 L) in a completely randomized design for anaerobic incubation with 3 replicates. All treatments and control were moistened to 60% of their water holding capacity and incubated for 100 days at 25°C in the dark. Water content was regularly checked gravimetrically and adjusted with de-ionized water. Carbon mineralization was measured as CO_2-C using alkaline trap (Tufekcioglu et al., 2001) during 100 days of incubation. The emitted CO_2 was trapped in 10 ml of NaOH which was titrated with HCl on days 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80, 90 and 100 after carbonate precipitation with $BaCl_2$.

Analytical methods

Soils from the jars were analyzed for selected chemical properties; soil organic carbon, microbial biomass C and N, Total N. Ammonium nitrogen and nitrate nitrogen contents were extracted with 2M KCl (1:10 w/v) after shaking for 2 h and determined colorimetrically, using the salicylate method as the variation of Berthelot-Phenate method. Microbial biomass C and N were determined by fumigation and extraction technique as described by Vance et al. (1987). SOC was measured using wet oxidation with $K_2Cr_2O_7$; while Total N was measured using Kjeldahl method as described by Gupta (2006).

Statistical analysis

The statistical analyses were performed using SPSS 19.0 program.

Table 1. Physical and chemical properties of soils and biochar.

Parameter	Soil (High OM)	Soil (Low OM)	Biochar
pH	6.12	6.02	9.89
Total N (g kg^{-1})	0.7	0.34	6.89
Available N (mg kg^{-1})	Nd	Nd	*
Organic Carbon (g kg^{-1})	38.2	10.1	415.3
Available P (mg kg^{-1})	23.8	19.3	*
Total P (g kg^{-1})	Nd	Nd	10.26
Available K (mg kg^{-1})	185.6	180.1	25.9
Particle Size (g kg^{-1})			
Sand	500	520	Nd
Silt	190	200	Nd
Clay	310	280	Nd
Textural Class (USDA)	Clay Loam	Clay Loam	Nd
Bulk Density (g cm^{-3})	1.38	1.42	Nd

*<LOD of the technique, Nd = Not determined.

After testing of assumptions, One-Way analysis of variance (ANOVA) was performed followed by Duncan Multiple Range Test (DMRT). Results marked as significantly different are different at $P<0.05$ unless specified in text. All reported values are means of three replicates.

RESULTS

Microbial soil respiration

Biochar application to soil had effects on CO_2-C release (Figure 1) with respect to soil alone. Difference was found for CO_2-C among the rates of application in the two soils. The mineralization of C was slightly depressed by 1% biochar addition and 2% biochar addition; however, stimulated by 0.5% biochar addition. The respiration rate of 0.5% biochar was higher at the beginning than the control until 20 days incubation (15 mg CO_2-C $g^{-1}d^{-1}$) for high organic matter soil (Figure 1a) and 15 days incubation (15.4 mg CO_2-C $g^{-1}d^{-1}$) for the low organic matter soil (Figure 1b). There was a sharp decline in all respiration rates during the first 25 days of incubation after which the respiration rate became steady. It was observed that the higher the rate of biochar applied, the lower the amount of CO_2-C released, which is an indication that there is decreased decomposition following biochar application to soils. High organic matter soil recorded higher soil respiration rate than low organic matter soil throughout the incubation period.

Soil organic carbon (SOC)

SOC increased with the increasing biochar application in all treatments for both high organic matter soil and low organic matter soil at 50 and 100 days of incubation (Table 2). Soil + 1% biochar and Soil + 2% biochar were significantly ($P<0.01$) higher than control (soil). The highest SOC value (58.8 g kg^{-1}) was shown by Soil + 2% biochar of the high organic matter soil at 100 days incubation.

N mineralization

The levels of NO_3^--N increased between 20 and 40 days for both soils (Table 3). Mineralization was highest in control (Soil), followed by Soil + 0.5% biochar. Biochar application significantly ($P<0.05$) reduced mineralization at 20, 40, 60 and 90 days for the high organic matter soil; while significant ($P<0.05$) reduction by biochar was observed at 40 and 100 days for the low organic matter soil. The highest NO_3^--N levels were recorded at 70 days for both soils. Between 20 and 40 days, NH_4^+-N levels reduced in all soils (Table 4). Greatest NH_4^+-N reduction was observed at 90 days, indicating net immobilization. Rates of immobilization were significantly ($P<0.05$) highest in treatment receiving 2% biochar relative to other treatments. Control (Soil) was significantly ($P<0.05$) higher than Soil + 2% biochar at 40 and 90 days for the high organic matter soil; while significant differences among treatments were observed at 20 and 90 days for the low organic matter soil.

Soil microbial biomass carbon (SMBC)

Variability of SMBC under different rates of biochar was large as shown in Figure 2. A sharp increase in SMBC was observed at 20 days for both soils with a further

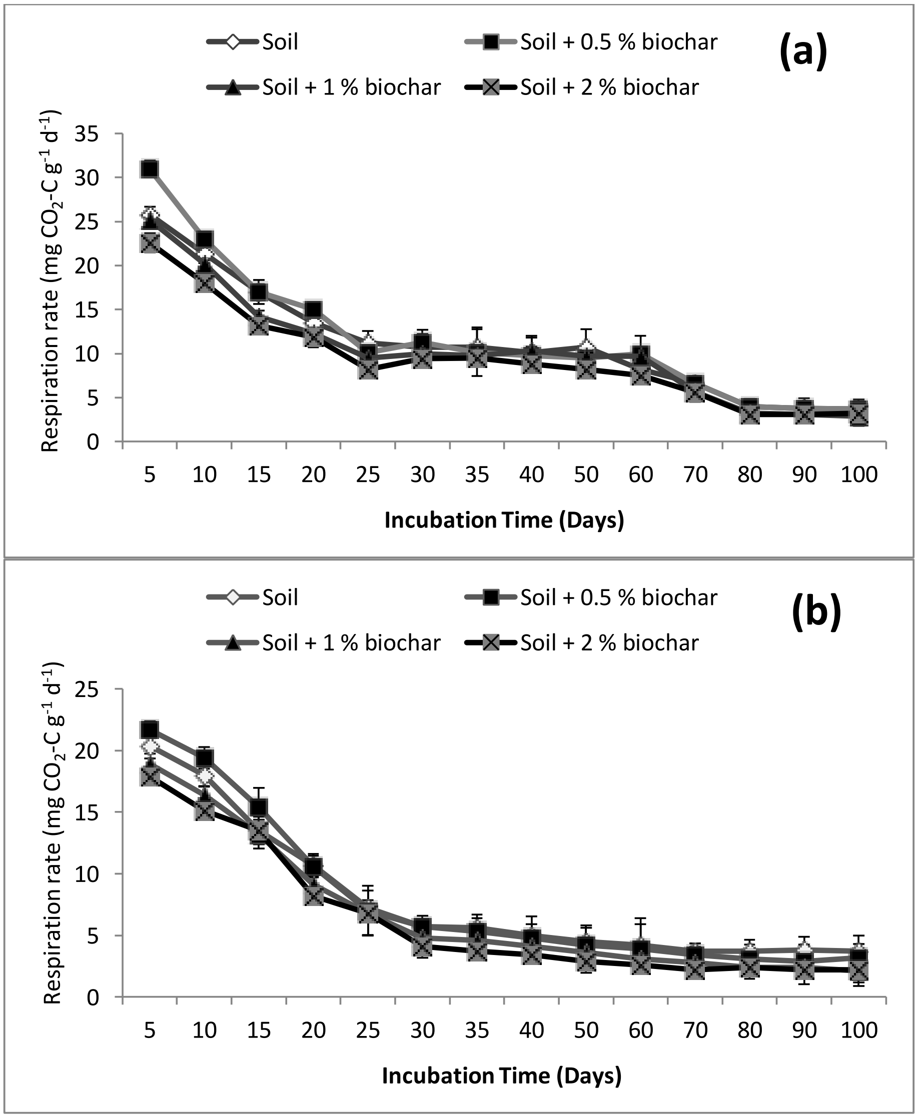

Figure 1. Respiration rates of high organic matter soil (a) and low organic matter soil (b) amended with biochar at 0.5, 1 and 2% levels (Means ± SE, n = 3).

Table 2. SOC of high organic matter soil (a) and low organic matter soil (b) at 50 days and 100 days of incubation as affected by biochar additions (Mean ± SE, n = 3).

Soil code	Treatments	SOC (g kg^{-1})	
		50d	100d
(a)	Soil	37.3±1.12 ^{d}	37.6±1.79 ^{c}
	Soil + 0.5 % biochar	53.1±0.56 ^{c}	53.1±1.12 ^{b}
	Soil + 1 % biochar	56.4±1.12 ^{b}	55.8±1.96 ^{b}
	Soil + 2 % biochar	57.8±0.56 ^{a}	58.8±0.85 ^{a}
(b)	Soil	9.7±1.71 ^{d}	10.2±1.71 ^{d}
	Soil + 0.5 % biochar	21.8±1.12 ^{c}	22.5±1.71 ^{c}
	Soil + 1 % biochar	28.1±1.71 ^{b}	27.6±1.16 ^{b}
	Soil + 2 % biochar	36.7±1.41 ^{a}	37.1±1.71 ^{a}

Means followed by different letters are significantly different (P<0.01).

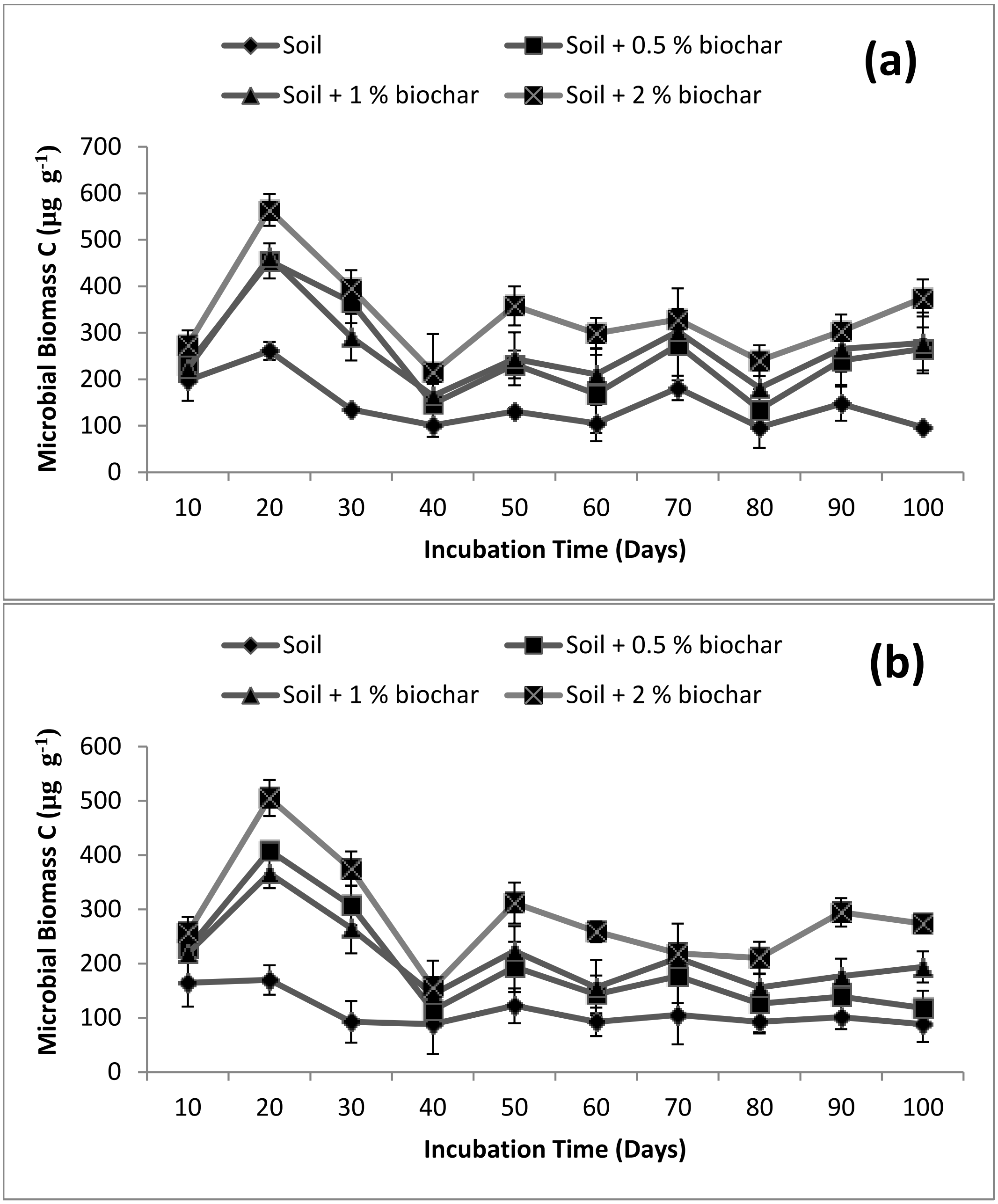

Figure 2. Soil MBC for high organic matter soil (a) and low organic matter soil (b) amended with biochar at 0.5, 1 and 2% levels (Mean ± SE, n = 3).

decline at 40 days. SMBC was highest at 20 days for both high organic matter soil and low organic matter soil (Figure 2a and b). The results of the soil microbial biomass analysis also indicate that the high organic matter soil contains the greatest microbial biomass C. Treatment receiving 2% biochar was significantly ($P<0.05$) higher than other treatments throughout the incubation period. The variations in the microbial biomass C among the different soil types is an indication of the differences in their microbial activities.

Soil microbial biomass nitrogen

At day 50 of the high organic matter soil (Table 5), treatment receiving 2% biochar showed the highest SMBN (111.9 µg g^{-1}) and it was significantly ($P<0.001$) higher than other treatments; while for the low organic matter soil, treatment receiving 2% biochar (80.8 µg g^{-1}) was also significantly ($P<0.001$) higher than other treatments. At day100 of the high organic matter soil (Table 5), the treatment receiving 2% biochar showed the

Table 3. NO$_3^-$-N levels in biochar-amended high organic matter soil (a) and low organic matter soil (b) during incubation.

Soil code	Treatments	NO$_3^-$-N (mg kg^{-1})					
		20 d	40 d	60 d	70 d	90 d	100 d
(a)	Soil	15.32±0.27^{a}	23.37±0.90^{a}	19.17±1.11^{a}	33.79±1.27^{a}	26.84±1.08^{a}	27.13±0.55^{a}
	Soil + 0.5 % BC	15.19±0.24^{a}	21.47±1.59^{b}	17.34±0.10^{b}	33.44±2.65^{a}	25.10±1.24^{ab}	24.94±0.05^{a}
	Soil + 1 % BC	14.15±0.47^{b}	21.06±0.62^{b}	16.10±1.07^{b}	31.74±1.83^{a}	24.22±0.57^{b}	24.38±3.35^{a}
	Soil + 2 % BC	13.93±0.49^{b}	21.28±0.36^{b}	16.77±0.34^{b}	32.94±0.06^{a}	23.30±1.06^{b}	26.43±1.74^{a}
(b)	Soil	6.52±0.47^{a}	7.99±0.76^{ab}	9.73±0.43^{b}	26.68±2.04^{a}	12.60±3.26^{a}	17.56±1.76^{a}
	Soil + 0.5 % BC	6.44±0.33^{a}	9.44±1.42^{a}	9.35±1.10^{a}	25.55±2.72^{a}	11.94±0.83^{a}	15.67±0.56^{ab}
	Soil + 1 % BC	6.51±0.22^{a}	6.99±1.47^{b}	8.56±0.57^{a}	24.35±1.06^{a}	9.81±0.17^{a}	14.72±0.81^{b}
	Soil + 2 % BC	5.97±0.68^{a}	8.81±0.25^{ab}	8.46±0.83^{a}	23.68±2.05^{a}	9.54±0.97^{a}	14.21±1.90^{b}

Means followed by different letters are significantly different ($P<0.05$), BC = Biochar.

Table 4. NH$_4^+$-N levels in biochar-amended high organic matter soil (a) and low organic matter soil (b) during incubation.

Soil code	Treatments	NH$_4^+$-N (mg kg^{-1})					
		20 d	40 d	60 d	70 d	90 d	100 d
(a)	Soil	3.28±2.19^{a}	0.70±0.05^{a}	2.42±0.59^{a}	7.23±0.81^{a}	0.52±0.08^{a}	0.73±0.10^{a}
	Soil + 0.5 % BC	2.85±0.98^{a}	0.58±0.08^{a}	3.37±1.05^{a}	5.27±2.50^{a}	0.470±0.03^{a}	0.68±0.13^{a}
	Soil + 1 % BC	3.26±1.14^{a}	0.60±0.13^{a}	2.60±0.33^{a}	2.27±1.56^{a}	0.30±0.05^{b}	0.67±0.08^{a}
	Soil + 2 % BC	2.60±035^{a}	0.38±0.18^{b}	2.00±1.28^{a}	2.00±0.35^{a}	0.28±0.03^{b}	0.57±0.19^{a}
(b)	Soil	4.42±2.05^{a}	0.68±0.06^{a}	3.15±0.33^{a}	2.92±2.05^{a}	0.45±0.06^{a}	0.72±0.10^{a}
	Soil + 0.5 % BC	1.97±0.86^{b}	0.67±0.08^{a}	2.70±0.61^{a}	2.62±0.72^{a}	0.43±0.01^{a}	0.72±0.10^{a}
	Soil + 1 % BC	2.62±1.17^{ab}	0.78±0.03^{a}	2.33±0.31^{a}	2.32±0.89^{a}	0.32±0.05^{b}	0.72±0.14^{a}
	Soil + 2 % BC	1.75±0.08^{b}	0.67±0.10^{a}	2.00±1.22^{a}	2.90±1.33^{a}	0.30±0.03^{b}	0.73±0.08^{a}

Means followed by different letters are significantly different ($P<0.05$), BC = Biochar.

highest SMBN (76.67 µg g^{-1}) and it was significantly ($P<0.001$) different from other treatments. Treatments receiving 0.5 and 1% biochar were not significantly different from each other. For the low organic matter soil, treatment receiving 2% biochar (74.6 µg g^{-1}) was significantly ($P<0.001$) higher than other treatments.

Total N

The Total N values following biochar addition are shown in Figure 3. The high organic matter soil was higher in soil Total N (Figure 3a). Higher biochar application rate increased soil Total N throughout the incubation period in relation to control. Treatment receiving 2% biochar showed the highest Total N value and it was significantly ($P<0.05$) higher at 70 and 100 days. Slight increase in Total N was shown by Soil + 2% biochar of the low organic matter soil in the first 20 days (Figure 3b). Soil + 2% biochar was significantly ($P<0.05$) higher at 10, 20, 60 and 80 days with respect to other treatments. The control soil showed the lowest soil Total N value throughout the 100 days incubation.

DISCUSSION

Many research works conducted in China have shown that biochar application to agricultural soils has little or no effect on carbon mineralization (CO_2-C efflux). There is decreased decomposition or negative priming following biochar application to soils which inadvertently leads to a reduction in soil respiration. Findings from this research showed that biochar treatment with highest application rate 2%, which is equivalent to 40 t ha^{-1} recorded the lowest mineralization, and it is in agreement with other findings (Liu et al., 2011; Case et al., 2014; Schimmelpfennig et al., 2014). Soil + 2% biochar reduced CO_2-C mineralization by 15.8 % in the high organic matter soil and 16.1 % in the low organic matter soil at 10 days incubation. Even though improvement in the growth of soil microorganisms following biochar application has been reported (Chen et al., 2015; Lu et al., 2015), it did not amount to an increase in soil respiration. The reason that can be adduced to this could be that the fine particles in biochar might have taken up the evolved CO_2-C to an extent; thereby limiting its release to the atmosphere.

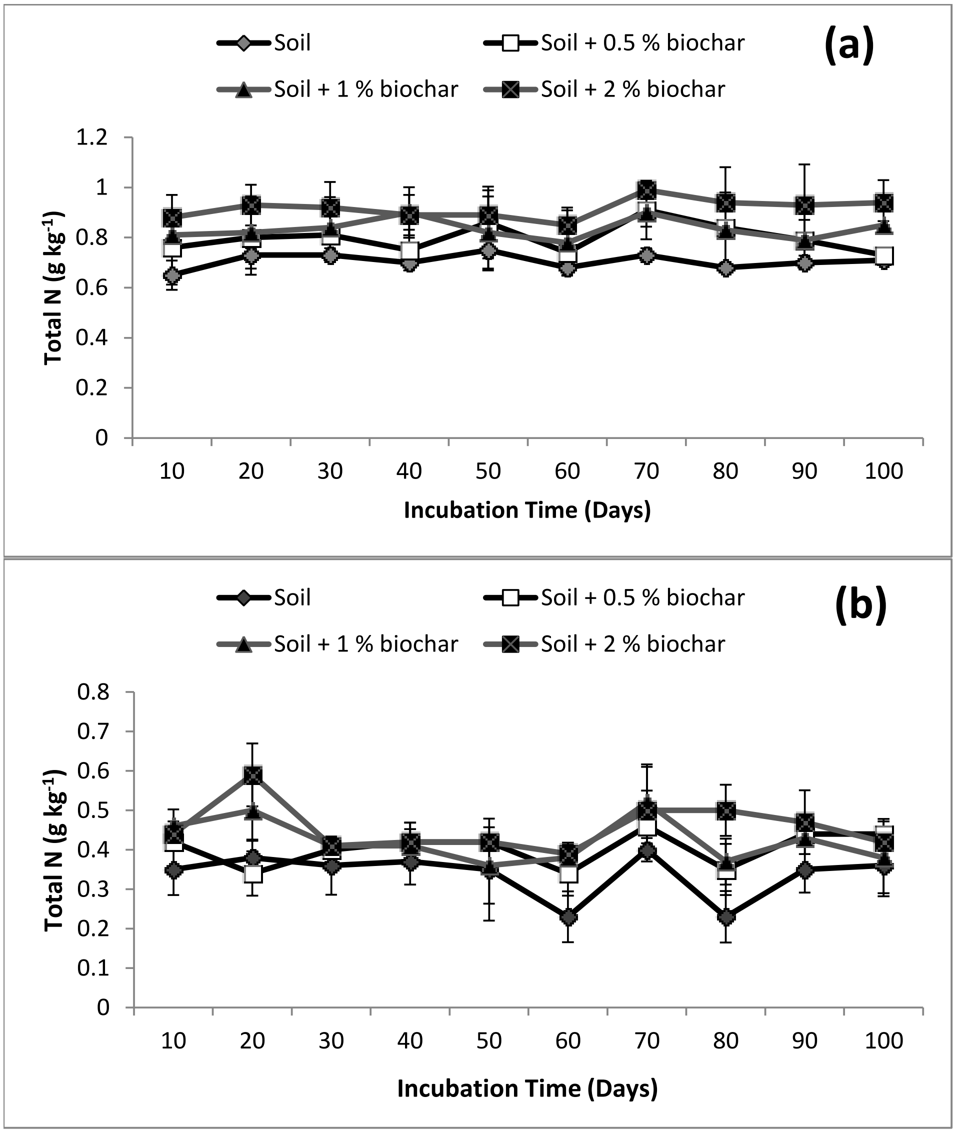

Figure 3. Soil Total N for high organic matter soil (a) and low organic matter soil (b) amended with biochar at 0.5, 1 and 2% levels (Mean ± SE, n = 3).

Biochar additions largely increased SOC and contributed to carbon storage. This finding is in agreement with the work of Biederman and Harpole (2012). The observed increases in SOC following biochar addition were expected, considering the high carbon content (81%) and recalcitrant carbon of biochar.

Mineral nitrogen content (NH_4^+-N and NO_3^--N) in the rhizosphere soil is an important indicator of threats to soil by nitrogen saturation (Fingerman et al. 2011). The N mineral forms are the forms in which agricultural crops take in nitrogen from soil. The findings from this research showed that biochar when added to soil reduced N mineralization and accumulation of NO_3^--N and NH_4^+-N which is in consonance with other works (Novak et al., 2010; Taghizadeh-Toosi et al., 2011; Zavalloni et al., 2011). High biochar concentration significantly reduced NO_3^--N and NH_4^+-N concentrations. The reason for this could be as a result of a change in soil pH that follows biochar addition which inadvertently affects the structure of soil microbial organisms.

The changes showed in SMBC among treatments points out the activities of microorganisms and breakdown of organic matter. The results from this study established that SMBC increased with biochar application relative to control, which is an indication that biochar addition to soils can accelerate the growth of microbes (mostly bacteria and fungi). Same results have been reported by several authors (Anderson and Domsch, 1993; Tian et al., 2008; Kolb et al., 2008; Aciego and Brookes, 2009; Liang et al., 2010; Lehmann et al., 2011).

The effect of biochar on soil microbial biomass and activity depends mainly on biochar type (feedstock and pyrolysis temperature). For SMBN, biochar had positive effects on soil microbial biomass nitrogen. The addition of biochar increased the microbial composition of both soils and enhanced the release of biomass N. Biochar concentration also affected SMBN release from soils following the death of these microbes. This result is in consonance with the work of Zhang et al. (2014).

Total N is the sum of total kjeldahl nitrogen (ammonia, organic and reduced nitrogen) and nitrate-nitrate. Biochar additions increased soil Total N, which is consistent with the work of Zhang et al. (2012b) who recorded a significant maize increase, accompanied by increased soil Total N content following application of different levels of a nutrient rich wheat-straw biochar (20 and 40 t ha^{-1}); but this is in contrast to the findings of Jones et al. (2012). The tendency of biochar amendment to increase soil Total N depends on the feedstock used in biochar production as well as the pyrolysis temperature. It also depends on soil properties as well as the prevailing weather and climatic conditions. Biochar properties such as large surface area and high porosity could also be responsible for the changes in Total N when added to the soil.

Conclusion

In conclusions, this study shows that the addition of biochar to Mollisols reduced soil respiration rate throughout the 100-days incubation period. Higher biochar concentration caused a further decline in soil respiration rates. Incorporation of biochar to soils increased SOC and soil Total N content; hence high biochar rate can be applied to soils as amendment to boost SOC and soil Total N. A positive effect on soil microbial biomass carbon SMBC and soil microbial biomass nitrogen SMBN was also shown by biochar. However, biochar addition reduced mineral soil nitrogen in the forms of NO_3^--N and NH_4^+-N.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

REFERENCES

Aciego PJC, Brookes PC (2009). Substrate inputs and pH as factors controlling microbial biomass, activity and community structure in an arable soil. Soil Biology and Biochemistry 41:1396-1405.

Agegnehu G, Bass AM, Nelson PN, Bird MI (2016). Benefits of biochar, compost and biochar-compsot for soil quality, maize yield and green-house gas emission in a tropical agricultural soil. Science of the Total Environment 543: 295-306.

Anderson TH, Domsch KH (1993).The metabolic quotient for CO_2 (qCO_2) as a specific activity parameter to assess the effects of environmental conditions, such as pH, on the microbial biomass of forest soils. Soil Biology and Biochemistry 25:393-395.

Biederman LA, Harpole WS (2012). Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. Global Change Biology Bioenergy. doi:10.1111/gcbb.12037.

Case SDC, McNamara NP, Reay DS, Whitaker J (2014). Can biochar reduce soil greenhouse gas emissions from a Miscanthus bioenergy crop? Global Change Biology Bioenergy 6:76-89.

Chen J, Liu X, Li L. et al. (2015). Consistent increase in abundance and diversity but variable change in community composition of bacteria in top soil of rice paddy under short term biochar treatment across three sites from South China. Applied Soil Ecology 91:68-79.

Clough TJ, Condron LM (2010). Biochar and the nitrogen cycle. Journal of Environmental Quality 39:1218-1223.

Cornelissen G, Jubaedah, Nurida NL, Hale SE, Martinsen V, Silvani L, Mulder J (2018). Fading positive effect of biochar on crop yield and soil acidity during five growth seasons in an Indonesian Ultisol. Science of the Total Environment 634:561-568.

Cross A, Sohi SP (2011). The priming potential of biochar products in relation to labile carbon contents and soil organic matter status. Soil Biology and Biochemistry 43:2127-2134.

Fingerman KR, Berndes G, Orr S, Richter BD, Vugteveen P (2011). Impact assessment at the bioenergy-water nexus. Biofuel Bioproductivity and Bioresource 5:375-386.

Glaser B, Lehmann J, Zech W (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review. Biology and Fertility of Soils 35:219-230.

Gupta PK (2006). Soil, Plant, Water and Fertilizer analysis. Agrobios India Publishing pp. 132-135.

Jeffery S, Abalos D, Prodana M, Bastos AC, van Groenigen JW, Hungate BA, Verheijen F (2017). Biochar boosts tropical but not temperate crop yields. Environmental Research Letters 12:053001.

Jeffery S, Verheijen FGA, van der Velde M, Bastos AC (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agricultural Ecosystem and Environment 144:175-187.

Jones DL, Rousk J, Edwards-Jones G, Deluca TH, Murphy DV (2012). Biochar mediated changes in soil quality and plant growth in a three year field trial. Soil Biology and Biochemistry 45:113-124.

Keith A, Singh B, Singh BP (2011). Interactive priming of biochar and labile organic matter mineralization in a smectite-rich soil. Environmental Science and Technology 45:9611-9618.

Kolb SE, Fermanich KJ, Dornbush ME (2008). Effect of charcoal quantity on microbial biomass and activity in temperate soils. Soil Science Society of America Journal 4:1173-1181.

Kuzyakov Y, Subbotina I, Chen H, Bogomolova I, Xu X (2009). Black carbon decomposition and incorporation into soil microbial biomass estimated by C-14 labeling. Soil Biology and Biochemistry 41:210-219.

Law BE, Kelliher FM, Baldocchi D, Anthoni P (2001). Spatial and temporal variation in respiration in a young ponderosa pine forests during a summer drought. Agriculture and Forest Meteorology 110:27-43.

Lehmann J, Abiven S, Kleber M, Zimmerman AR (2015). Persistence of biochar in soil.in: Lehmann J, Joseph S, (editors). Biochar for Environmental Management, Chapter 10: Earthscan, USA. pp. 235-281.

Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC Joseph CA (2011). Biochar effects on soil biota – A review. Soil Biology and Biochemistry 43:1812-1836.

Liang B, Lehmann J, Sohi SP, Thies JE, O'Neill B, Trujillo L, Gaunt J, Solomon D, Grossman J, Neves EG, Luizão FJ (2010). Black carbon affects the cycling of non-black carbon in soil. Organic Geochemistry 41:206-213.

Liu YX, Yang M, Wu YM, Wang HL, Chen YX, Wu WX (2011). Reducing CH_4 and CO_2 emissions from waterlogged paddy soil with biochar. Journal of Soil Sediments 11:930-939.

Lu H, Lashari MS, Liu X et al. (2015). Changes in soil microbial community structure and enzyme activitywith amendment of biochar-manure compost and pyroligneous solution in a saline soil from central China. European Journal of Soil Biology 70:67-76.

Luo Y, Durenkamp M, De Nobili M, Lin Q, Brookes PC (2011). Short term soil priming effects and the mineralisation of biochar following its incorporation to soils of different pH. Soil Biology and Biochemistry 43:2304-2314.

Luo YQ, Wan SQ, Hui DF, Wallace LL (2001). Acclimatization of soil respiration to warming in a tall grass prairie. Nature 413:622-625.

Moreira EE, Ribeiro AB, Mateus EP, Mexia JT, Ottosen LM (2005). Regressional modeling of electrodialytic removal of Cu, Cr and As from CCA treated timber waste: application to sawdust. Wood Science and Technology 39:291-309.

Mukherjee A, Zimmerman AR (2013). Organic carbon and nutrient release from a range of laboratory-produced biochars and biochar–soil mixtures. Geoderma pp. 193-194:

Novak JM, Busscher WJ, Watts DW, Laird DA, Ahmedna MA, Niandou MAS (2010). Short term CO_2 mineralization after addition of biochar and switchgrass to a Typic Kandiudult. Geoderma 154:281-288.

Prayogo C, Jones JE, Baeyens J, Bending GD (2014). Impact of biochar on mineralization of C and N from soil and willow litter and its relationship with microbial community biomass and structure. Biology and Fertility of Soils 50:695-702.

Schimmelpfennig S, Mueller C, Gruenhage L, Koch C, Kammann C (2014). Biochar, hydrochar and uncarbonized feedstock application to permanent grassland-effects on greenhouse gas emissions and plant growth. Agriculture Ecosystem and Environment 191:39-52.

Schulz H, Glaser B (2012). Effects of biochar compared to organic and inorganic fertilizers on soil quality and plant growth in a greenhouse experiment. Journal of Plant Nutrition and Soil Science 175:410-422.

Sohi SP, Krull E, Lopez-Capel E, Bol R (2010). A review of biochar and its use and function in soil. Advances in Agronomy 105:47-82.

Spokas KA, Cantrell KB, Novak JM, Archer DA, Ippolito JA, Collins HP, Boateng AA, Lima IM, Lamb MC, McAloon AJ, Lentz RD, Nichols KA (2012). Biochar: A synthesis of its agronomic impact beyond carbon sequestration. Journal of Environmental Quality 41:973-989.

Spokas KA, Reicosky DC (2009). Impacts of sixteen different biochars on soil greenhouse gas production. Annals of Environmental Science 3:179-193.

Taghizadeh-Toosi A, Clough TJ, Condron LM, Sherlock RR, Anderson CR, Craigie RA (2011). Biochar incorporation into pasture soil suppresses in situ nitrous oxide emissions from ruminant urine patches. Journal of Environmental Quality 40:468-476.

Tian Y, Haibara K, Toda H, Ding F, Liu Y, Choi D (2008). Microbial biomass and activity along a natural pH gradient in forest soils in a karst region of the upper Yangtze River, China. Journal of Forestry Research 13:205-214.

Tiessen H, Cuevas E, Chacon P (1994). The role of soil organic-matter in sustaining soil fertility. Nature 371:783-785.

Tufekcioglu A, Raich JW, Isenhart TM, Schultz RC (2001). Soil respiration within riparian buffers and adjacent crop fields. Plant and Soil 229:117-214.

Vance ED, Brookes PC, Jenkinson DS (1987). An extraction method for measuring soil microbial biomass C. Soil Biology and Biochemistry 19:703-707.

Wardle DA, Nilsson MC, Zackrisson O (2008). Fire-derived charcoal causes loss of forest humus. Science 320:629-629.

Zavalloni C, Alberti G, Biasiol S, Vedove GD, Fornasier F, Liu J (2011). Microbial mineralization of biochar and wheat straw mixture in soil: a short-term study. Applied Soil Ecology 50:45-51.

Zhang AF, Liu YM, Pan GX, Hussain Q, Li LQ, Zheng JW, Zhang XH (2012b). Effect of biochar amendment on maize yield and greenhouse gas emissions from a soil organic carbon poor calcareous loamy soil from Central China Plain. Plant and Soil 351:263-75.

Zhang QZ, Dijkstra FA, Liu XR, Wang YD, Huang J, Lu N (2014). Effects of Biochar on Soil Microbial Biomass after Four Years of Consecutive Application in the North China Plain. PLoS ONE 9(7):e102062.

Zimmerman AR, Gao B, Ahn MY (2011). Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. Soil Biology and Biochemistry 43:1169-1179.