ABSTRACT

Subtropical recent alluvial soils are low in organic carbon (C). Thus, increasing organic C is a major challenge to sustain soil fertility. Biochar amendment could be an option as biochar is a C-rich pyrolyzed material, which is slowly decomposed in soil. We investigated C mineralization (CO₂-C evolution) in two types of soils (recent and old alluvial soils) amended with two feedstocks (sugarcane bagasse and rice husk) (1%, weight/weight), as well as their biochars and aged biochars under a controlled environment (25 ± 2 °C) over 85 d. For the recent alluvial soil (charland soil), the highest absolute cumulative CO₂-C evolution was observed in the sugarcane bagasse treatment (1 140 mg CO₂-C kg⁻¹ soil) followed by the rice husk treatment (1 090 mg CO₂-C kg⁻¹ soil); the lowest amount (150 mg CO₂-C kg⁻¹ soil) was observed in the aged rice husk biochar treatment. Similarly, for the old alluvial soil (farmland soil), the highest absolute cumulative CO₂-C evolution (1 290 mg CO₂-C kg⁻¹ soil) was observed in the sugarcane bagasse treatment and then in the rice husk treatment (1 270 mg CO₂-C kg⁻¹ soil); the lowest amount (200 mg CO₂-C kg⁻¹ soil) was in the aged rice husk biochar treatment. Aged sugarcane bagasse and rice husk biochar treatments reduced absolute cumulative CO₂-C evolution by 10% and 18%, respectively, compared with unamended recent alluvial soil, and by 10% and 18%, respectively, compared with unamended old alluvial soil. Both absolute and normalized C mineralization were similar between the sugarcane bagasse and rice husk treatments, between the biochar treatments, and between the aged biochar treatments. In both soils, the feedstock treatments resulted in the highest cumulative CO₂-C evolution, followed by the biochar treatments and then the aged biochar treatments. The absolute and normalized CO₂-C evolution and the mineralization rate constant of the stable C pool (Km) were lower in the recent alluvial soil compared with those in the old alluvial soil. The biochars and aged biochars had a negative priming effect in both soils, but the effect was more prominent in the recent alluvial soil. These results would have good implications for improving organic matter content in organic C-poor alluvial soils.

Key Words: aged biochar, biochar amendment, charland, CO₂ emission, CO₂-C evolution, recent alluvial soil, soil organic carbon, soil organic matter

Carbon mineralization in subtropical alluvial arable soils amended with sugarcane bagasse and rice husk biochars

Mohammad Arifur RAHMAN¹, Mohammad Abdul KADER²,³,⁵, Mohammad JAHIRUDDIN³,⁵, Mohammad Rafiqul ISLAM¹ and Zakaria Mohammad SOLAIMAN²

¹Regional Agricultural Research Station (RARS), Bangladesh Agricultural Research Institute (BARI), Jamalpur 2000 (Bangladesh)
²School of Agriculture, Geography, Environment, Ocean and Natural Sciences, University of South Pacific, Apia 1343 (Samoa)
³Department of Soil Science, Bangladesh Agricultural University (BAU), Mymensingh 2202 (Bangladesh)
⁴UWA School of Agriculture & Environment and the UWA Institute of Agriculture, Perth, WA 6009 (Australia)
⁵School of Veterinary and Life Science, Murdoch University, Murdoch, WA 6150 (Australia)

(Received August 14, 2020; revised November 26, 2020; accepted December 24, 2020)

INTRODUCTION

The Bengal Delta, also known as the Ganges-Brahmaputra-Meghna Delta, is the second largest delta in the world (Darby et al., 2020). It covers more than 100 000 km² and has been continuously gaining land by 17 km² year⁻¹ over the last five decades (Sarker et al., 2013). On average, 844 billion cubic meters of water flow across the delta during the monsoon season (June to October) in the three main rivers (the Ganges, known as Padma in Bangladesh; the Brahmaputra, known as Jamuna in Bangladesh; and the Meghna), which account for about 80% of the landmass in the floodplain (Rakib et al., 2017). This huge water flow brings large amounts of sediments to the Bengal Delta, around 1–2.4 billion metric tons per year (Rahman et al., 2018). Due to anthropogenic intervention, the river discharge rate has been declining, which has caused riverbed siltation as well as deposition of sediments in specific points along the river channel and formation of recent alluvium called charland in Bangladesh (Rahman et al., 2018; Darby et al., 2020). A large population of around 6.5 million people live on charland due to the high population density in the mainland of Bangladesh (EGIS, 2000; Sarker et al., 2003). The livelihood of the charland people is mostly dependent on agriculture. Crop productivity in charland is low as the soils are inherently less fertile and the soils are light textured, have undeveloped structure, and have low organic matter content. The organic matter also decomposes rapidly after ripening of sediments due to the sandy texture that allows aeration and the prevailing subtropical humid climate that

*Corresponding author. E-mail: m_jahiruddin@yahoo.com.
favors high microbial activity. Improving the organic matter content of charland soil following traditional methods, e.g., natural vegetation, green manuring, and addition of readily available organic matter such as cow dung, poultry manure, and compost, takes a long time. Thus, amendment of charland soils with pyrolyzed organic biomass, known as biochar, could be an option for carbon (C) enrichment, since biochar C has been estimated to retain in soil for long duration from hundreds to thousands of years (Lehmann et al., 2009).

Biochar application can lead to C sequestration (Cha et al., 2016; Ding et al., 2016) and can improve soil properties. For example, it can increase water retention (Shafie et al., 2012), decrease soil acidity (Zhang et al., 2013; Madiba et al., 2016), increase cation exchange capacity (CEC) and nutrient content (Agegnehu et al., 2015; Wang et al., 2015; Ding et al., 2016; Novak et al., 2016), increase microbial biomass C and enzyme activities (Karimi et al., 2020), increase mycorrhizal root colonization (Solaiman et al., 2010, 2019), reduce CO₂ and N₂O emissions (Lone et al., 2015; Solaiman and Anawar, 2015), and improve soil fertility and crop yield (Khan et al., 2013; Butnan et al., 2015; Anawar et al., 2017; Griffin et al., 2017).

Biochar C is more stable, both chemically and biologically, than its original feedstock due to its aromatic structure (Jindo et al., 2014). This high stability of biochar C popularize the use of biochar as an agent of C sequestration in soil. As observed by Lehmann et al. (2006), a large portion of initial C (about 50%) is retained after conversion of biomass to biochar compared with biomass burning (3%) and natural decomposition (<10%–20% after 5 to 20 years), though it largely varies depending on the type of biomass used. The agriculture, forestry, and land use sectors consider to reduce gas emissions (Ledo et al., 2018) and gas emission reduction can be achieved through C sequestration (Smith, 2004).

The influence of biochar amendments on microbial decomposition of inherent soil organic matter (SOM) could be positive (Fang et al., 2014), negative (Keith et al., 2011) or neutral (Kuzyakov et al., 2009). Straw addition to soil with or without biochar increased CO₂-C emissions while biochar alone (2%) reduced it (Odugbenro et al., 2019). Many factors influence the decomposability of biochar in soil, e.g., the quality and quantity of amended biochar, the pyrolysis temperature, the duration of decomposition, and soil pH, moisture, reactive minerals, and native SOM and clay contents (Ameloot et al., 2013b; Fang et al., 2014; Sun et al., 2016, Han et al., 2020).

Carbon mineralization in biochar-amended problem soils has been examined by many researchers (Bolan et al., 2012; Fernández et al., 2014), but mostly in acid soils (Zhao et al., 2015) and saline soils (Sun et al., 2016). There is a lack of information on the decomposability of sugarcane bagasse and rice husk biochars and aged biochars in recent alluvial soil (charland soil), a problem soil in the Bengal Delta.

It is hypothesized that the addition of biochars to organic C (OC)-poor recent alluvial soils will enrich soils organic C (SOC) quickly as they are less prone to microbial decomposition and can reduce the decomposition of native SOM through negative priming effect. Thus, we examined the effects of addition of sugarcane bagasse, rice husk, and their biochars and aged biochars on C mineralization in a recent alluvial soil. An old alluvial soil was used in this study as a control. The C mineralization results from this study under a controlled environment might help in elucidating the inclinations of applications of sugarcane bagasse and rice husk-derived biochars and aged biochars in charland soils under field conditions.

MATERIALS AND METHODS

Soils

Two soils, a recent alluvial soil (Typic Endoaquents as per USDA Soil Taxonomy) and an old alluvial soil (Aeric Hapludults as per USDA Soil Taxonomy), were used in this study. The soils (0–15 cm depth) were collected from river borne sediments (recent alluvial soil) in Char Joitherpur (24°54′00″ N and 89°58′48″ E) and from RARS (Regional Agricultural Research Station) farm (old alluvial soil) located in Jamalpur (24°56′24″ N and 89°55′48″ E), Bangladesh. The recent alluvial soil was a sandy loam with the following properties: pH (water) = 6.9, SOC (Walkley-Black method) = 0.41 g kg⁻¹, total N (Kjeldahl method) = 0.04 g kg⁻¹, Olsen P = 10.0 mg kg⁻¹, NH₄-OAC-extractable K = 0.044 cmol(+) kg⁻¹, and CEC = 6.5 cmol(+) kg⁻¹. The old alluvial soil was a silt loam with the following properties: pH = 6.4, SOC = 2.76 g kg⁻¹, total N = 0.28 g kg⁻¹, Olsen P = 12.1 mg kg⁻¹, NH₄-OAC-extractable K = 0.086 cmol(+) kg⁻¹, and CEC = 8.1 cmol(+) kg⁻¹.

Production and characterization of biochar

Two locally available agro-industrial by-products, rice husk and sugarcane bagasse, were used as feedstocks for biochar production. Biochar was produced in an earthen kiln (2.5 m in length, 2 m in diameter) made with clayey soil and brick. The kiln was covered with a coarse iron sheet along with a chimney; there were 20 holes in the kiln for aeration. To ensure an anoxic condition for pyrolysis, an iron drum (100 cm in length, 60 cm in diameter) with an almost airtight cover was placed into the kiln to which the feedstock was filled for pyrolysis. The temperature of pyrolysis (about 600 °C) was recorded at 30-min intervals using a digital temperature recorder by placing the sensor into the kiln through an aeration hole. A high pyrolysis temperature was selected to produce very stable biochar (Ameloot et al., 2013a). Feedstocks were sun-dried and weighed before pyrolysis, and the weight of biochar after...
pyrolysis was recorded at ambient temperature. Biochar yield (\%) was calculated using the following formula: biochar yield = (weight of biochar/weight of feedstock) × 100%. Sub-samples of each biochar were physically and chemically characterized using the procedure described by Karimi et al. (2019) and Khajavi-Shojai et al. (2020). Aged biochars were produced using the \( \text{H}_2\text{O}_2 \) \((30\%)\) oxidation method described by Mia et al. (2017), as used for chemical stability determination of biochar. Briefly, 1.0 g biochar was mixed with 400 mL \( \text{H}_2\text{O}_2 \), in a conical flask and heated in a water bath at 60 °C temperature for 24 h. A 0.45-μm membrane filter was used to collect the oxidized biochars through filtration followed by washing with water and drying in an oven at 80 °C. The chemical stability (\%) of biochar was estimated using the following formula: chemical stability = (weight of filtrate/weight of biochar) × 100%.

**Experimental setup**

The C mineralization (in terms of CO\(_2\)-C evolution) in the soils mixed with feedstock (rice husk and sugarcane bagasse) and biochar was studied through an incubation experiment in a controlled environment under aerobic conditions for 85 d. Briefly, soil (200 g) was air-dried and passed through a 2-mm sieve. Each feedstock, biochar, and aged biochar were mixed with soil at 1% (weight/weight). In total, there were 7 treatments for each soil: unamended (control) and their biochars (RHB, SBB, ASBB, ARHB, SB, RH, and ASB). After mixing, the mixtures were filled into PVC tubes (7 cm in diameter) and compacted to a bulk density of 1.4 g cm\(^{-3}\). The PVC tubes were placed inside closed jars and incubated at 25 °C for 85 d. The initial weight of each jar was recorded. The jars were sealed air-tightly.

**Measurement of CO\(_2\)-C evolution**

The CO\(_2\) emitted from soil column was trapped into a vial containing 10 mL \(1 \text{ mol L}^{-1} \text{ NaOH}\). The vials containing NaOH were removed at days 1, 2, 3, 6, 8, 12, 15, 20, 25, 28, 36, 43, 53, 68, and 85, and the excess NaOH was back titrated with 0.5 mol L\(^{-1}\) HCl after precipitation of carbonate in the presence of \( \text{BaCl}_2 \) solution (Sleutel et al., 2010). Jars were kept open for 2 h after removal of the NaOH-containing vials for oxygen replenishment. The water content of soil column was adjusted fortnightly to maintain 50% water-filled pore space (Sleutel et al., 2010; Kader et al., 2013).

**Calculation of C mineralization and statistics**

A parallel first- and zero-order kinetic model was used to describe OC mineralization biologically and mathematically. This model allows the division of SOC into two pools, an easily decomposable labile pool and a more resistant stable pool (Sleutel et al., 2010). The model is described below:

\[
C_t = C_i(1 - e^{-K_1 t}) + K_s t
\]

where \( C_t \) represents the measured cumulative amount of C mineralized at time \( t \); \( C_i \) represents the labile C pool; \( K_1 \) represents the mineralization rate constant of the labile C pool; and \( K_s \) represents the mineralization rate constant of the stable C pool.

All the data were statistically analyzed using IBM SPSS 25.0 (IBM, Armonk, USA). Nonlinear regression was used to fit the C mineralization data into the first- and zero-order kinetic model using the Levenberg-Marquardt algorithm. Analysis of variance (ANOVA) at \( P < 0.05 \) followed by Duncan’s multiple range test was used to test differences in the C mineralization parameters among the different treatments.

**RESULTS**

**Characteristics of biochars**

Pyrolysis of sugarcane bagasse and rice husk feedstocks yielded 55% and 60% biochar, respectively (Table I). The sugarcane bagasse biochar had the following properties: maximum water holding capacity (MWHC) = 367%, chemical stability (\( \text{H}_2\text{O}_2 \) oxidation) = 55%, pH (\( \text{H}_2\text{O} \)) = 8.8, OC (dry combustion) = 580 g kg\(^{-1}\), total N (Kjeldahl) = 10.5 g kg\(^{-1}\), and CEC = 19.8 cmol(+) kg\(^{-1}\). The rice husk biochar had the following properties: MWHC = 154%, chemical stability = 65%, pH = 9.6, OC = 450 g kg\(^{-1}\), total N = 8.6 g kg\(^{-1}\), and CEC = 18.5 cmol(+) kg\(^{-1}\). All parameters, except total N, were higher after pyrolysis at 600 °C compared with feedstocks.

**C mineralization in recent alluvial soil**

**CO\(_2\)-C evolution rate.** The CO\(_2\)-C evolution rate increased initially followed by a gradual decrease over time
For all treatments, the highest CO$_2$-C evolution rate was observed after 2–3 d of incubation, after which it declined gradually; the lowest rate was observed at 85 d (Fig. 1). A significant variation in CO$_2$-C evolution rate was observed among the treatments. Application of feedstocks increased ($P < 0.05$) CO$_2$-C evolution rates by more than five-fold compared with the control.

The highest CO$_2$-C evolution rate in the two feedstock treatments was observed within the first 1–2 d of the incubation. Thereafter, it decreased sharply up to day 15 (Fig. 1). Up to day 25 of the incubation, there was a significant variation in the rate of CO$_2$-C evolution between the treatments. From day 30 onwards, the variation became marginal. Treatments with biochar and aged biochar derived from sugarcane bagasse reached peak CO$_2$-C evolution on day 3, which then dropped sharply to day 6, after that the CO$_2$-C evolution declined gradually until the end of the incubation (85 d).

Cumulative C mineralization. Cumulative C mineralization was expressed both as an absolute and a normalized CO$_2$-C evolution. The highest absolute cumulative CO$_2$-C evolution was observed in the SB treatment (1 140 mg CO$_2$-C kg$^{-1}$ soil) followed by the RH treatment (1 090 mg CO$_2$-C kg$^{-1}$ soil); the lowest (140 mg CO$_2$-C kg$^{-1}$ soil) was in the ARHB treatment. The two feedstock treatments were substantially different from their respective biochar treatments throughout the study. The absolute cumulative C mineralization in the SBB and RHB treatments were not statistically different from that of the ASBB and ARHB, respectively, as well as the control. Absolute cumulative CO$_2$-C evolution from SB and RH treatments were 84% and 86% lower, respectively, compared with that in their respective biochar treatments after 85 d of incubation. Surprisingly, there were no differences in absolute cumulative CO$_2$-C evolution observed between the biochar treatments and their respective aged biochar treatments. The SBB and RHB treatments produced statistically identical absolute cumulative CO$_2$-C evolution, which were lower than the control. Absolute cumulative C mineralization followed the order of SB > RH > control > ASBB > SBB > RHB > ARHB. However, normalized cumulative C mineralization followed a different order of control > RH > SB > RHB > SBB > ASBB > ARHB (Fig. 3); i.e., it followed the order of feedstock > biochar > aged biochar. Cumulative C mineralization accounted for 11.2% and 15.5% of total SOC for the SB and RH treatments, 1.6% and 1.7% of total SOC for the SBB and RHB treatments, and 1.5% and 1.2% of total SOC for the ASBB and ARHB treatments, respectively (Fig. 3). Surprisingly, a large proportion (54%) of total SOC was mineralized within 85 d in the recent alluvial soil.

C mineralization in the old alluvial soil

Throughout the incubation period, the maximum CO$_2$-C evolution rate was observed on
day 2 for all the treatments, with the RH treatment showing the highest CO$_2$-C evolution rate (Fig. 4). Aged biochars of both sugarcane bagasse and rice husk had lower CO$_2$-C evolution rates compared with the control, following the order of SBB > RHB > control > ASBB > ARHB. The CO$_2$-C evolution peaked on day 2 and then dropped sharply to day 3. There were distinct differences among treatments until day 20; thereafter, all treatments showed almost similar CO$_2$-C evolution rate, which declined steadily up to the end of the incubation (85 d), except for the feedstock treatments.

At the later incubation stage, there were no significant differences ($P > 0.05$) in CO$_2$ evolution rate among the biochar and aged biochar treatments. Amendment of soil with both feedstocks increased CO$_2$-C evolution rate by more than three times compared with the control. Similar to the recent alluvial soil, after peaking, there was a gradual decline in CO$_2$-C evolution rate, with the minimum level observed on 85 d of incubation (Fig. 4). Both feedstock treatments showed statistically similar CO$_2$-C evolution rates, and both biochar treatments showed a statistically similar rate as the control. Conversely, both the aged biochars exhibited lower CO$_2$-C evolution rates than the control.

Cumulative C mineralization. Absolute cumulative C mineralization varied significantly among the treatments. It ranged from 196 to 1312 mg CO$_2$-C kg$^{-1}$ soil at the end of the 85-d incubation (Fig. 5). The highest absolute cumulative C mineralization was observed in the SB treatment followed by the RH treatment (1234.1 mg CO$_2$-C kg$^{-1}$ soil); the lowest was observed in the ARHB treatment (Fig. 5). Absolute cumulative C mineralization in the SBB, RHB, ASBB, and ARHB treatments differed significantly, with values of 380, 465, 225 and 196 mg CO$_2$-C kg$^{-1}$ soil, respectively. Biochar treatments had 65% and 69% lower absolute cumulative C mineralization compared with their feedstock treatments for sugarcane bagasse and rice husk, respectively. The ASBB and ARHB treatments resulted in 15% and 33%, respectively, lower cumulative C mineralization compared with their respective biochar treatments, and 10% and 18% compared with the control after the 85-d incubation. The trend of absolute cumulative C mineralization in the old alluvial soil differed slightly from that in the recent alluvial soil, with the order being SB $\geq$ RH $\geq$ SBB $\geq$ control $\geq$ ASBB $\geq$ ARHB. Similar to the recent alluvium soil, normalized cumulative C mineralization followed a different order from the absolute data, with the order of control $\geq$ RH $\geq$ SB $\geq$ RHB $\geq$ SBB $\geq$ ARHB $\geq$ ASBB (Fig. 6). However, the normalized data followed a similar trend in both old and recent alluvium soil, except ARHB and ASSB treatments.

Cumulative C mineralization accounted for 11.6% and 13.5% of total SOC in the SB and RH treatments, 2.8% and 3.9% of total SOC in the SBB and RHB treatments, and 2.1% and 2.2% of total SOC in the ASBB and ARHB treatments, respectively (Fig. 5), and 13.6% of total SOC in the control.
Prediction of C mineralization in the recent and old alluvial soils

The present incubation study was performed over 85 d in order to determine the fate of SOC after a 3-month cropping cycle with extrapolation by fitting the mineralization data to a mathematical model. Most of the amendment treatments exhibited an exponential model initially, followed by a linear model. All the estimated parameters derived after fitting the measured C mineralization data of recent and old alluvial soils into a first- and zero-order kinetic model are shown in Table II. The fitness of the model was good, with $R^2$ values close to 1 and low standard errors. Three parameters, namely $C_f$, $K_f$, and $K_s$, were estimated both from absolute and normalized C mineralization data.

Labile C pool ($C_f$). The results for $C_f$, both expressed as absolute and normalized values, in recent alluvial soil treated with organic amendments are presented in Table II. The organic amendments significantly ($P < 0.01$) influenced both absolute and normalized $C_f$. The $C_f$ value varied from 71.6 to 582.1 mg C kg$^{-1}$ soil or 8.3 to 173.4 mg C g$^{-1}$ SOC. The SB treatment had the highest $C_f$, followed by the RH treatment; the lowest $C_f$ was observed in the control when expressed as an absolute value. The biochar treatments were statistically similar to the control. However, the control had the highest $C_f$, followed by the RH and SB treatments; the lowest $C_f$ was observed in the RHB treatment when expressed as a normalized value. All the treatments were statistically similar except the control, RH and SB treatments.

The $C_f$ differed significantly among the treatments in old alluvial soil, both when expressed as absolute ($P < 0.03$) and normalized values ($P < 0.01$) (Table II). The absolute $C_f$ ranged from 159.6 to 681.1 mg C kg$^{-1}$ soil. The normalized $C_f$ ranged from 11.8 to 81.5 mg C g$^{-1}$ SOC, with the highest value recorded in the control closely followed by the RH treatment and the lowest value in the ARHB treatment (Table II). The RH treatment had a higher $C_f$ compared with the SB treatment. Both aged biochar treatments had slightly higher normalized $C_f$ values than their respective biochar treatments, but all were statistically similar. The normalized $C_f$ values of amended treatments followed the order of RH > SB > ASBB > ARHB > SBB > RHB. The two feedstock treatments differed in the distribution and mineralization rate of C in the labile and stable pools (Table II). Overall, the normalized mineralization rate of the labile C pool was larger than that of the stable C pool for all treatments; however, the opposite was found for the absolute mineralization rate.

Mineralization rate constant of labile C pool ($K_f$). The $K_f$ values differed significantly ($P < 0.01$) among the treatments in recent alluvial soil. The values of both absolute and normalized $K_f$ were the same and ranged from 2.8 to 22.2 mg C kg$^{-1}$ soil week$^{-1}$ or mg C g$^{-1}$ SOC week$^{-1}$.

### TABLE II

Estimated parameters$^{ab}$ of a fitted parallel first- and zero-order kinetic model from absolute and normalized C mineralization data of a recent alluvial soil and an old alluvial soil, unamended (control, CK) and amended with sugarcane bagasse (SB), rice husk (RH), sugarcane bagasse biochar (SBB), rice husk biochar (RHB), aged sugarcane bagasse biochar (ASBB), and aged rice husk biochar (ARHB).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>From absolute C mineralization</th>
<th>From normalized C mineralization</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C_f$ (mg C kg$^{-1}$ soil)</td>
<td>$K_f$ (mg C kg$^{-1}$ soil week$^{-1}$)</td>
<td>$K_s$ (mg C g$^{-1}$ SOC)</td>
</tr>
<tr>
<td>CK</td>
<td>71.6$^{bc}$</td>
<td>22.2a</td>
<td>13.0c</td>
</tr>
<tr>
<td>SB</td>
<td>582.1a</td>
<td>2.8c</td>
<td>48.5a</td>
</tr>
<tr>
<td>SBB</td>
<td>102.6b</td>
<td>7.5a</td>
<td>7.9cd</td>
</tr>
<tr>
<td>ASBB</td>
<td>137.6b</td>
<td>9.4b</td>
<td>5.2d</td>
</tr>
<tr>
<td>RH</td>
<td>568.6a</td>
<td>4.0b</td>
<td>44.6a</td>
</tr>
<tr>
<td>RHB</td>
<td>122.4b</td>
<td>19.1a</td>
<td>7.6cd</td>
</tr>
<tr>
<td>SE$^{c}$</td>
<td>3.69</td>
<td>0.351 2</td>
<td>0.306 6</td>
</tr>
<tr>
<td>P value</td>
<td>0.000</td>
<td>0.000 3</td>
<td>0.000</td>
</tr>
</tbody>
</table>

**Old alluvial soil**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>From absolute C mineralization</th>
<th>From normalized C mineralization</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CK</td>
<td>227.5c</td>
<td>3.3d</td>
<td>13.2e</td>
</tr>
<tr>
<td>SB</td>
<td>497.8b</td>
<td>8.8ab</td>
<td>66.8a</td>
</tr>
<tr>
<td>SBB</td>
<td>191.4c</td>
<td>7.6bc</td>
<td>17.9d</td>
</tr>
<tr>
<td>ASBB</td>
<td>270.4c</td>
<td>6.2c</td>
<td>6.5f</td>
</tr>
<tr>
<td>RH</td>
<td>681.1a</td>
<td>6.2c</td>
<td>50.4b</td>
</tr>
<tr>
<td>RHB</td>
<td>159.6c</td>
<td>10.2a</td>
<td>23.9c</td>
</tr>
<tr>
<td>SE$^{c}$</td>
<td>162.2c</td>
<td>7.4bc</td>
<td>12.4e</td>
</tr>
<tr>
<td>P value</td>
<td>0.036 98</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

$^a$ $C_f$ is the labile C pool; $K_f$ is the mineralization rate constant of the labile C pool; $K_s$ is the mineralization rate constant of the stable C pool.

$^b$ Values followed by the same letter within each column for each soil type are not significantly different at $P < 0.05$ according to Duncan's multiple range test.

$^c$ Standard error.
(Table II). The control had the highest $K_f$ value whereas the SB treatment had the lowest value. The biochar treatments had statistically similar $K_f$ values, which were higher than those of their respective feedstock treatments as well as their aged biochar treatments. The $K_f$ values for the feedstock and aged biochar treatments were statistically similar.

Both the absolute and normalized $K_f$ values were the same; they differed significantly ($P < 0.01$) among the treatments in old alluvial soil. The $K_f$ values ranged from 3.3 to 10.2 mg C kg$^{-1}$ soil week$^{-1}$ or mg C g$^{-1}$ SOC week$^{-1}$ (Table II). The SB treatment had a higher $K_f$ value than the RH treatment. Aged biochar treatments had lower $K_f$ values compared with their respective biochar treatments. The biochar treatment had a lower $K_f$ value than the feedstock treatment for sugarcane bagasse but not for rice husk. The $K_f$ of the amendment treatments followed the order of RHB $>$ SB $>$ SBB $>$ ARHB $>$ RH $>$ ASBB.

Mineralization rate constant of stable C pool ($K_s$). Both the absolute and normalized $K_s$ values differed significantly ($P < 0.01$) among the treatments in recent alluvial soil (Table II). The absolute $K_s$ values ranged from 2.0 to 48.5 mg C kg$^{-1}$ soil week$^{-1}$, while the normalized $K_s$ values ranged from 0.2 to 31.5 mg C g$^{-1}$ SOC week$^{-1}$. The highest absolute $K_s$ value was observed in the RH treatment, followed by the SB treatment, the control, and then the SBB, RHB, ASBB, and ARHB treatments. The $K_s$ values of the aged biochar treatments were statistically similar but slightly smaller than those of their respective biochar treatments. The control had the highest normalized $K_s$ value, followed by the RH and SB treatments. The normalized $K_s$ values in the rest of the treatments were statistically similar, although the aged biochar treatments always had smaller $K_s$ values than their respective biochar treatments. Both the absolute and normalized $K_s$ values followed a similar trend: feedstock $>$ biochar $>$ aged biochar. Compared with the SB treatment, the absolute $K_s$ value of the SBB treatment was 84% lower and that of the ASBB was 89% lower. Compared with the RH treatment, the absolute $K_s$ value of the RHB and ARHB treatments were 83% and 96% lower, respectively. Normalized $K_s$ values were 85% and 92% lower in the SBB and ASBB treatments, respectively, compared with the SB treatment, and 88% and 97% lower in the RHB and ARHB treatments, respectively, compared with the RH treatment.

The absolute and normalized $K_s$ values differed significantly ($P < 0.01$) among the treatments in old alluvial soil (Table II). The absolute $K_s$ values ranged from 6.5 to 66.8 mg C kg$^{-1}$ soil week$^{-1}$. The highest absolute $K_s$ value was observed in the SB treatment, followed by the RH treatment; the latter was significantly lower than the former. Biochar and aged biochar treatments had significantly lower absolute $K_s$ values compared with their respective feedstock treatments. The SBB and ASBB treatments had significantly lower $K_s$ values compared with the RHB and ARHB treatments, respectively. The control and ARHB treatment had statistically similar absolute $K_s$ values. The absolute $K_s$ values followed the order of SB $>$ RH $>$ RHB $>$ SBB $>$ ARHB $>$ ASBB. Normalized $K_s$ values were much lower than absolute $K_s$ values for all the treatments but followed a similar trend except for the control. The SB treatment had the highest normalized $K_s$ value, followed by the RH treatment; the ASBB treatment had the lowest normalized $K_s$ value. The normalized $K_s$ values followed the order of SB $>$ RHB $>$ SBB $>$ ARHB $>$ ASBB.

In old alluvial soil, both the absolute and normalized $K_s$ values followed a similar trend: feedstock $>$ biochar $>$ aged biochar. Normalized $K_s$ values of biochar and aged biochar treatments were significantly lower compared with those of their respective feedstock treatments. Absolute $K_s$ values were 73% lower in the SBB treatment than in the SB treatment, and 64% lower in the ASBB treatment than in the SBB treatment. Absolute $K_s$ values were 53% and 75% lower in the RHB and ARHB treatments, respectively, than in the RH treatment. Normalized $K_s$ values were 79% and 93% lower in the SBB and ASBB treatments, respectively, than in the SB treatment. Normalized $K_s$ values were 63% and 83% lower in the RHB and ARHB treatments, respectively, than in the RH treatment. The old alluvial soil had consistently higher absolute and normalized $K_s$ values compared with the recent alluvial soil for all organic amended treatments except for the normalized $K_s$ values in the RH treatment.

DISCUSSION

C mineralization rate

The labile C pool in soil, which is more susceptible to microbial attack, primarily contributes to soil C mineralization. Since the incorporation of any C-rich amendment alters the balance between labile and stable C pools in soil, biochar may affect C mineralization, either positively or negatively (Munda et al., 2018). The C mineralization rate in both the studied soils increased rapidly in the first 2–3 d following the addition of feedstocks and biochars, and then declined gradually towards a stable rate. Zimmerman et al. (2011) also observed a C mineralization peak in biochar- and wheat straw-amended soils in the first 2–5 d of incubation. An immediate flush of CO$_2$ release from soil following the addition of organic amendments is frequently reported in the literature. This initial flush might be related to the mineralization of the labile C fraction and stimulation of native SOC mineralization. Thus, it is expected that a high initial flush will occur from the addition of biochar, which has a lot of labile organic matter composed of cellulose and hemicellulose, as observed here in both soils. However, a relatively smaller initial CO$_2$ flush was observed from
biochar treatments compare with their respective feedstock treatments, indicating that biochar still has a labile portion of C. Indeed, this initial flush was observed in many studies after biochar amendment (Zimmerman et al., 2011; Munda et al., 2018; Paetsch et al., 2018; Liu et al., 2019). It indicates that microorganisms quickly adapt to use biochar C; however, this might be a short-term response to biochar amendment (Jiang et al., 2016). The fast microbial response to biochar could be due to the microorganisms known as r-strategists, which can quickly adapt to new available C sources. The presence of volatile organic matter in biochar may promote the r-strategists. Moreover, soil microbial activity might be increased as biochar amendment can improve the microbial habitat (Lehmann et al., 2011; Quilliam et al., 2013), resulting in a higher rate of C mineralization during the initial phase (Smith et al., 2010). Soil microbes re-mineralize soil nutrients and concurrently co-metabolize resistant organic matter in the process (Kuzyakov et al., 2000; Kuzyakov, 2010).

No such initial CO$_2$ flush was observed in the aged biochar treatments except for the ASBB treatment in the recent alluvial soil. This is in line with Liu et al. (2019), who did not observe an initial CO$_2$ flush in aged biochar-amended paddy soil. This result is expected as the labile C compounds present in biochar are depleted during the aging/chemical oxidation procedure, leaving behind only the recalcitrant biochar residue (Naisse et al., 2015; Paetsch et al., 2017, 2018). The small initial flush from the ASBB treatment in recent alluvial soil might be due to the presence of some labile materials in this soil. Different aquatic and terrestrial plant and animal residues are unevenly distributed in recent alluvial soil during sedimentation.

After the initial CO$_2$ flush, C mineralization rate declined and stabilized over time with the depletion of the labile C pool. These findings indicate that after biochar amendment, C mineralization was stimulated initially for a short term due to the newly available C sources (Smith et al., 2010).

Addition of SB and RH to soil increased ($P < 0.05$) the CO$_2$-C evolution rate by 5 times compared with the control, except for SB in the recent alluvial soil. Both the SBB and RHB treatments had statistically similar CO$_2$-C evolution rate, particularly in the old alluvial soil. These results indicate that biochar amendment largely influences the stabilization of SOC and the mitigation of CO$_2$ emissions from soil.

Cumulative C mineralization

The absolute cumulative C mineralization in the SBB, RHB, ASBB, and ARHB treatments over the 85-d incubation were 380, 465, 225, and 196 mg CO$_2$-C kg$^{-1}$ soil, respectively, in the old alluvial soil and 187, 156, 201, and 142 mg CO$_2$-C kg$^{-1}$ soil in the recent alluvial soil. This result is similar to the absolute cumulative C mineralization (250–350 mg CO$_2$-C kg$^{-1}$ soil) recorded in a 60-d incubation experiment using a sub-tropical soil amended with rice husk biochar (Jegajeevagan et al., 2016). The SBB and RHB treatments had statistically similar absolute cumulative C mineralization, and their aged biochar treatments (ASBB and ARHB) also had similar values. Similarly, Youssaf et al. (2017) observed that, compared with the control, the biochar-amended soil released significantly less ($P \leq 0.05$) CO$_2$-C over 120 d, whereas the bio-waste-amended soils significantly increased ($P \leq 0.05$) cumulative C mineralization. Cumulative C mineralization over the 85-d incubation period in the SBB and RHB treatments accounted for 1.6%–3.9% of total SOC, while that in the ASBB and ARHB treatments accounted for 1.2%–2.2%. The results are in line with the findings of previous reports. For example, Jegajeevagan et al. (2016) found that < 0.2% of the C in rice husk biochar was mineralized when incubated in soil for 60 d and Bruun et al. (2011) found that < 5% of the C in wheat straw biochar was mineralized when incubated in soil for 100 d. Moreover, our results are within the range of the maximum mineralized amount of biochars (15%–20% of total SOC) (Han et al., 2020).

In general, the absolute CO$_2$-C evolution from the SB, SBB, and ASBB treatments were slightly higher than those from the RH, RHB, and ARHB treatments in both soils. Conversely, the normalized data showed the opposite trend; the CO$_2$-C evolution in RH, RHB, and ARHB treatments were higher than those from the SB, SBB, and ASBB treatments. This might be due to the higher OC content in SB, SBB, and ASBB than in RH, RHB, and ARHB (Table I), as the amendment addition was done on a weight basis (1%) not on an OC basis. Thus, a higher absolute CO$_2$-C evolution from the SB, SBB, and ASBB treatments is logical. However, the opposite trend was observed for the normalized data, which indicates that SB, SBB, and ASBB are less prone to microbial decomposition compared with RH, RHB, and ARHB.

C mineralization prediction

The stable fraction of organic matter remains in soil for a long time after addition. Thus, the amount of stable OC should be determined from long-term incubations over one or more years at a temperature and moisture comparable to field conditions. However, such long-term incubations are not practical; hence, the present study was done over a 3-month period with an aim to extrapolate long-term C mineralization by fitting a suitable kinetics model of C mineralization to these data. In the present study, C mineralization data fit well to the parallel first- and zero-order kinetic model and three parameters ($C_1$, $K_1$, and $K_a$) were estimated. Other researchers (Ameloot et al., 2013a; Jegajeevagan et al., 2016)
2016) reported that the first- and zero-order kinetic model is able to describe cumulative C mineralization well in biochar-amended soils. The labile C pool is small but highly bioavailable and has a fast rate of decomposition ($K_f$), which controls instantaneous fluxes. Conversely, the stable C pool is large, has a slow rate of decomposition ($K_s$), and controls long-term storage (Cheng et al., 2008). Thus, the stable C pool is important for predicting SOC retention capacity or C sequestration. The normalized data are more important than the absolute data, as they represent the actual substrate availability to microbial decomposition.

Partitioning of normalized C mineralization data through modelling showed that both the feedstock treatments had higher $C_f$ (labile C pool) values compared with their respective biochar and aged biochar treatments. This is logical as the pyrolysis of feedstock during biochar production process polycondenses short-chain aromatic-C and carboxyl-C (labile C) into recalcitrant C (Lehmann et al., 2006; Jindo et al., 2014; Han et al., 2020). As expected, the differences in $C_f$ value between biochar and aged biochar treatments were not consistent or notable. However, significant and notable differences were observed in $K_s$ values among the treatments, which allowed us to examine the long-term decomposability of organic amendments in the study soils (Sleutel et al., 2010). The lower $K_s$ values in aged biochar and biochar treatments compared with their respective feedstock treatments clearly suggest that biochar C will remain in soil for a long time, making the biochars suitable for C enrichment. Indeed, the retention time of biochar C in soil has been estimated to be at least hundreds, but more likely thousands of years (Lehmann et al., 2009).

Comparisons of C mineralization among treatments

C mineralization from amended recent and old alluvial soils was studied over a 3-month period. The organic amendments were two types of feedstock (SB and RH), their biochars (SBB and RHB), and aged biochars (ASBB and ARHB). The two feedstock treatments had substantially different C mineralization rates compared with their respective biochar treatments over the 85-d incubation period. Both absolute and normalized CO$_2$-C evolution were reduced by 60%–80% in biochar treatments compared with their feedstock treatments. Absolute CO$_2$-C evolution was 10%–30% lower in aged biochar treatments than in biochar treatments after 85-d incubation. However, the difference in CO$_2$-C evolution was much larger when normalized. Aged biochar treatments had 7%–43% less normalized CO$_2$-C evolution compared with biochar treatments. Normalized mineralization rate of the stable C pool ($K_s$) in biochar treatments was 62%–87% lower compared with their respective feedstock treatments. Aged biochar treatments further reduced the $K_s$ value by 43%–78% compared with the biochar treatments (Table II). This result was expected for three reasons. First, pyrolysis of feedstock during the biochar production process left behind mainly the recalcitrant residues consisting of aromatic OC and condensed aromatic OC, which are not suitable for microbial decomposition (Lehmann et al., 2006; Han et al., 2020). Second, the aging process (artificial weathering) of biochar through chemical treatments further depleted the labile C fraction in biochar and increased carboxyl and carboxylic functional groups as well as biological stability (Naisse et al., 2015; Mia et al., 2017). Third, aged biochar may contain some toxic chemicals that were used in the ageing process or mineral adsorptive protection, which inhibit microbial decomposition (Ventura et al., 2015).

Furthermore, the biochar and aged biochar treatments reduced absolute CO$_2$-C evolution by 16%–30% and 10%–36%, respectively, compared with the control for recent alluvial soil. For old alluvial soil, only the aged biochar treatments reduced absolute CO$_2$-C evolution compared with the control (by 10%–18%). Liu et al. (2019) reported a decrease of 38.8% in C mineralization in paddy soil with addition of aged biochar but an increase of 28.9% with addition of fresh biochar, compared with the control. However, in the current study, when CO$_2$-C evolution was normalized, a greater reduction was observed for both the biochar and aged biochar treatments in both soils. Compared with the control, the biochar treatments showed a 71%–97% reduction in normalized CO$_2$-C evolution and the aged biochar treatments showed a 83%–98% reduction. These results indicate that biochars and aged biochars have a negative priming effect (PE) on CO$_2$-C evolution. Biochars produced at high temperatures are commonly reported to induce negative PEs (Zimmerman et al., 2011; Lu et al., 2020). Negative PEs induced by biochars pyrolyzed at high temperatures are thought to result from a reduction in the availability of native SOC, due to (1) the increase in adsorption capacity of biochar (Kimetu and Lehmann, 2010; Cross and Sohi, 2011), because of the increase of specific surface area of biochar and the decrease of mineralizable C (Kasozi et al., 2010; Conte and Laudicina, 2017), and (2) the formation of stable aggregates that physically protect SOC (Kader et al., 2010; Lu et al., 2014). Another reason is that soil microbes prefer the labile SOC from biochar instead of native SOM and thus the decomposition of native SOC decreases (Whitman et al., 2014; Zimmerman and Ouyang, 2019).

Comparisons of C mineralization between recent and old alluvium soils

The type and amount of biochar, biochar production conditions, soil conditions (e.g., clay content, moisture, and temperature), and time are all important in determining biochar decomposition and C sequestration in soil (Naisse et al., 2015; Han et al., 2020). Absolute CO$_2$-C evolution in
all treatments in the recent alluvial soil was always higher than that in the recent alluvial soil. This was expected, as the old alluvial soil had a higher native SOC content (6.4 g kg\(^{-1}\)) compared with the recent alluvial soil (0.41 g kg\(^{-1}\)). However, the normalized CO\(_2\)-C evolution was also showed the similar trend like the absolute CO\(_2\)-C evolution; always higher in the old alluvial soil than in the recent alluvial soil except the RH treatment. This was not expected. It might be because there were some positive PEs of biochars on mineralization of native SOC in old alluvial soil. Indeed, the recent alluvial soil contained very little native SOC, most of which was very labile as indicated by the higher normalized C\(_f\) value (173.4 mg C g\(^{-1}\) SOC) compared with the old alluvial soil (81.5 mg C g\(^{-1}\) SOC) (Table II). The positive PEs induced by organic amendments have generally been described to the stimulation of soil microorganisms following addition of organic amendments, which results from co-metabolism or nutrient mining (Kimetu and Lehmann, 2010; Luo et al., 2011; Ramirez et al., 2012). This has also been observed under C-limiting conditions (Whittman et al., 2014), similar to the recent alluvial soil with low C\(_f\) value. Our results indicate that the quantity and quality of native SOM influence the PE of native SOM following addition of organic amendments. This could explain the variation in PEs observed in previous studies (Kuzyakov et al., 2009; Keith et al., 2011; Fang et al., 2014).

The normalized K\(_s\) values for all treatments were smaller in recent alluvial soil than in old alluvial soil, except for in the RH treatment. This indicates that biochars and aged biochars will be retained longer in the recent alluvial soil than in the old alluvial soil. Thus, amendment with biochars or aged biochars could enrich SOC in organic C-poor recent alluvial soil.

CONCLUSIONS

The C mineralization in terms of CO\(_2\)-C evolution markedly varied with feedstock type and hence with biochars and aged biochars. There was an initial rapid increase in C mineralization in the first 2–3 d followed by a slow decrease until reaching a steady state. The feedstock treatments resulted in the highest cumulative CO\(_2\)-C evolution, followed by the biochar treatments and then the aged biochar treatments. For both feedstock and biochar, the sugarcane bagasse treatments resulted in slightly higher CO\(_2\)-C evolution compared with the rice husk treatment, but the trend was not consistent. Between the two soils, a slower C mineralization rate was observed in the recent alluvium soil than in the old alluvium soil. A negative priming effect of biochar and aged biochar amendments was observed in both the soils. These showed that biochar and aged biochar amendments could improve SOC content in the organic C-poor recent alluvial soil. Further study is needed to assess C mineralization in biochar-amended soils under varying soil moisture contents, particularly under flooding conditions that occur in Bangladesh.

ACKNOWLEDGEMENT

We thank the BARC (Bangladesh Agricultural Research Council) for awarding a postgraduate scholarship with research support to the first author through the NATP (National Agricultural Technology Program) Phase-II Project.

REFERENCES


