Effects of biochar on soil properties and erosion potential in a highly weathered soil

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Highly weathered soils in humid Asia are characterized by low soil fertility and high soil erosion potential. This study evaluates the influences of biochar made from the waste wood of white lead trees (Leucaena leucocephala Lam. de Wit) on the physicochemical and biological properties of long-term cultivated, acidic Ultisol. This study used three application rates (0%, 2.5%, and 5% (wt/wt)) of the biochar with an incubation period of 105 d for all cases. Soils were collected at 21 d, 42 d, 63 d, 84 d and 105 d during the incubation period to evaluate changes in soil properties over time. A simulated rainfall event (80 mm h\(^{-1}\)) was performed to estimate soil loss for all treatments at the end of the incubation time. Experimental results indicate that applying biochar improved the physicochemical and biological properties of the highly weathered soils, including significant increases in soil pH from 3.9 to 5.1, cation exchange capacity from 7.41 to 10.8 cmol (+) kg\(^{-1}\), base cation percentage from 6.40 to 26.0%, and microbial biomass carbon (MBC) from 835 to 1262 mg kg\(^{-1}\). Compared with the control (i.e., no biochar), biochar application decreased bulk density from 1.4 to 1.1 Mg m\(^{-3}\), increased \( K_{sat} \) by 1.8 times and increased the mean weight diameter (MWD) of soil aggregates from 2.6 cm to 4.0 cm. Incorporating biochar into the soil significantly reduced soil loss by 50% and 64% at 2.5% and 5% application rates, respectively, compared with the control. The formation of macropores in the biochar-amended soils is the critical factor to improve soil erosion potential. Based on these results, a 5% application rate of biochar is considered as suitable for highly weathered soil because this application rate efficiently improves soil physicochemical properties and reduces soil loss.

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1. Introduction

Highly weathered soils are typically characterized by strong acidity, low clay activity, and poor fertility, and are considered to be degraded soils. Soil degradation, including decreased fertility and increased erosion, is a major concern in global agriculture, and particularly in subtropical and tropical areas (Jiangping, 1999). Intensive, long-term cultivation of these highly weathered soils often results in their degradation, which includes soil acidification, soil organic matter (SOM) depletion and severe soil erosion (De Meyer et al., 2011; Hoyos, 2005). The decrease in soil organic carbon (SOC) caused by long-term cultivation decreases the aggregate stability of the soil and increases its erosion potential (Annabi et al., 2011; Tejada and Gonzalez, 2007). Therefore, the effective maintenance of SOM in degraded soils can help preserve soil fertility and reduce erosion susceptibility by promoting soil aggregation stability, and improving hydraulic conductivity and water retention ability (Auerswald et al., 2003; Tejada and Gonzalez, 2007).

Biochar is a carbon-rich product produced by the slow thermochemical pyrolysis of biomass materials. Organic wastes, such as livestock manures, sewage sludge, crop residues and composts are converted to biochars and then applied to soils as an amendment. In the past, organic amendments and polymers such as polyacrylamides (PAM) were used to improve soil physicochemical properties and protect soils from erosion (Busscher et al., 2011). However, the depletion of soil organic matter and the high cost of PAM application are serious problems to overcome.

Many studies have shown that biochar is a useful resource to improve the physicochemical properties of soil, effectively maintain SOM levels, increase fertilizer-use efficiency and increase crop production, particularly for long-term cultivated soils in subtropical and tropical regions (Chan et al., 2007, 2008; Deenik et al., 2011; Van Zwieten et al., 2010). Furthermore, the application of biochar to soils might be a practical method to aid in the long-term maintenance of the soil organic carbon contents and soil fertility. The application of biochar to soils can maintain SOM levels and soil aggregation stability (Kimetu and Lehmann, 2010; Tejada and Gonzalez, 2007; Trompowsky...
et al., 2005) because biochar is characterized by recalcitrant C from microbial degradation and by a charged surface with organic functional groups. Reducing soil erosion potential, maintaining SOM, and improving soil aggregative stability are critical processes. Previous studies have demonstrated the importance of SOM to the physiochemical properties of soil (Materechera, 2009; Wuddivira et al., 2009) and erosion susceptibility (Auerswald et al., 2003; Tejada and Gonzalez, 2007). Many studies have reported the use of biochar as an amendment for crop production, and improving the chemical properties in highly weathered tropical soils (Iswaran et al., 1980; Liang et al., 2006). However, few studies have investigated the effects of biochar on soil physical properties and soil erodibility (Atkinson et al., 2010; Hammes and Schmid, 2009).

Highly weathered soils, which account for approximately 10% of Taiwan, are some of the most common types of agricultural soils in Taiwan. This is particularly true in northern Taiwan (a subtropical climate), an area of rice and tea production, and in southern Taiwan (a tropical climate), an area of rice and pineapple production. Under humid subtropical and tropical climates, highly weathered soils with intensive cultivation are characterized by a very low pH (≤ 5.0), and low soil organic matter (≤ 1%), CEC, and base saturation percentage (BS). Huang (1986), Lin and Hung (2000), and Lin (2002) studied the soil erosion rates of highly weathered soils in Taiwan, and indicated that the soils have moderate to serious soil losses ranging from 10 to 280 tons ha⁻¹ yr⁻¹. Similar climates and soil degradation problems appear in Trinidad and Tobago (Wuddivira and Camps-Roach, 2007; Wuddivira et al., 2009), where the most critical factors influencing the degradation are SOM content and soil aggregation stability. Previous studies on amending soils with biochar typically focused on restoring soil fertility and crop production. Few studies have discussed the influences of biochar on the physical properties of soil and erodibility in highly weathered soils. The objectives of this study were (1) to evaluate the effects of wood biochar on the physical properties and erosion potential of highly weathered soils, and (2) to assess the relationships between soil properties and soil erosion potential.

2. Methods and materials

2.1. Soil and biochar

Soil samples (0–25 cm) were collected from a terrace located at field erosion experimental plots at the National Pingtung University of Science and Technology, southern Taiwan (about E 120°37'11"; N 22°38'54""). The soil was classified as a Typic Paleudults based on Soil Taxonomy (Soil Survey Staff, 2010). Pineapple (Ananas comosus (L.) Merr.) is the dominant crop on this terrace. The biochar used in this study was supplied by Taiwan Forestry Research Institute (TFRI) and was produced from the wood of white lead trees (Leucaena leucocephala (Lam.) de Wit). The waste wood of the pineapple (Ananas comosus (L.) Merr.) was used to measure the aggregate stability of 2-mm air-dried aggregates (35 g). Four cm amplitude was applied for 5 min vertical movement to a nest of sieves (>2000, 1000–2000, 500–1000, 250–500, 250–106, <106 mm) immersed in a container of tap water (101 mS/cm). The material that remained after wet-shaking in each sieve was carefully removed, and the mean weight diameter (MWD) of the aggregate size was calculated using

\[ MWD = \frac{\sum_{i=1}^{n} x_i w_i}{n} \]

where n is the number of sieves, and x and w are diameter and weight, respectively.

The specific surface areas of soil and biochar were determined by N adsorption isotherms at 77.3 K interpreted by the BET equation (Brunauer et al., 1938) (PMI Automated BET Sorptometer BET-202A). Soil microbial biomass carbon (MBC) was determined via fumigation and extraction (Brookes et al., 1985; Vance et al., 1987). The MBC was only determined at 0, 21, 63 and 105 days during the incubation period. Fifteen grams of subsample of the incubated soil was fumigated with ethanol-free chloroform for 24 h at 25 °C. After chloroform removal, the subsample was extracted with 200 ml 0.5 M K₂SO₄ solution for 30 min. Organic carbon in the extract was measured by wet digestion with dichromate and titration with FeSO₄.

2.2. Incubation experiment

Incubation experiments were conducted to evaluate the effects of biochar on the physiochemical properties of soil. Fifteen kg samples of the study soils were placed in plastic pots (measuring approximately 30 cm in width and 40 cm in depth) and then mixed with biochar at three application rates (0%, 2.5% and 5% (w/w)). Soil and biochar were mixed thoroughly, and then wetted with deionized water to approximately 60% water content (i.e., the field water capacity of the soil). The amended control was also subject to disruption of mixing. The incubated pots were placed in a room at 28 °C and weighed every 5 d to maintain a constant moisture content. All treatments were carried out in triplicate. The incubation time was 105 d in total, and soils were analyzed at 21 d, 42 d, 63 d, 84 d, and 105 d to determine their physical and chemical properties.

2.3. Soil and biochar analyses

Soil samples were air dried and ground to pass through a 2-mm sieve for subsequent analysis. The particle size distribution was determined by the pipette method (Gee and Bauder, 1986). Soil pH was determined by a ratio of soil to water of 1:2.5 (McLean, 1982). Total soil C and N contents were measured with a Fisons NA1500 elemental analyzer (Thermo Electron Corporation, Waltham, Massachusetts, USA). Soil organic carbon (SOC) was determined by wet oxidation method (Nelson and Sommers, 1982). Each extracted fraction was analyzed for total organic C (O.J. Analytical 1010) using the heat-persulfate oxidation method. The cation exchange capacity (CEC) and exchangeable bases were measured using the ammonium acetate (pH = 7) method (Thomas, 1982). Bulk density was determined by the core method (Blake and Hartge, 1986). Saturated hydraulic conductivity (Kₛₜ) was measured in saturated soil packed in 100 cm³ columns. The Kₛₜ was measured in the laboratory using the Klute and Dirksen (1986) falling-head method with distilled water. Modified fast-wetting in water, as proposed by Le Bissonnais (1996), was used to measure the aggregate stability of 2-mm air-dried aggregates (35 g). Four cm amplitude was applied for 5 min vertical movement to a nest of sieves (>2000, 1000–2000, 500–1000, 250–500, 250–106, <106 mm) immersed in a container of tap water (101 mS/cm). The material that remained after wet-shaking in each sieve was carefully removed, and the mean weight diameter (MWD) of the aggregate size was calculated using

\[ MWD = \frac{\sum_{i=1}^{n} x_i w_i}{n} \]

where n is the number of sieves, and x and w are diameter and weight, respectively.

Fourier-transform infrared (FTIR) analysis was performed to test the quality of the study biochar. Ground biochar (0.3–0.5 mg) was embedded in potassium bromide (KBr) pellets (99.5–99.7 mg) and measured on an FTIR spectrometer (VECTOR 22, Bruker, USA) with a 4 cm⁻¹ resolution and 100 scans between wavenumbers of 4000 and 400 cm⁻¹ (Chun et al., 2004). To analyze C forms from the FTIR spectra, we subtracted the background of the KBr window, automatically corrected the baseline and smoothed the spectra, identified the peaks, and normalized the spectra on a reduced portion of the wavenumbers (4000–500 cm⁻¹).
2.5. Soil micromorphology

Kubiena boxes were used to collect undisturbed blocks of unamended and amended soils during the incubation period to make thin sections. After air drying, vertically-oriented thin sections measuring 2.5 × 5 cm and 30 μm thick were prepared by Spectrum Petrographics (Winston, OR, USA). The thin sections were used to observe soil structures under a polarized microscope (AFX-II Type, Nikon Precision Instruments, Belmont, CA). The biochar sample was viewed by optical microscopy with reflected light and then scanning electron microscopy (SEM) (Hitachi, S-3000N, Japan) to identify its micro-scale structure. A back-scattered electron image representing the mean atomic abundance in a back-and-white image was observed from the surface of the samples coated by Au. The mineral phases of the sample were identified using SEM and energy-dispersive spectroscopy (EDS) (Horiba, EMAX-ENERGY EX-200, Japan), with 15 kV and 180 pA for the acceleration voltage and beam current, respectively, in a vacuum of 25 Pa with an Au coating. Analyzed points were selected using back-scattered electron images to avoid damaging samples.

2.6. Determination of soil losses

The soil erosion experiment was conducted using simulated rainfall equipment with 9.5 m in height (drop diameter is 2.5 mm and terminal velocity is 8.5 m s⁻¹), and all processes followed the ASTM-D7101 standard (American Standard Testing Materials, ASTM). Soil erosion processes are widely performed in the field and laboratory using rainfall simulators and these simulations play an important role in controlling repeatable conditions and adjusting the required rainfall intensity (Tejada and Gonzalez, 2007). The erosion experiment simulated a rainfall intensity of 80 mm h⁻¹ and a 10% slope gradient because this is the average slope gradient in the field.

2.7. Statistical analysis

The rainfall experiment for all the treatment was in triplicate. The triplicate data were subjected to mean separation analysis using the 1-way ANOVA test at a significance of p = 0.05. The differences between mean values were identified using Duncan's test. Pearson's correlation coefficients were calculated to determine how the soil properties are related.

3. Results

3.1. Properties of the studied soil and the biochar

Table 1 lists the properties of the soil and the biochar. The soil was very acidic (pH < 4.0) and had low levels of total organic carbon (TOC) (4.37%) and soil organic carbon (SOC) (<2.0%), which is typical for soils in humid tropical regions. A low CEC might be the result of low organic matter content and low clay activity in the soil. In addition, heavy rainfall (>2500 mm yr⁻¹) in the study area resulted in intensive leaching.

Biochar made from the wood of white lead trees (L. leucocephala (Lam.) de Wit) has an extremely high pH (>9.0) and a high liming potential on acid soils. The biochar in this study had 78.3% TC and 0.64% total nitrogen (TN), but relatively low levels of SOC (<2.0%) which was determined by Walkley–Black method. The SOC estimated in this study was considered as oxidisable carbon contents in the soil and the biochar. This indicates the recalcitrant nature of the biochar in the soils. The Fourier-transform infrared spectra (FTIR) of the biochar (Fig. 1) show large proportions of OH stretching vibrations of the H-bonded hydroxyl (O–H) group of phenol (aromatic compound), implying that most of the C was stable in the biochar. The high specific surface area (SSA) and porous characteristics (Fig. 1) of the biochar might be the reason for the higher CEC (22.3 cmol (+) kg⁻¹) in the biochar than in the study soil. Table 1 shows that the exchangeable cations of the biochar were all higher than those of the study soils, especially in calcium and potassium. This finding is consistent with the EDS results of the biochar (Fig. 1).

3.2. Changes in soil chemical properties

Table 2 shows the chemical, physical, and biological properties of the amended soils after incubation. After applying biochar to the soils and incubating for 105 d, the amended soils had a significantly higher soil pH (at least 0.5 units) than the control samples (Fig 2a). There were no significant differences of SOC contents (determined by Walkley–Black method) between unamended and amended soils, even at the end of the incubation. Additionally, the SOC contents show no obvious changes throughout the incubation period for all treatments (Fig 2b).

In addition to soil pH, the CEC significantly increased from 7.41 to 9.26 (2.5%) and 10.8 cmol (+) kg⁻¹ (5%) (p < 0.05) with the application of biochar. The biochar-amended soils also showed an increase in the CEC with incubation time (Fig 2c). The exchangeable K, Ca, and Mg contents also significantly increased in the biochar-amended soil compared with the control. Both biochar application rates increased the BS from 6.40% to 14.2% (2.5%) and 26.0% (5%) (>00) after incubation of 105 d, indicating an increase in the nutrient status of highly weathered soils after biochar application.

3.3. Changes in soil porosity properties

During the incubation duration, consistent bulk density (Bd) about 1.10 Mg m⁻³ was found for the amended soils; however, rapid increase of Bd was found in the control at 21 d and then maintained a consistent value at about 1.42 Mg m⁻³ to the end of the incubation (Fig. 2e). After incubation of 105 d, the Bd of the biochar-amended soils significantly decreased from 1.42 Mg m⁻³ to <1.15 Mg m⁻³, and rate of decrease increased with the biochar application rate (Table 2). Other than changes in the Bd, the biochar-amended soils exhibited significantly higher total porosities (>50%) than the unamended controls (41%) after 105 d incubation (Table 2). Fig. 2f further shows a variation of porosity during the incubation duration; the control and 2.5% biochar-amended soil presented unobvious changes throughout the duration, and a gradual decrease in porosity appeared in the 5% biochar-amended soil.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Soil</th>
<th>Wood biochar</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>3.95 ± 0.02</td>
<td>9.94 ± 0.22</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>16.2 ±  a</td>
<td>-</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>40.2 ±</td>
<td>-</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>43.6 ±</td>
<td>-</td>
</tr>
<tr>
<td>TOC (%)</td>
<td>4.37 ± 1.04</td>
<td>78.3 ± 2.21</td>
</tr>
<tr>
<td>TN (%)</td>
<td>0.29 ± 0.02</td>
<td>0.64 ± 0.07</td>
</tr>
<tr>
<td>C/N</td>
<td>152 ± 3.02</td>
<td>121 ± 28.6</td>
</tr>
<tr>
<td>SOC (%)</td>
<td>1.90 ± 0.20</td>
<td>1.82 ± 0.14</td>
</tr>
<tr>
<td>Exc. Ca (cmol (+) kg⁻¹)</td>
<td>7.41 ± 1.05</td>
<td>22.3 ± 1.65</td>
</tr>
<tr>
<td>Exc. Mg (cmol (+) kg⁻¹)</td>
<td>0.37 ± 0.05</td>
<td>8.84 ± 0.73</td>
</tr>
<tr>
<td>Exc. K (cmol (+) kg⁻¹)</td>
<td>0.02 ± 0.01</td>
<td>0.41 ± 0.00</td>
</tr>
<tr>
<td>Exc. Na (cmol (+) kg⁻¹)</td>
<td>0.19 ± 0.14</td>
<td>0.19 ± 0.03</td>
</tr>
<tr>
<td>SSA (m² g⁻¹)</td>
<td>29.4</td>
<td>340</td>
</tr>
</tbody>
</table>

ND: not detectable.


* Not determine.
Fig. 2g indicates that MWD of soil aggregation was consistently higher for the biochar-amended soils than the control after incubation of 21 d; however, significant differences between the amended soils and the control were found after incubation of 84 d. An obvious peak that occurred at 21 d was found for all treated soils. Furthermore, applying biochar to the soil caused a significant increase in the saturated hydraulic conductivity (Ksat). At the end of the incubation, the Ksat values of the amended soils were twice as high as the control soils (Table 2), although there were great variances found at the beginning of the incubation, especially for the 5% biochar amended soil (Fig. 2h). After incubation of 21 d, the Ksat stabilized gradually and kept higher consistently for the biochar-amended soils to the end of the incubation.

### 3.4. Changes in soil microbial activity

To understand the changes of soil microbial activity after biochar application, the microbial biomass carbon (MBC) contents were determined at 0 d, 21 d, 63 d, and 105 d of incubation. Results indicate that the biochar application significantly increased the MBC at the beginning of incubation, 63 d and 105 d (only in 5% application rate). The differences were statistically significant \((p < 0.05)\), except for the analytical results at 21 d (Fig. 3). In addition, the highest contents of MBC were found at 21 d for each treated soil, which were 3200 mg kg\(^{-1}\) for 5% biochar-amended soil, 1145 mg kg\(^{-1}\) for 2.5% biochar-amended soil and 1759 mg kg\(^{-1}\) for the control, respectively.
3.5. Soil losses

Table 2 shows the soil loss rate under a simulated rainfall intensity of 80 mm h$^{-1}$. The highest soil loss rate (1458 ± 50.0 g m$^{-2}$) occurred in the control soil, and the lowest (532 ± 106 g m$^{-2}$) occurred in the amended soil with the highest application rate (5%). The soil loss rate significantly decreased as the biochar application rate increased, indicating that...
biochar largely ameliorated soil erosion potential in highly weathered soils.

4. Discussion

4.1. Effects of biochar on the chemical properties of highly weathered soil

The results of this study confirmed the effectiveness of wood biochar in improving the physical and chemical properties of soil that is highly weathered. The results indicated that the improvements in soil characteristics varied with variations in the amount of biochar added to the soil. Incubation results indicated that soil pH, CEC, and BS increased significantly after the addition of biochar, particularly at the application rate of 5%. The high liming potential of the biochar (pH > 9.0) raised the pH of the highly weathered soil. Our results further showed that pH increased significantly with increasing application rates of biochar, reflecting the fact that the liming potential increased with increasing application rates of biochar. This correlated with the results of Yuan and Xu (2011), who indicated a significantly positive linear correlation between biochar-treated soil pH and biochar pH (r² = 0.46, p < 0.05). In this study, the biochar-treated soil did not exhibit a significant increase in SOC levels, which agreed with Lehmann (2007) who indicated that original nutrients in the soils lead to an increase in microbial activity was further demonstrated by a significantly positive correlation between pH and MBC in the soils (Table 3). Additionally, the biochar was characterized by porous structure (Fig. 1a). Because of this porosity, higher amounts of biochar in the treated soil increased the habitat for microbes to grow. Joseph et al. (2010) indicated that most of biochar has a high concentration of macro-pores that extends from the surface to the interior, and minerals and small organic particles might accumulate in these pores.

4.2. Effects of biochar on the physical properties of highly weathered soil

Few studies have been published on the influences of biochar on the physical properties of soils (Atkinson et al., 2010). In addition to improved chemical properties of the soils, our results indicated a particularly significant improvement in the physical properties of the highly weathered soil. The results indicated a significant decrease in Bd, and an increase in porosity, Ks, and the MWD of soil aggregates in the biochar-amended soils, even at the low application rate (2.5%) after incubation of 105 d (Table 2).

During the incubation duration, the values of Bd kept higher in the biochar-amended soils than in the control after 21 d. Before 21 d, the rapid increase in the control's Bd might be caused by gradual infilling of clays into pores of the soil, which reflected that the incubated soils are stable and approached field condition after 21 d. For the biochar-amended soils, physical dilution effects might have caused reduced Bd levels, which agreed with Busscher et al. (2011) who indicated that increasing total organic carbon by the addition of organic amendments in soils could significantly decrease Bd. Furthermore, the decrease in Bd of the biochar-amended soils appears to have also been the result of alteration of soil aggregate sizes, as shown by Tejada and Gonzalez (2007) who amended the following soils by using organic amendments in Spain. In our study, micromorphological observations of the amended soils indicated the flocculation of soil microaggregates after the addition of biochar (Fig. 4a; b).

The porosity could also be effectively improved by application of the biochar and hydraulic conductivity as well. Asai et al. (2009) indicated that the incorporation of biochar into rice-growing soils changed the pore-size distribution, which increased water permeability. Regarding the porosity and hydraulic conductivity of the amended soils, we considered the redistribution of the proportion of soil aggregate sizes to be a critical factor in influencing the physical and chemical properties of the soil (Table 2). The incorporated biochar could function as a binding agent that connects soil microaggregates to form macroaggregates. The oxidized biochar surface, which included hydroxyl groups and carboxylic groups, could adsorb soil particles and clays (Fig. 4c) to form macroaggregates under acidic environments. Our incubation study showed that the biochar-amended soils seemed to have larger soil aggregates than the control after 21 d although significant difference of MWD was just found after 63 d between the amended soils and the
Changes of soil aggregate appeared to be determined by microbial activity during the incubation period (Figs. 2g; 3). The largest MWD of aggregate for each treated soil occurred at 21 d, while maximum MBC contents were also found at that time. Consistently significantly higher MBC content for 5% biochar-amended soil throughout the incubation duration obviously facilitated the aggregation of soil particles at the end of the incubation.

Furthermore, the porosity seemed to present an opposite trend to soil aggregation during the incubation especially for the 5% biochar-amended soil. Obvious increase of MWD of aggregate led to decrease of porosity of the 5% biochar-amended soil from the beginning to the end of the incubation. This might indicate that a high application rate (5%) of the biochar might more facilitate to connect with microaggregates to form macroaggregates in the soils (Fig. 4; b) with time, followed by decreasing porosity.

With respect to the mechanism of macroaggregate formation in the amended soils in this study, we inferred that the mucilage produced by microbial activity (Fig. 3) and hyphae in the interface between soil particles and biochar (Fig. 4d) caused soil particles to bind and microaggregates to form macroaggregates. The increasing MWD of the soil aggregates of the biochar-amended soils after 105 d incubation can be attributed to an increase in the amount of oxidized functional groups after mineralization of the biochar (Cheng et al., 2006), which facilitated flocculation of both the soil particles and the biochar. Six et al. (2004) demonstrated that organic amendments can connect soil particles through electrostatic attraction, leading to the formation of microaggregates. Liu et al. (2012) provided that soil aggregate sizes and stability could be significantly increased through the addition of biochar to the soil, especially for the silt loam soil in the Loess Plateau in China.

Table 3
Pearson’s correlation coefficients among soil properties across the incubation period in the study (n = 9).

<table>
<thead>
<tr>
<th></th>
<th>pH</th>
<th>SOC</th>
<th>CEC</th>
<th>BS</th>
<th>MBC</th>
<th>Bd</th>
<th>Po</th>
<th>Ksat</th>
<th>MWD</th>
<th>SL</th>
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<tr>
<td>pH</td>
<td>1.00</td>
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<tr>
<td>SOC</td>
<td>0.56</td>
<td>1.00</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>CEC</td>
<td>0.93**</td>
<td>0.48</td>
<td>1.00</td>
<td></td>
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<td></td>
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<tr>
<td>BS</td>
<td>0.78**</td>
<td>0.65</td>
<td>0.73*</td>
<td>1.00</td>
<td></td>
<td></td>
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<tr>
<td>MBC</td>
<td>0.89**</td>
<td>0.43</td>
<td>0.95**</td>
<td>0.74*</td>
<td>1.00</td>
<td></td>
<td></td>
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<tr>
<td>Bd</td>
<td>−0.96**</td>
<td>−0.64</td>
<td>−0.93**</td>
<td>−0.72*</td>
<td>−0.87**</td>
<td>−0.81**</td>
<td>1.00</td>
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<tr>
<td>Po</td>
<td>0.92**</td>
<td>0.68*</td>
<td>0.91**</td>
<td>0.69*</td>
<td>0.81**</td>
<td>−0.99**</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Ksat</td>
<td>0.61*</td>
<td>0.68*</td>
<td>0.54</td>
<td>0.33</td>
<td>0.34</td>
<td>−0.74**</td>
<td>0.81**</td>
<td>1.00</td>
<td></td>
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<tr>
<td>MWD</td>
<td>0.96**</td>
<td>0.36</td>
<td>0.81**</td>
<td>0.71*</td>
<td>0.81**</td>
<td>−0.86**</td>
<td>0.80**</td>
<td>0.49</td>
<td>1.00</td>
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<tr>
<td>SL</td>
<td>−0.92**</td>
<td>−0.72*</td>
<td>−0.84**</td>
<td>−0.76**</td>
<td>−0.72*</td>
<td>0.95**</td>
<td>−0.96**</td>
<td>−0.84**</td>
<td>−0.82**</td>
<td>1.00</td>
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</tbody>
</table>

SOC: soil organic carbon; CEC: cation exchange capacity; BS: base saturation percentage; MBC: microbial biomass carbon; Bd: bulk density; Po: porosity; Ksat: saturated hydraulic conductivity; MWD: mean weight diameter of soil aggregates; SL: soil loss. *: \( p < 0.05 \); **: \( p < 0.01 \).

Fig. 4. Micrographs of thin sections of soils without and with amendment of biochar: (a) soil aggregates with 2.5% application rate of biochar with plain polarized light (PPL); (b) soil aggregates with 5% application rate of biochar with plain polarized light (PPL); (c) combination of clays and biochar in the 5% application rate of biochar with plain polarized light (PPL); and (d) hyphae between interface of the biochar and soil particle in 5% application rate of biochar-amended soil (PPL).
4.3. Improvement of soil erosion potential after the addition of biochar

In this study, the soil loss rate decreased significantly as more biochar was added, indicating that the biochar incorporation reduced the potential for soil erosion in the highly weathered soil. The results of the ANOVA and the correlation analysis (Tables 2 and 3, respectively) showed that the rate of soil loss was affected by several physical properties of the soil, including Bd, porosity, Ksat, and aggregate sizes. Several studies have demonstrated that the addition of organic matter to soil reduces soil erosion by increasing the sizes of the soil aggregates, as well as by stabilizing the aggregates (Moutier et al., 2000; Tejada and Gonzalez, 2007; Wuddivira et al., 2009). Based on our results, we deduced that the major reason for reduction of soil loss after the addition of biochar was the redistribution of the relative proportions of soil aggregate sizes. Cantón et al. (2009) indicated that aggregate stability and macroaggregate formation were important factors in maintaining soil porosity and decreasing soil erosion. As a result of the increase in microbial activity after the addition of the biochar to the soil, macroaggregates were therefore formed in the soils. The increased microbial activity in the soils after biochar incorporation was demonstrated by an increase in MBC content throughout incubation duration, except for the date of 21 d (Fig. 3). The presence of hyphae at the interface between the biochar and the soil particles (Fig. 4d) also further proved the facilitation of microbial activities by biochar incorporation into the soils. Barthès and Roose (2002) indicated that soil loss correlated negatively with stable macroaggregate (>0.2 mm) content (r = 0.99, p < 0.01) in topsoils under a given simulated rainfall intensity (60 mm h⁻¹). Moreno-de las Heras (2009) found that the addition of organic matter to form stabilized soil aggregates reduced the potential of soil erosion.

As a whole, this study showed that the incorporation of biochar into highly weathered soil clearly improved the physical properties of the soil, and reduced the potential for soil erosion. Annabi et al. (2011) further indicated that organic amendments that were more resistant to mineralization showed improved stabilization of macroaggregates than organic additives that decomposed easily.

5. Conclusions

Biochar prepared from the waste wood of white lead trees through slow pyrolysis is an acid-neutralizing material for highly weathered soils, and is a potential source of nutrients. The persistent characteristics of the biochar ensure long-term benefits for the soils. Our incubation experiments showed that wood biochar not only improved the chemical and biological properties of the soil, including increasing soil pH, CEC, BS, and microbial activity, but also improved the physical properties of the soil, such as Bd, Ksat, aggregate stability, and erosion resistance. These results suggest that the addition of wood biochar effectively improved poor soil characteristics in highly-weathered soil, and reduced soil losses. The results of this study could be used to avoid rapid soil degradation in subtropical and tropical regions.

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References


