

Physicochemical properties of biochar derived from wood of *Gliricidia sepium* based on the pyrolysis temperature and its applications

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Abstract: Biochar (BC) represents biomass such as wood, grass, and manure, decomposed by pyrolysis typically produced under conditions of limited oxygen (O_2) and low to moderate temperatures ($<600^\circ C$). The application of BC to improve physicochemical properties of soil and boost plant growth is increasingly gaining attention. Most studies reporting the underlying mechanisms of BC-based soil improvement describe changes in water holding capacity based on the difference in the type of soil and intrinsic properties of the BCs. The physical and chemical properties of BC itself depend considerably on the pyrolysis temperature and the feedstock used for its production. Previous studies that investigated changes in soil physical properties due to pyrolysis at temperatures ranging between $200^\circ C$ and $300^\circ C$ described changes in soil water retention. In this study, we used *Gliricidia sepium*, a fast growth legume tree, as the feedstock for producing BC. The objective of this study was to evaluate the effects of a wide range of pyrolysis temperatures ($300^\circ C$ to $800^\circ C$) on the physicochemical properties of BC derived from *G. sepium* wood, and thereafter evaluate the effect on soil physical properties in a pot incubation test with BC produced at $400^\circ C$ and $800^\circ C$ in sandy soil. The physicochemical properties of BCs generated from *G. sepium* wood changed considerably as the pyrolysis temperature increased. A significant increase in the carbon (C)/nitrogen (N) ratio and pH of the BC was observed at elevated pyrolysis temperatures, which may be attributed to the high total C content of the generated ash. Biochar produced at $400^\circ C$ showed the most promising results by enhancing the soil fertility based on its low bulk density and high cation exchange capacity. The water holding index is significantly negatively correlated to soil bulk density so the low bulk density of produced at $400^\circ C$ helps improve the water holding capacity of sandy soil in this study. Consequently, BC produced at $400^\circ C$ is the most promising soil conditioner for elevating soil fertility and the water holding index. Hence, it is suggested that BC produced at $400^\circ C$ can improve agricultural production and can contribute energy biomass production on oligotrophic lands consequently reducing the chances of land degradation.

Key words: biochar—*Gliricidia sepium*—physical and chemical properties—pyrolysis—temperature—water holding capacity

Biochar (BC) is a general term for biomass products of thermal decomposition, such as wood, grass, and manure under conditions of low oxygen (O_2) and temperature (Lehmann and Joseph 2009). The application of BC for improving soil fertility has

recently gained attention. First, the application of BC to soil increases carbon (C) sequestration and has the potential to mitigate the adverse effects of climate change. BC can remain in the soil for a long time without undergoing excessive degradation suggesting

its utility for C sequestration (Lehmann et al. 2006; Lehmann 2007). Fang et al. (2014) reported that BC synthesized from *Eucalyptus saligna* at $550^\circ C$ had an estimated residence time of 610 years in an entisol incubated at $20^\circ C$ for 12 months. BC application to soil allows C sequestration as soil organic C, and a sequestration based on an increase in the vegetation on highly weathered soil (Lorenz and Lal 2014). Lal (2016) stated that no-till farming and agroforestry combined with BC application can help mitigate climate change and improve soil conservation and food security. The formula for calculating the amount of greenhouse gases absorbed following the application of BC to soil is listed in the Intergovernmental Panel on Climate Change guidelines for national greenhouse gas inventories (Calvo Buendia et al. 2019).

Secondly, BC amendment can improve soil chemical and physical properties and enhance the plant growth (van Zwieten et al. 2010). The addition of BC to acidic soil increases the soil pH and decreases aluminum (Al) saturation, the two common major constraints influencing agricultural production in humid tropical regions (Glaser et al. 2002). Furthermore, BC application increases soil cation exchange capacity (CEC) (van Zwieten et al. 2010) and decreases nutrient leaching from agricultural soil (Lehmann et al. 2003). Moreover, application of BC has a positive influence on soil physical properties, such as bulk density (BD) and water holding capacity (WHC). Soil WHC follow-

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ing BC application is particularly improved both directly and indirectly. Ulyett et al. (2014) reported that the high surface area of BC produced from deciduous mixed wood chips contributed directly to improving WHC of sandy loam soils. Furthermore, soil pore distribution was altered by switchgrass (*Panicum virgatum* L.) BC application, and indirectly improved the soil WHC of loamy sand and silt loam soils (Novak et al. 2012). Obia et al. (2016) reported that maize (*Zea mays* L.) cob-based BC applications induced soil aggregation and improved WHC of sand, sandy loam, and loamy sand soil types. Most studies attempting to discern the specific mechanism by which BC improves soil WHC have based their observations on the difference in soil types and intrinsic characteristics such as porosity and hydrophobicity of the BCs used in the study (Li et al. 2021).

The physical and chemical properties of BC itself depend considerably on the feedstock and pyrolysis temperature, respectively (Kloss et al. 2012; Kim et al. 2012). Kloss et al. (2012) reported high salt and ash content in wheat (*Triticum aestivum* L.) straw-derived BC compared to *Populus* sp. and spruce (*Picea*) woodchip-derived BC. Gaskin et al. (2008) reported that the C content in poultry litter-based BC was a meager 40% when compared to that of pine (*Pinus*) chip-derived BC with 78% C content. Previous studies included limited pyrolysis temperature-based experimental conditions, mainly within the range of 100°C to 300°C, with a few studies including temperatures of 600°C to 700°C and 900°C (Wang et al. 2019), 400°C to 500°C (Gaskin et al. 2008), and 300°C to 500°C (Kim et al. 2012). Previous studies have not taken into account the physical properties of the soil supplemented with BCs, and this aspect requires more in-depth investigations (Haidi et al. 2016).

In this study, we used the fast-growing legume tree *Gliricidia sepium* as the starting material for synthesizing BC. *G. sepium* is commonly used as a hedge around houses and farms, while its leaves are used as animal feed (Stewart et al. 1996). Its fast growth makes it a promising starting material for biomass power generation commonly used in the South and Southeast Asia (Ratnasiri 2008). Furthermore, it is anticipated that *G. sepium* can be planted for biomass power generation on land that is less productive thus avoiding competition with other food chain systems. In Indonesia, the oligotrophic

lands currently cultivating biomass, such as *G. sepium*, are estimated to be around 3.5 million ha (Jaung et al. 2018).

A total of 11.98 million Mg of fresh poultry manure was estimated to be produced in 2017 in United States of America (Hoover et al. 2019). The manure has traditionally been applied to surrounding crop and pasturelands to recycle nutrients. Poultry litter's effectiveness on crop yield is influenced by soil properties, tillage, application practice, and crop species (Lin et al. 2018). According to Bohara et al. (2019), the application of poultry litter along with pinewood BC could benefit crop production by improving soil WHC.

The objective of this study was to evaluate the effect of a wide range of pyrolysis temperatures (300°C to 800°C) on the physicochemical properties of BC derived from *G. sepium* wood and to also evaluate the effects of its application on the physical properties (such as WHC) of sandy soil along with poultry manure. To the best of our knowledge, this is the first study evaluating BC from *G. sepium* produced at different pyrolysis temperatures.

Material and Methods

Biochar Production. A biomass plantation of *G. sepium* in Sri Lanka was thinned in March of 2017 to provide the feedstock for the BC used in this study. Approximately 50 mm diameter stems were cut into 50 to 100 mm long chips, dried at 80°C for 1 week, and then pyrolyzed in a custom-made electronic furnace under O₂ limited conditions. The maximum temperature points used in this study were 300°C, 400°C, 600°C, and 800°C, for samples BC300, BC400, BC600, and BC800, respectively.

The heating rate was 1°C min⁻¹, and the maximum temperature was maintained for 3 hours. After cooling to room temperature (20°C), the BC samples were crushed and sieved to produce a homogenous sample composed of 2 mm fragments for the incubation tests and the remaining tests. Nonpyrolyzed chips (feedstock) for comparison with the BC samples were used as controls.

Molecular and Physical Characteristics of Biochar. The BC yields were calculated based on the mass change before and after charring. The BC samples and feedstock were finely crushed, and the BC300, BC400, BC600, and feedstock powders were analyzed using Fourier-transform infrared spectroscopy (FT-IR) and solid-state ¹³C nuclear magnetic

resonance (NMR). The surface area (SA) of all the powdered samples was determined using a method by the Brunauer–Emmett–Teller–N₂ SA analysis. The FT-IR absorbance was measured from 4,000 to 400 cm⁻¹ with 32 scans per sample and 4 cm⁻¹ resolution (Nicolet6700, ThermoFisher Scientific, USA). The ¹³CNMR (JNM-ECA500, JEOL, Japan) was performed using the MAS/DD method at 10 kHz with 320 cumulative scans. SA was measured using a surface area analyzer (Autosorb iQ, Quantachrome, USA). Feedstock and BC were dried in a 105°C oven to determine the BD, and then packed into a 100 cm⁻³ core, followed by BD calculations of each sample. All analyses were conducted at Akita Prefectural University laboratories with the exception of NMR analyses which were conducted at Akita University.

Chemical Characteristics of Biochar. The pH was measured by boiling the BC with ion exchange water (3g:100 mL) in a glass beaker for 5 min and measuring the pH of the solution using a pH meter (LAQUA-74BW, Horiba, Japan). Ash content was measured by weighing 5 g of BC into a porcelain crucible, heating to 300°C for one hour, 400°C for one hour, or 500°C for four hours in a muffle furnace, followed by sample ignition at 800°C for one hour in the same furnace. Total C and nitrogen (N) content of the feedstock and BC samples were measured using an elemental analyzer (Sumigraph NC-22, SCAS, Japan). Water extractable cations were removed by suspending 5 g of BC first in 200 mL of ion exchange water and then in 80% methanol with continuous shaking for one hour. After percolation, feedstock and BC samples were dried at 105°C for 24 hours, followed by assessment of exchangeable cations (potassium [K], sodium [Na], calcium [Ca], and magnesium [Mg]) and CEC using the semi-micro Schollenberger method (Sparks et al. 1996). Available phosphorus (AP) in the feedstock, as well as the BC samples were measured using the Truog method (Sparks et al. 1996). All analyses were conducted in laboratories at Akita Prefectural University.

Water Holding Capacity in Sandy Soil after Incubation with Biochar. Table 1 outlines the data from the WHC experiments. Samples BC400 and BC800 were used since they had minimum BD and maximum SA, respectively, as shown in table 2. Sandy soil was collected in March of 2018 from a pine forest floor on the coastal sand dunes located in Akita, Japan, which consisted of 93.9%

Table 1

Summary of treatment conditions.

Treatment	BC	Application rate of BCs (%w w ⁻¹)	Application rate of manure (%w w ⁻¹)
NN0	—	—	—
NN2	—	—	0.25
NN5	—	—	0.50
L10	BC400	1.5	—
L30	BC400	3.0	—
L32	BC400	3.0	0.25
L35	BC400	3.0	0.50
H10	BC800	1.5	—
H30	BC800	3.0	—

Notes: BC = biochar. BC400 = BC produced at 400°C. BC800 = BC produced at 800°C. NN0 = no BC, 0% manure. NN2 = no BC, 0.25% manure. NN5 = no BC, 0.5 % manure. L = low pyrolysis BC (BC400). H = high pyrolysis (BC800). 10 = 1.5% BC, 0% manure. 30 = 3.0% BC, 0% manure. 32 = 3.0% BC, 0.25% manure. 35 = 3.0% BC, 0.50% manure.

Table 2

Yield and physical properties of feedstock and biochar.

Feedstock/biochar	Yield (%)	Surface area (m ² g ⁻¹)	Bulk density (g cm ⁻³)
Feedstock	100	ND	0.162b
BC300	49.9	0.860	0.155bc
BC400	39.7	0.840	0.153c
BC600	33.1	19.3	0.175a
BC800	29.1	136	0.180a

Notes: BC# = biochars produced at 300°C, 400°C, 600°C, or 800°C. ND = not detected. Different alphabetical letters in bulk density indicate significant differences among biochars by one-way ANOVA (Tukey-HSD test, $p < 0.05$).

sand, 1.3% silt, and 6.1% clay: the soil was classified as an entisol. The soil pH (H₂O) was 6.35, the total C content was 0.161%, the total N content was 0.00962%, and the CEC was 4.13 cmolc kg⁻¹. Sandy soil (400 g) and 6.0 g (1.5% w w⁻¹) or 12 g (3.0% w w⁻¹) of BC400 or BC800 were mixed thoroughly. In addition, we also evaluated the effect of organic matter by mixing 400 g of sandy soil and 12 g (3.0% w w⁻¹) of BC400 and 1.0 g (0.25% w w⁻¹) or 2.0 g (0.50% w w⁻¹) of poultry manure. The poultry manure was purchased as a commercial product from a local agricultural supplier. Properties of the poultry manure were as follows: the pH (H₂O) was 8.35, the total C content was 14.2%, the total N content was 4.67%, and the CEC was 19.2 cmolc kg⁻¹. A control plot for analysis of samples without BCs was established (NN0: no BC, 0 % manure; NN2: no BC; and NN5: no BC, 0.5 % manure in table 1). The mixtures were poured into pots with an outer diameter, height, and volume of 114 mm, 92 mm, and 400 mL, respec-

tively (AP pot No. 4, Apple Wear, Inc., Osaka, Japan). The pots were incubated outdoors in a field at Akita Prefectural University for 96 days (from September 15 to December 20, 2019). The total amount of rainfall and the mean temperature during the incubation were 721 mm and 12.4°C, respectively.

Soil sample cores (100 mL) were collected after an incubation period of 96 days. Volumetric water content was determined using the sand column method while the moisture tension was calculated as $\log_{10}(h \times 102) = 0$ to 1.5, and 1.8 to 3.0, respectively, as detected by the pressure plate method where h is a column of water (m). After the $\log_{10}(h \times 102)$ 3.0 measurement, the cores were heated to 105°C for 24 hours in a drying oven followed by soil BD estimations of each sample. To obtain a synthetic description of water retention, the WHC was estimated using equation 1, which calculates the water holding index (WHI) as the average volumetric water content at an interval of $\log_{10}(h$

$\times 102)$ 0.6 to 3.0 after the integral retention index (Terribile et al. 2018):

$$WHI(\%) = \frac{1}{\log(h_{10} \times 102) - \log(h_1 \times 102)}$$

$$\sum_{i=1}^9 \frac{1}{2} \{ \log(h_{i+1} \times 102) - \log(h_i \times 102) \} (\theta_i + \theta_{i+1}), \quad (1)$$

where, h_i and θ_i mean column of water (m) and water content (%) at measure procedure of i ($i = 1$ to 9) as presented in table S1. Higher values of WHI are representative of better soil WHCs. All analyses were conducted in laboratories at Akita Prefectural University.

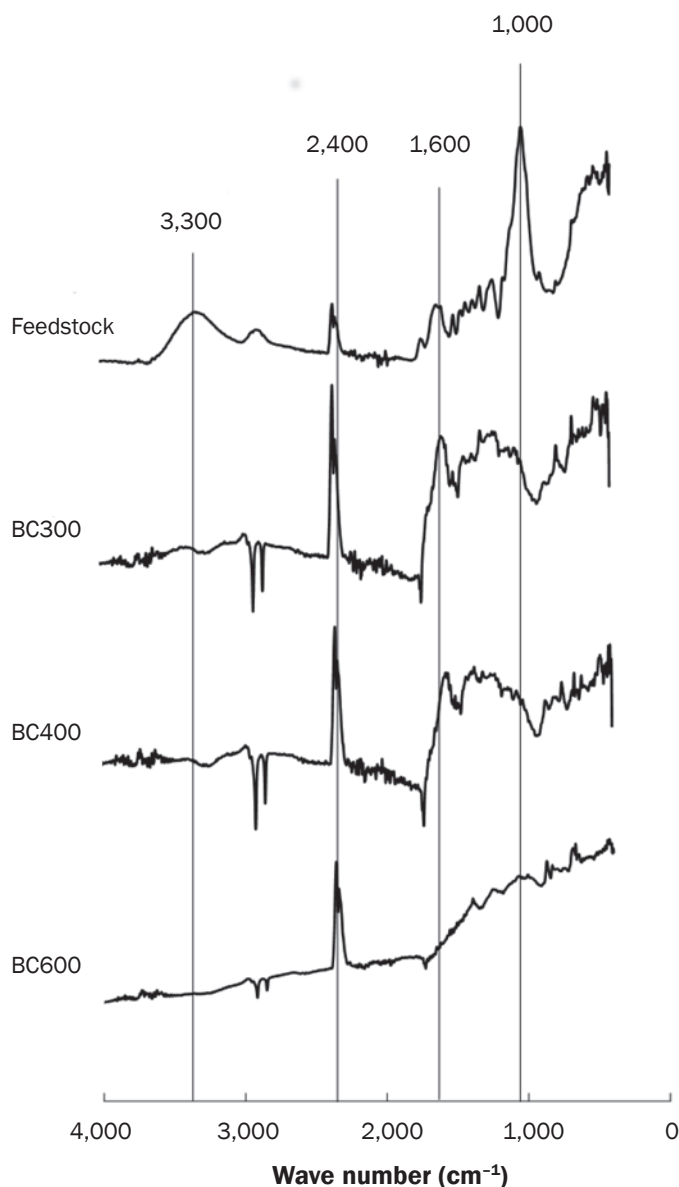
Statistical Analysis. All statistical analyses were performed using EZR (Version 1.00, Saitama Medical Center, Jichi Medical University, Saitama, Japan) (Kanda 2013), a graphical user interface for R (The R Foundation for Statistical Computing, Vienna, Austria). More precisely, it is a modified version of R Commander designed to add statistical functions frequently used in biostatistics (Kanda 2013). One-way analysis of variance was performed to evaluate the physical and chemical properties of the BC samples. A multiple linear regression was performed to predict WHI and soil BD based changes exerted by BC, pyrolysis temperature, and application of poultry manure.

Results and Discussion

Molecular Characteristics of Feedstock and Biochars. FT-IR spectra of BC300, BC400, BC600, and feedstock powders are shown in figure 1. A pyrolysis temperature of 300°C results in a considerable disappearance in the peak around 1,000 cm⁻¹, indicating losses of cellulose, lignin, and hemicellulose (Cheng et al. 2006; Kloss et al. 2012), which are the main components of *G. sepium*. The O-H stretch peak also disappeared around 3,300 cm⁻¹ (Kloss et al. 2012). The carboxylic-C stretch peak at 1,600 cm⁻¹ is visible in the BC400 sample (Belimov et al. 2015), but is absent in the BC600 sample. The clear peak around 2,400 cm⁻¹ is representative of atmospheric carbon dioxide (CO₂). The ¹³C NMR spectra of BC300, BC400, BC600, and feedstock powders are shown in figure 2. A pyrolysis temperature of 300°C resulted in the disappearance of the O-alkyl (75 ppm) and di-O-alkyl (105 ppm) from cellulose (Baldock and Smernik 2002; Novak et al. 2009; Kim et al. 2012). In the BC300 and BC400 samples, a broad peak was observed

Figure 1

Fourier-transform infrared spectroscopy (FT-IR) spectra of feedstock and biochar produced at 300°C (BC300), 400°C (BC400), and 600°C (BC600).



around 129 ppm, which may be attributed to the presence of the aromatic C (Chun et al. 2004; Novak et al. 2009; Kim et al. 2012; Wu et al. 2012). The decrease of the peak around 129 ppm in the BC600 sample suggests that the structure of the aromatic group was disrupted.

Physical Properties of Feedstock and Biochars. Table 2 shows the physical properties of the feedstock and BC samples. Increasing pyrolysis temperatures decreased the yield of BC, while the SA considerably increased as the pyrolysis temperature

increased from 400°C to 600°C, and 600°C to 800°C. The change in BD was negligible with BC400 (0.153 g cm⁻³) having the lowest BD.

Chemical Properties of Feedstock and Biochars. Chemical properties of the feedstock and BC samples are presented in table 3. Total C, ash, and the C/N ratio significantly increased with an increase in the pyrolysis temperature ($p < 0.0001$, $p < 0.0001$, and $p < 0.0001$, respectively). The total N concentration of BC400 was the highest, and the total N concentration significantly decreased

with an increase in the pyrolysis temperature above BC400 ($p < 0.0001$). The pH value significantly increased with the increase in the pyrolysis temperature ($p < 0.0001$) and was alkaline. The pH of BC800 was measured to be 10.5. Similarly, AP significantly increased with an increase in the pyrolysis temperature ($p < 0.0001$) although the increase was statistically significant only at the highest temperature. The CEC value significantly increased up to 400°C (44.5 cmolc kg⁻¹) and decreased thereafter ($p = 0.0437$). The exchangeable K, Na, and Mg values at BC800 were maximum. The concentration of Ca increased up to pyrolysis temperatures of 600°C, decreasing thereafter.

Water Holding Capacity in Sandy Soil after Incubation with Biochar. Table 4 shows the results of the WHI and soil BD analyses, and table 5 shows the results of multiple linear regressions. Increasing the application of BC ($p < 0.001$) and manure ($p < 0.01$) significantly increased WHI. Compared to the NN0 treatment (no addition of BC or manure shown in table 1), the value of WHI of L35 (added 3.0% w w⁻¹ of BC400 with 0.50% w w⁻¹ of manure) increased by 6.1% (table 5). There were no significant differences in WHI among treatments using different pyrolysis temperatures. Soil BD was significantly decreased by BC applications ($p < 0.01$) and significantly increased after manure applications ($p < 0.001$) (table 5). The application of BC400 resulted in significantly lower soil BD when compared to BC800 ($p < 0.05$) (table 5). Our results showed that WHI was strongly negatively correlated to soil BD ($r = -0.625$, $p < 0.05$) (figure 3).

Discussion. Soil degradation is caused by mining, over-grazing, and over-cultivation, which leads to a decrease in agricultural productivity (United Nations Convention to Combat Desertification 2017); therefore, sustainable agriculture is pertinent. The use of BC in agriculture is important for improving soil health, which enhances the agricultural productivity (Spokas et al. 2012), but also since it contributes to soil C sequestration which ameliorates global warming (Azzi et al. 2021). Our study revealed that BC contributed to the improvement of soil physical properties, especially to soil WHC.

The use of local feedstocks for BC materials for integrated BC research is essential (Amonette et al. 2021). Although, *G. sepium* is an exotic species, it is widely used as

fuelwood, construction poles, crop supports, green manure, fodder, and bee forages (Simons and Stewart 1994). Previous studies on *G. sepium* mainly focused on biofuel production (Fakinle et al. 2017; Jaung et al. 2018) and its utilization as a suitable candidate of agroforestry systems (Szott et al. 1991; Rao and Mathuva 2000). This study reports on the physicochemical properties in BC derived from *G. sepium*.

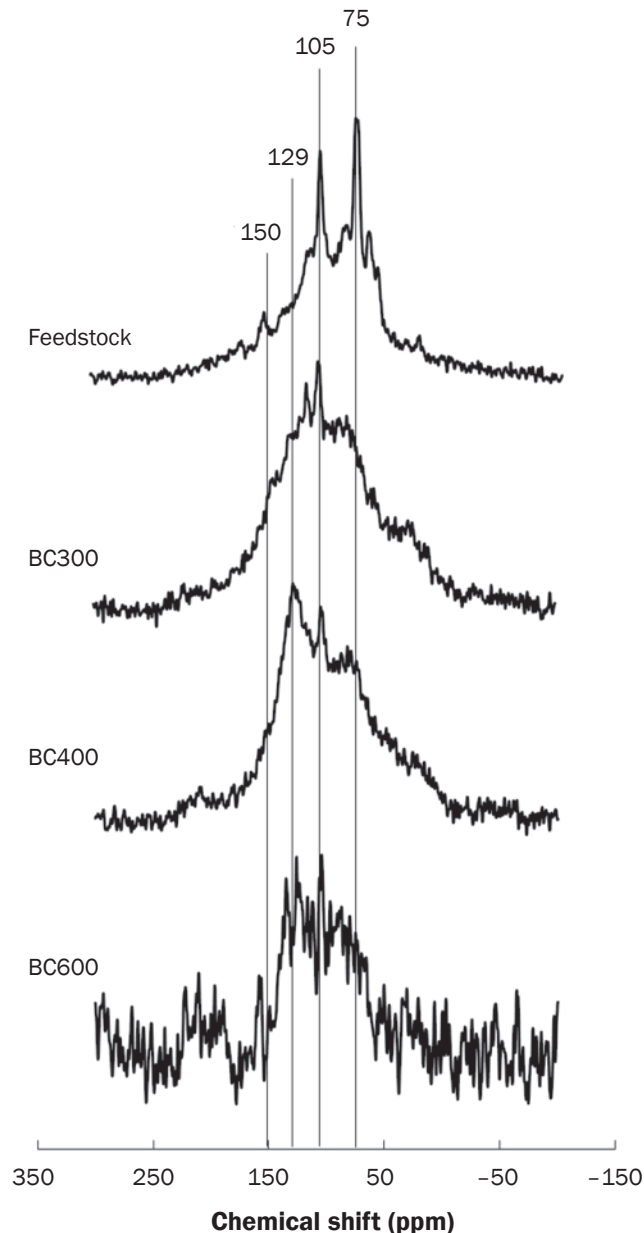
The physical and chemical properties of BC change considerably with increases in the pyrolysis temperature. The FT-IR and NMR spectra indicate the degradation of the main components of *G. sepium*, which consists of cellulose, lignin, and hemicellulose at temperatures of 250°C to 300°C (figures 1 and 2).

Biochar yields decreased by pyrolysis due to the decomposition and volatilization of aliphatic and aromatic compounds (table 2). High yields of BC can be economical, but there are trade-offs between BC yield and BC C sequestration in soil. Brunn et al. (2011) reported the highest C sequestration occurred in BC samples pyrolyzed at 500°C. The increase in SA is most likely due to the volatilization of aliphatic and aromatic compounds at temperatures up to 600°C. Beyond that point, O₂ activation may contribute to an increase in SA at 800°C (table 2). The decrease in BC mass represented by yield is more pronounced than the shrinkage of BC as represented by the SA data up to 400°C. This relationship is probably reversed above 400°C, contributing to changes in BD (table 2). Total C and ash increased with increases in the pyrolysis temperatures (table 3), and N significantly volatilized at high temperatures (>600°C) (table 3). The carbonates in ash were mainly alkaline in nature, which resulted in an alkaline BC (Yuan et al. 2011).

Acid carboxyl groups probably increased in BC300 compared to the feedstock, which subsequently decreased (Cheng et al. 2006; Kloss et al. 2012) and directly affected the CEC (Wu et al. 2012). Our results, that the CEC value significantly increased up to 400°C and decreased thereafter, are in agreement with those of Yuan et al. (2011), which showed a decrease in CEC and carboxyl groups in BCs derived from maize and soybean (*Glycine max* [L.] Merr.) straw and pyrolyzed at 700°C. The CEC values of *Gliricidia*-derived BC are higher than those of other woody-derived BCs pyrolyzed at 400°C. Kloss et al. (2012) reported CEC

Figure 2

The carbon-13 (¹³C) nuclear magnetic resonance (NMR) spectra of feedstock and biochar produced at pyrolysis temperatures of 300°C (BC300), 400°C (BC400), and 600°C (BC600).



values of BC made from spruce and poplar (*Populus*) of 7.35 cmolc kg⁻¹ and 14.4 cmolc kg⁻¹, respectively. Mukherjee et al. (2011) reported averaged CEC values of 16.2 and 21.0 cmolc kg⁻¹ for BC made from oak (*Quercus*), pine, and grass pyrolyzed at 400°C and 650°C, respectively. Singh et al. (2010) showed the CEC of *Eucalyptus*-derived BC to be 7.3 cmolc kg⁻¹. Biochar made from *Gliricidia* had higher pH values than other woody-derived BCs due to its high ash

content (Singh et al. 2010; Mukherjee et al. 2011; Kloss et al. 2012). Our results indicate that *Gliricidia* is a promising feedstock for BC generation at lower temperatures since it improves the chemical properties of soil by increasing the alkalinity and the CEC. Matovic (2011) reported the need for a low BC application rate (less than 5% w w⁻¹); however, the strategy is inadequate for improving the overall fertility of the soil. Nevertheless, BC addition aids in enhancing

Table 3
Chemical properties of biochars ($n = 3$).

Property	Feedstock	BC300	BC400	BC600	BC800
pH	7.63 (0.01)e	8.51 (0.01)d	9.88 (0.02)b	9.67 (0.09)c	10.3 (0.01)a
Ash (%)	3.29 (0.08)e	6.98 (0.17)d	8.41 (0.10)c	10.33 (0.11)b	12.10 (0.02)a
Carbon (%)	25.3 (6.57)c	57.7 (3.02)b	74.3 (1.97)a	83.6 (3.99)a	81.8 (4.12)a
Nitrogen (%)	0.347 (0.073)c	0.853 (0.066)a	0.866 (0.013)a	0.601 (0.022)b	0.599 (0.013)b
Carbon/nitrogen	72.1 (4.91)a	67.7 (1.70)a	85.8 (1.61)b	139 (4.98)c	137 (7.97)c
PA (mg P 100 g ⁻¹)	1.13 (0.10)b	1.45 (0.19)b	2.09 (0.07)b	2.61 (0.33)b	11.6 (1.67)a
CEC (cmolc kg ⁻¹)	10.6 (1.50)b	35.8 (6.76)ab	44.5 (5.80)a	28.1 (22.79)ab	29.1 (6.23)ab
Exchangeable cation (cmolc kg ⁻¹)					
Potassium	5.12 (0.54)c	14.8 (6.30)bc	26.0 (6.19)ab	19.6 (6.23)ab	38.2 (4.56)a
Sodium	1.31 (0.25)b	2.17 (1.25)ab	3.34 (0.90)ab	1.60 (0.66)ab	13.1 (9.64)a
Calcium	4.93 (1.44)b	1.60 (0.76)c	2.60 (0.57)bc	8.07 (0.28)a	3.31 (1.51)bc
Magnesium	4.64 (10.42)ns	4.01 (0.95)	2.36 (0.82)	1.81 (0.00)	0.714 (3.12)

Notes: BC# = biochars produced at 300°C, 400°C, 600°C, or 800°C. PA = plant available phosphorus. CEC = cation exchange capacity. Means are followed by standard deviation in parentheses. Means with different alphabetical letters indicate significant differences among biochars within each item using one-way analysis of variance (Tukey-HSD test, $p < 0.05$). ns = no significant difference among biochars.

Table 4
Soil water holding index (WHI) and soil bulk density (BD) ($n = 3$).

Treatment	WHI (%)	Soil BD (g cm ⁻³)
NN0	29.3 (0.6)e	1.41 (0.00)a
NN2	30.3 (0.2)de	1.41 (0.02)a
NN5	31.6 (0.6)cde	1.42 (0.02)a
L10	32.2 (0.4)bcd	1.32 (0.06)ab
L30	34.5 (1.5)ab	1.24 (0.05)b
L32	34.6 (0.2)ab	1.25 (0.10)b
L35	35.4 (0.8)a	1.29 (0.04)ab
H10	32.0 (1.0)bcde	1.33 (0.03)ab
H30	34.0 (0.6)abc	1.31 (0.01)ab

Notes: NN0 = no biochar, 0% manure. NN2 = no biochar, 0.25% manure. NN5 = no biochar, 0.5% manure. L10 = low pyrolysis biochar produced 400°C, 1.5 % biochar, 0% manure. L30 = low pyrolysis biochar produced 400°C, 3.0% biochar, 0% manure. L32 = low pyrolysis biochar produced 400°C, 3.0% biochar, 0.25% manure. L35 = low pyrolysis biochar produced 400°C, 3.0% biochar, 0.50% manure. H10 = high pyrolysis biochar produced 800°C, 1.5% biochar, 0% manure. H30 = high pyrolysis biochar produced 800°C, 3.0% biochar, 0% manure. Means are followed by standard deviation in parentheses. Different alphabetical letters indicate statistically significant differences between treatment within each item using multiple comparisons (Tukey test, $p < 0.05$).

the rhizosphere soil fertility and contributes to enhancing plant growth (Elad et al. 2011).

The BD of BCs was significantly changed by pyrolysis temperatures (table 2), but no significant correlation between WHI and pyrolysis temperature was observed (table 5). Our results showed that WHI was strongly related to soil BD ($r = -0.625$, $p < 0.05$) (figure 3), whereas soil BD was significantly influenced by a change in pyrolysis temperature. The use of BC decreased soil BD and likely altered soil pore distribution as BC underwent decomposition and redistribution allowing the water to be phys-

ically held in the new soil pores occurring between decomposed BC and soil particles. Furthermore, the SA of BCs increased with an increase in pyrolysis temperatures (table 2). The SA of BC800 was 161 times that of BC400 (table 2), but the WHI of soil treated with BC400 tended to be greater than that of soil treated with BC800 (table 4). In contrast, the BD of soil treated with BC400 was significantly lower than that of the soil treated with BC800 (table 4, figure 3). Consequently, the low BD of BC contributed to improving the WHC of sandy soil.

The decrease in soil BD following BC application induced an increase in soil WHC and is consistent with the results reported in previous studies. Novak et al. (2012) measured the WHC of ultisol replenished with BC derived from switchgrass, peanut (*Arachis hypogaea*) hulls, or pecan (*Carya illinoensis*) shells. The surface areas of the three BCs varied by up to a factor of 555 resulting in a decrease in soil BD and a significant increase in soil WHC. Basso et al. (2013) incubated sandy soil with BC derived from the pyrolysis of red oak (*Quercus rubra*) wood at 500°C and measured the soil BD and WHC for 91 days. The soil BD of untreated soil increased, whereas the soil BD of BC-treated soil remained unchanged with an increase in the WHC.

Ulyett et al. (2014) argued that the large SA of BC helped improve soil WHC; however, the present study and that of Novak et al. (2012) indicated that the SA of BC does not affect soil WHC. The application of BC with a high SA helps in improving soil WHC based on the size of the BC pores (Novak et al. 2012). Future studies aimed at measuring pore size distribution will help understand the relationships between the physical properties of BC and soil WHC. Obia et al. (2016) attributed improved soil WHC following BC application to accelerated soil aggregation. The incorporation of organic matter induces soil aggregation (Wortmann and Shapiro 2008). However, soil aggregation was not observed in the present study (data unreported) due to the low content of total C of the sandy soil (0.161%), which suggested the number of microorganisms present in the

Table 5

Summary of multiple linear regressions of water holding indices (WHI) and soil bulk densities (BD) by some biochar and poultry manure properties.

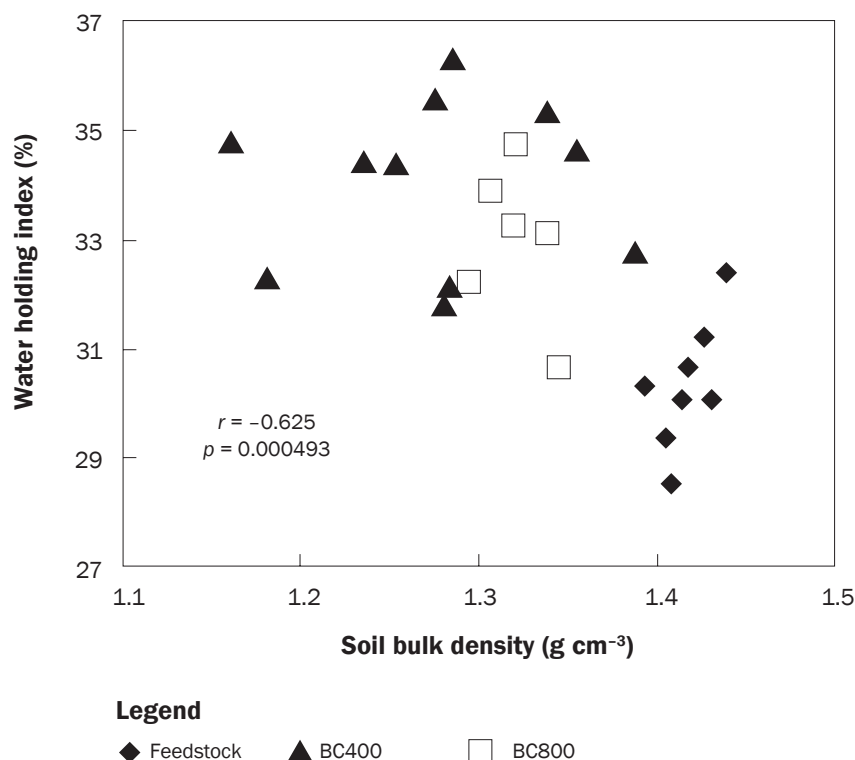
Variables	WHI	Soil BD
Application rate of biochar	1.46***	-0.032**
Pyrolysis temperature	ns	0.000137*
Application rate of manure	0.723**	0.0789***

Note: ns = not significant.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Figure 3

Correlation between soil bulk density and water holding index of feedstock and biochar (BC) produced at 400°C (BC400) and 800°C (BC800).



soil was very low; this may play an important role in soil aggregation. The reason that soil BD increased even when adding poultry manure in the present study could be due to low content of total C. Composted manure application decreases soil BD as well as increases SOC (Adekiya 2019; Khaliq and Abbasi 2015), although the present study shows the opposite effect of poultry manure concerning soil BD. Sufficient SOC accumulation by future continuous application of poultry manure can change the tendency of soil BD changes.

Poultry manure application significantly increased the WHI (table 5). Contrary to our results, addition of both poultry litter and pine wood BC significantly increased the soil WHC while the water available to plants was increased by pine tree-derived BC and decreased by poultry litter, which may be attributed to the strong bonds formed between poultry litter and water (Bohara et al. 2019). The difference of poultry manure on WHI between our result and Bohara et al. (2019) may be attributed to the degree of weathering while poultry litter is stocked.

In this study, BC400 generated high CEC and the highest WHI, making it a promising soil conditioner for plant production. For integrated BC research, mechanistic research using local feedstock BC is important across various climates, soil types, and vegetative conditions (Amonette et al. 2021). Biochar made from *G. sepium* may be an important candidate in South and Southeast Asian countries where the species abundance is widespread.

This study describes the change in the physicochemical properties of BC and soil physical properties after the introduction of BC for short incubation periods focusing on the pyrolysis temperature used for the synthesis of the BC. Assessing long-term monitoring of the effect of BC application was requested for one of future research directions (Zhang et al. 2021). For our research, long-term monitoring will be also needed to clarify the long-term effect of this type of BC.

Summary and Conclusions

The physical and chemical properties of BCs generated from *G. sepium* wood changed considerably as the pyrolysis temperatures were increased resulting in an increase in the C/N ratio and pH of the BC, which may be attributed to an increase in total C and ash. The effect of BC on the fertility of the soil moisture condition may not be attributed to the high SA, but rather on its low BD, which may help in improving the WHC of the sandy soil. The improved soil water content is a result of interactions between BC and sandy soil rather than the porosity of the BC itself; therefore, it is necessary to consider the physical characteristics of the soil in addition to that of the BC itself for field applications. In this study, BC400 had the highest WHI, which may be attributed to low BD, and high CEC, while its high yield makes it a promising soil conditioner. Since the effect of BCs on soils are long-lasting, future studies monitoring the long-term effects of BC are important. Our group intends to conduct long-term studies monitoring the effects of *G. sepium*-derived BC.

Supplemental Material

The supplementary material for this article is available in the online journal at <https://doi.org/10.2489/jswc.2022.00083>.

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