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Influence of soil properties and feedstocks on biochar potential for carbon mineralization and improvement of infertile soils

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ABSTRACT

The impact of biochar (BC) application on soil varies with BC feedstock and soil type. The objective of this study was to investigate the linkage between the properties and surface functionality of various BCs and their role in the rehabilitation of two infertile soils. Sandy loam (SL) and sandy (S) soils were collected from agricultural areas in Korea and Vietnam, respectively. The BCs of amur silvergrass residue (AB), paddy straw (PB), and umbrella tree (UB) were applied to the soils at a rate of 30 t ha^{-1} and incubated at 25 °C for 90 d. Soil carbon (C) mineralization was investigated by a periodic measurement of CO_2 efflux. Soil texture strongly influenced the CO_2 efflux more than the BC type as indicated by 2–4 folds increase in cumulative CO_2-C efflux from the SL soil compared to that from the S soil. For the PB-, AB-, and UB-treated S soils, the values of cation exchange capacity (CEC) were increased by 906%, 180%, and 130%, respectively, compared to that of the control; however, for the PB-treated SL soil, only a 13% increase in CEC was found. The pH in the PB-treated S soil sharply increased by 4.5 units compared to that in the control, due to a high concentration of readily soluble compounds in the PB and the low buffering capacity of the S soil. The S soil was more sensitive to the addition of BCs than the SL soil. A more prominent improvement in soil fertility can be achieved by BC application to the sandy soil having low clay, nutrient, and organic matter contents.

1. Introduction

Soil fertility is defined as the ability of soil to supply proportionate and sufficient nutrients and water to plants in the absence of toxic elements (Havlin et al., 2014). Soil is an essential resource for sustainable agriculture and food production; however, the risk of rapid soil degradation is rising globally (Symeonakis et al., 2016). Infertile soils are not only formed by anthropogenic factors (e.g., human activities) but also by pedogenic/natural factors (e.g., parent materials) (Lal, 2015). The restoration of infertile soils has increasingly been recognized as a vital option for promising the food security (Mekuria et al., 2016). Furthermore, the sequestration of carbon in soil is essential for the enhancement of soil quality (Körschens et al., 2014; Zhang and Ok, 2014; Bruun et al., 2015). Thus, the development of innovative amendments that enrich carbon content and ameliorate the infertile soils is necessary.

Biochar (BC) is a carbon-rich material produced from biomass pyrolysis or gasification processes in an oxygen-limited environment (Lehmann and Joseph, 2009). Biochar is a cost-effective amendment for the management and rehabilitation of infertile soils; it has received

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intensive interest in the last decade (Park et al., 2015; Rizwan et al., 2016). Biochar enhances soil fertility directly by providing essential soil nutrients and soil organic/inorganic carbon (Coomes and Miltner, 2016; El-Naggar et al., 2018a) or indirectly by neutralizing soil acidity (Zhang et al., 2017). The addition of BC can stimulate microbial activity, retain soil nutrients, immobilize toxic contaminants, and improve soil physicochemical properties such as cation exchange capacity (CEC), water holding capacity (WHC), and soil aeration (Igalavithana et al., 2015; Igalavithana et al., 2017; El-Naggar et al., 2018b) Contrary to other organic amendments such as compost and biosolids, BC can remain in the soil for thousands of years due to its strong recalcitrant nature (Kuzyakov et al., 2014). Based on these properties, the potential use of BC has been widely recognized as a means of carbon sequestration in a soil (Awad et al., 2013; Mandal et al., 2016; El-Naggar et al., 2018a).

However, the influence of BCs on soil fertility and soil carbon sequestration varies with the feedstocks and pyrolysis conditions of BCs (Jeffery et al., 2011). The influence of BCs on soil fertility also depends upon the characteristics of the soil mineralogy and texture (Butnan et al., 2015). Kloss et al. (2014) found that the application of woodchip BC increased the yield of mustard by two-fold in a silty loam soil compared to that in a sandy loam soil. Similarly, Kolb et al. (2009) reported that the addition of BC derived from mixed feedstocks to soils increased the total nitrogen (TN) in a sandy loam soil, but had no influence on a clay loam soil. However, there is a lack of knowledge about how biochars derived from different feedstocks, and with different surface functionality and structural features, may influence the quality of various infertile and different textured soils. Selecting suitable BCs in consideration of site-specific conditions is highly recommended for field applications (Abiven et al., 2014). Therefore, further research on evaluating the influence of BCs applied to infertile soils of different textures and mineralogies is needed.

This study hypothesized that the addition of different BCs has contrasting priming effects depending on the soil properties and the raw materials of the BCs. In addition, the potential of BCs for driving significant and positive changes in soil properties is assumed to be higher in the low-buffered-coarse-textured soil. Therefore, the objective of this study was to assess the effects of three BCs with various properties on the carbon mineralization and quality improvement in two soils with different textures.

2. Materials and methods

2.1. Soil characterization

Sandy loam soil (SL) with high concentrations of metals/metalloids and low nutrient availability was collected from two sites adjacent to the Seosung mine in Seosan-si and the Tancheon mine in Gongju-si, Chungcheongnam-do, Korea, and blended into a composite sample (Figure A.1). Sandy soil (S) with very low concentrations of nutrients and low WHC was collected from different farms that grew cassava, sugar cane, watermelon, sweet potato, and peanut from Thua Thien Hue province, Vietnam, and blended into a composite sample. Soil samples were air-dried and passed through a 2-mm stainless steel sieve. Soils were characterized for selected physicochemical properties (Table 1). Soil textures were validated using the pipette method (Gee et al., 1986). The WHC was estimated on a gravimetric basis using the core method (Veihmeyer and Hendrickson, 1931). The total metal contents (As, Cd, Cr, Cu, Ni, Pb, Zn, Mn, Co, and Sr) of the soils were determined according to the USEPA method 3051A (USEPA, 1996). Digestion was carried out with a microwave-assisted digestion unit (MARS: HP-500 plus, CEM Corp., USA) and the metal concentrations were measured using an inductively coupled plasma optical emission spectroscopy (ICP-OES: Optima 7300 DV, Perkin Elmer, USA).

Table 1
Physicochemical properties of the soils used in the experiment.

Physicochemical properties		
Texture	Sand (S)	Sandy loam (SL)
Sand (%)	94	59.72
Silt (%)	0.32	31.08
Clay (%)	5.68	9.2
WHC[a] (%)	13.28	39.76
Total As (mg kg^{-1})	0.00 ± 0.40	1458.97 ± 577.46
Total Cd (mg kg^{-1})	0.03 ± 0.10	16.03 ± 0.56
Total Cr (mg kg^{-1})	0.47 ± 0.35	40.17 ± 3.25
Total Cu (mg kg^{-1})	3.10 ± 0.51	55.77 ± 2.34
Total Ni (mg kg^{-1})	2.80 ± 1.60	27.27 ± 0.00
Total Pb (mg kg^{-1})	2.37 ± 1.39	2224.43 ± 182.47
Total Zn (mg kg^{-1})	5.53 ± 2.60	1277.70 ± 42.25
Total Mn (mg kg^{-1})	1.30 ± 0.35	1600.60 ± 236.47
Total Co (mg kg^{-1})	0.00 ± 0.00	11.83 ± 1.27
Total Sr (mg kg^{-1})	0.30 ± 0.10	11.10 ± 0.66

[a] Water holding capacity.

2.2. Biochar production and characterization

Amur silvergrass (AB: *Miscanthus sacchariflorus*) residues were collected from Korea, paddy straw (PB: *Oryza sativa*) and umbrella tree (UB: *Maesopsis eminii*) residues were collected from Indonesia, and their BCs were derived from each residue. Detailed information for BC manufacturing conditions and characterization were described by previous studies of Lee et al. (2013a) and Lee et al. (2013b). The major properties of the BCs are presented in Table A.1. The morphology and elemental composition of the BCs were investigated using a scanning electron microscopy (Hitachi S-4800 with ISIS 310, Japan) operated at 15 keV with energy dispersive X-ray spectroscopy (SEM-EDX). The surface functionality and structural features of the BCs were characterized using a Fourier transform infrared spectroscopy (FTIR: Frontier, PerkinElmer, USA) at a resolution of 4 cm^{-1} and a Raman spectrometer (ARAMIS: Horiba Jobin, Japan) with a resolution better than 2 cm^{-1} at room temperature, respectively.

2.3. Incubation experiment

An incubation experiment was conducted. Each BC (i.e., PB, UB, and AB) was applied to a 100-g soil sample at a rate of 30 t ha^{-1} along with the control, to which no BC was added. Each treatment was triplicated. Each BC was thoroughly mixed with each soil sample in a high-density polyethylene bottle using a spatula. Soil moisture contents were periodically maintained at 70% of the soil WHC using distilled water. The BC-treated soils were incubated at 25 °C for 90 d in an automatic incubator (MIR-554, SANYO, Electronic, Co., Ltd., Tokyo, Japan).

2.4. CO_2 efflux

Soil C mineralization was investigated by measuring the CO_2 efflux during incubation. For CO_2 trapping, the vials containing 5-mL of 1 M NaOH were placed in each incubation bottle for 1, 3, 5, 7, 15, 30, 60 and 90 d. The CO_2 trapped in the NaOH was precipitated by adding 0.5 M $BaCl_2$ solution. The total C (TC) of the trapped CO_2 was determined by titrating against 0.1 M HCl using a phenolphthalein indicator (Zibilske, 1994). Three bottles containing a NaOH vial were each incubated without soil and BC under the same condition as a blank.

2.5. Soil analyses

Soil pH and electrical conductivity (EC) were analyzed in a suspension of 1:5 soil to distilled water using a pH-EC meter (Orion Versa Star Multiparameter, Thermo Scientific, USA). Exchangeable cations