SEWAGE SLUDGE BIOCHAR ENHANCES SOIL HEALTH AND CROP PRODUCTIVITY IN STRONGLY ACIDIC SOIL

Core Ideas

- Adoption of sewage sludge derived biochar in agriculture in search for an efficient sludge management technique that minimize environmental contamination risks.
- Assessing the effect of sewage sludge derived biochar in crop production and crop productivity.
- Comprehend the efficacy of sewage sludge derived biochar on enhancing soil physical, chemical, and biological properties, and overall soil health.

Abbreviations

CEC, cation exchange capacity; EC, electric conductivity; HDPE, high density polyethylene; OC, organic carbon; SOM, soil organic matter; TK, Total potassium; TN, Total nitrogen; TOC, total organic carbon; TP, Total phosphorus; WHC, water holding capacity.

Abstract

Amending soils with sewage sludge biochar is a promising waste management strategy and value-added approach to reuse the waste while minimizing environmental contamination risks. Soil pot experiment was conducted to examine the effect of a 300°C sludge-biochar in soil health and crop productivity using a strongly acidic soil. Three treatments of the soil pots were included: 1% biochar– (10 g kg^{-1} biochar/soil ratio), 2% biochar– (20 g kg^{-1} biochar/soil ratio), and control (soil without biochar). Winter wheat (*Triticum aestivum* L.), spinach (*Spinacia oleracea*), and mung bean (*Vigna radiata*) were grown sequentially in the soil pots over 9 months under greenhouse and field conditions. Plant biomass and soil health parameters were assessed. Soils amended with 2% biochar demonstrated higher biomass in winter wheat, spinach, and mung bean compared to unamended control treatments. The effect of sludge biochar was not observed in soil bulk density; however, soil aggregates stability was higher in soils amended with 2% biochar (24.17%) compared to control (21.38%). Soil acidity was corrected in soils amended with 2% biochar (pH value 6.5) compared to control (5.8), electric conductivity (EC) was higher in 1% biochar (0.25 dS m^{-1}) compared to control (0.20 dS m^{-1}). Respiration rate was higher in 1% biochar (0.52 mg CO2 g^{-1} dry soil) compared to control (0.43 mg CO2 g^{-1}), and total organic carbon (TOC) was lower in soils amended with biochar compared to control. Sewage sludge derived biochar improved crop production and soil health in strongly acidic soils and should be adopted in commercial agriculture.

Keywords: sewage sludge, biochar, soil health, plant growth.

1.0 Introduction

Sewage sludge is the solid residue generated in the wastewater treatment facility. In the United States, adoption of sewage sludge in agriculture systems has not received standing attention due to sludge's offensive odor and heavy metal contents. However, recent studies have demonstrated that conversion of sewage sludge to biochar through thermochemical pyrolysis process could deodorize and suppress heavy metals in sewage sludge therefore, there should be no environmental risks using sewage sludge derived biochar as a soil amendment (Pescod, 1992; Evanylo, 2006; Guo et al., 2012; Agrafioti et al. 2013; Guo, 2020).

The quality of sewage sludge biochar is determined by pyrolysis temperature. For instance, Guo and Song (2012) reported that a low pyrolysis temperature (i.e., 300°C) helps conserving the feedstock N in biochar; also, pyrolysis helps rendering a porous, OC-enriched product with great physical, chemical, and biological properties, and significant concentrations of plant nutrient: 36 g kg^{-1} TN, 79 g kg^{-1} TP, 7.7 g kg^{-1} TK (Zhang et al., 2015; Roberts et al., 2017; Guo, et al., 2016; Guo, 2020). Therefore, when land applied at appropriate rates, biochar products concurrently improve crop production, regulate soil bulk density, reduce soil compaction, improve soil aggregate stability, increase soil WHC, reduce soil acidity, improve soil CEC, increase SOM, and TOC (Song and Guo, 2012; Ouyang et al., 2013 Guo et al., 2016, Gondek et al., 2019; Guo, 2020).

Sewage sludge biochar is a promising material to sustain crop productivity, and enhance soil physical, chemical, and biological properties, and overall soil health: a long-term capacity of a soil to function as an ecosystem to support plant, animals, and humans (Moebius-Clune et al., 2017). However, few studies have been conducted so far. The present research was aimed to understand amendment effects of sewage sludge biochar on soil health and plant growth in a strongly acidic soil.

2.0 Materials and Methods

2.1 Collection of research soil and sewage sludge derived biochar

The research soil was classified as downer sandy loam with a taxonomic name as coarse-loamy, siliceous, semiactive, mesic typic hapludults. The soil was collected from a restored forest parcel at Blackbird Creek Reserve (Townsend, DE). The 4-mm air-dried topsoil (0–20 cm) had a pH value of 5.0, which is classified as strongly acidic soil. Generally, such soils demonstrate lower mineral nutrient (K, Ca, Mg, and S) contents, lower base saturation (<30%), and are prone to aluminum (Al^{3+}) toxicity (Finkelnburg, 2020). Therefore, plant growth, crop development, and soil microbial processes are limited in strongly acidic soils (Moebius-Clune et al., 2017). Pre-pyrolyzed sewage sludge biochar through 300°C pyrolysis temperature was obtained from Soil Research Laboratory at Delaware State University. Prior to pyrolysis process, sewage sludge was collected from a wastewater treatment facility in Milford (DE). The sewage sludge derived biochar was sieved through 2-mm and proceeded with potting experiments.

2.2 Soil pot preparation and experimental design

Nine soil pots were prepared, representing two treatments and a control, and each treatment in triplicates: 1) 2% Sludge-biochar amendment—soil amended with sludge-biochar at 2% of its dry weight; 2) 1% Sludge-biochar amendment—soil amended with sludge-biochar at 1% of its dry weight; and 3) Control—soil without biochar amendments. The 1 and 2% sludge biochar amendments rates represent approximately 20 and 40 Mg ha^{1} in field applications, respectively. Precisely, 9 10 kg of the 4-mm Downer soil were transferred into a large (18.9 L) plastic bucket. Afterwards, biochar was thoroughly mixed with soil and tap water was further added to adjust the moisture content to 15%. The well-mixed and moisture-adjusted soils were then packed into HDPE buckets (21 cm bottom diameter, 24 cm top diameter, 23 cm height, and 9.45-L volume) to a 20 cm depth from the bottom, after compacting slightly by tapping the ground. The soil pots were placed in a greenhouse in a completely randomize experimental design.

2.3 Plant growth trials

Three crops including winter wheat (*Triticum aestivum* L.), spinach (*Spinacia oleracea*), and Mung bean (*Vigna radiata*) were sequentially grown in the pre-prepared soil pots over 9 months under greenhouse and field conditions (Figure 1). Firstly, wheat seeds were manually sown in each soil pot. The growth of wheat was monitored, and irrigation was applied as convenient. The wheat trial lasted for three months, and the above-ground biomass was harvested by cutting and grouped in each pot replicate, the dry weight was measured by oven drying at 65°C for 72 h. Afterwards, soil pots were moved outside the greenhouse exposing to direct sunlight for spinach and mung bean growth (Figure 1). Spinach growth trial lasted for three months, and the oven dry biomass was measured. Lastly, mung bean growth trial lasted for three months, and seed biomass was determined. Collected data was statistically analyzed to disclose the effect of sewage sludge derived biochar in plant growth.

Figure 1. Plant growth trial of winter wheat, spinach, and mung bean under greenhouse and field conditions.

2.4 Soil health assessment

The soil health parameters were assessed at the end of the plant growth trials. Soil health was determined by evaluating soil physical, chemical, and biological properties of the treated research soil. Soil physical properties was determined by analyzing soil bulk density and aggregates stability; soil chemical properties were assessed by reading soil pH and EC; and soil biological properties was measured by assessing soil respiration rate and total organic carbon. Basically, after plant growth trial, soil pots were settled, and soil bulk density was estimated by measuring the distance from the pot top edge to the soil surface. Afterwards, soil samples were collected using a 1.9 cm diameter soil probe. The probe was pushed vertically to the soil pot bottom to collect soil cores from random surface location of each soil pot. The amount of moist soil collected from each soil pot was approximately 100 g. The samples were grouped as treatments, mixed thoroughly, and kept at room temperature for further analysis.

2.4.1 Soil physical properties

Aggregates stability measures the ability of a soil to resist falling apart when hit by rain drops. Also, aggregates stability was measured using a simulated rain equipment (Figure 2) describing in the methods of Moebius-Clune et al., (2017).

Figure 2. Aggregates stability analysis. Displayed is the rain stimulator whose mechanism actions is equivalent to a thunderstorm ((Moebius-Clune, 2017).

2.4.2 Soil chemical properties

Treated soil pH and EC were measured using the methods of Song and Guo (2012) with slight modifications. Briefly, 10.0 g of air-dried soil (2-mm) was weight and soaked in deionized water at a 1:1 solid/water ratio and mixed thoroughly for five minutes. The slurry was then measured for pH using an Accumet AB15 pH meter and measured for electric conductivity (EC) using an CON510 conductivity /TDS meter (Oakton Instruments, Vernon Hills, Hills, IL).

2.4.3 Soil biological properties

The soil respiration rate analysis (Figure 3) was conducted using the methods described in the comprehensive assessment of soil health (Moebius-Clune, 2017). Soil total organic carbon (TOC) was determined using the chloroform fumigation-extraction method (Diaz-Raviña et al, 1992).

Figure 3. Soil respiration analysis experiment.

3.0 Results and Discussion

3.1 Plant growth trials

The effect of sludge derived biochar amendments on crop production was determined by assessing oven dry biomass of research crops (Figure 3). For winter wheat dry biomass, 2% biochar demonstrated higher yield (7.21 g), compared to 1% biochar (3.65 g) and unamended control treatment (2.88 g). Similarly, in spinach dry biomass, 2% biochar yielded 3.42 g, followed by 1% biochar (1.43 g) and unamended control treatments (1.08 g). For mung bean seed biomass, 2% biochar showed 18.60 g, followed by control treatment (12.05 g), and 1% biochar (8.75 g). All crops biomass experienced an upward trend as the application rate of biochar was increased from 1-2%: more biochar, more biomass yield; also, 2% amendment rate of biochar had higher yield compared to unamended control treatments. Recent studies presented similar findings. For instance, Silva et al. (2017) reported that soils amended with sludge derived biochar demonstrated higher biomass yield of eucalyptus seedlings compared to unamended control treatments. Also, outstanding research demonstrated that biomass yield of Chinese cabbage, wheat, cereals, tubers, roots, fibers, and turf grass was higher in soils amended with sludge derived biochar compared to those of unamended control treatments (Bierdeman, 2013; Reibe, 2015; Yue et al. 2017; Yu et al., 2018).

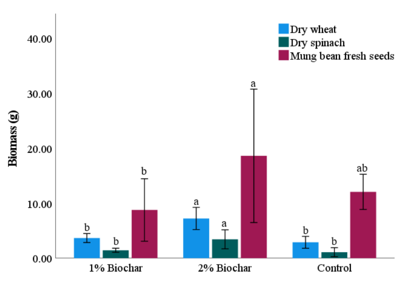

Figure 4. Effect of sewage sludge derived biochar amendments on wheat, spinach, and mung bean biomass. Means with common letters are not significantly different (P 0.05).

3.2 Effects of sewage sludge derived biochar amendments on soil physical properties

The effect of sewage sludge derived biochar amendments on soil physical properties is illustrated in Figure 5. The initial bulk density of the soil pots was ~1.1 g cm ^{3}. After 9-months of natural settling, the bulk density decreased. As observed (a), control treatments had a bulk density of 1.04 g cm^{-3}, followed by 2% and 1% biochar amendments both with 1.07 g cm^{-3}. According to such results, the effect of sludge derived biochar amendments was not observed in soil bulk density. However, researchers demonstrated that biochar amendments have a lower envelop density and therefore, can decrease soil bulk density if applied at significant rates (Guo, 2016; Verheijen et al., 2019; Guo, 2020), an additional method to measure bulk density is suggested.

Aggregates stability (b) was higher on 2% biochar treatment with 24.17%, followed by control (21.38%), and 1% biochar (20.95%). Adding biochar to soils increases soil aggregates stability (Herath et al., 2013), as biochar provides favorable conditions to enhance microbial function and structure to hold soil particle when hit by rain drops (Paz-Ferreiro et al 2012; Moebius-Clune et al., 2017).

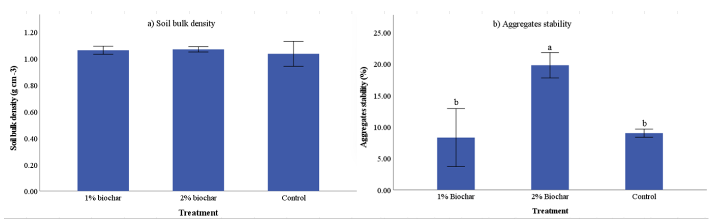

Figure 5. Effect of sludge derived biochar amendments on soil physical properties. Means with common letters are not significantly different (P 0.05).

3.3 Effects of sewage sludge derived biochar amendments on soil chemical properties

The effect of sludge derived biochar on soil chemical properties is illustrated in Table 1. The initial pH of the test soil and sewage sludge biochar was 5.0 and 7.2, respectively. As observed, soils amended with 2% biochar demonstrated higher pH value (6.5) compared to control (5.8) and 1% biochar (5.5). The addition of biochar to soils elevated soil pH as expected and significantly reduced soil acidity. The ideal soil pH to support plant growth range from 6.0–7.0 (Moebius-Clune et al., 2017; Finkelnburg, 2020; Guo, 2020).

Electric conductivity (EC) reading was below 0.26 dS m^{-1} in all treatments. Typically, plant growth is not limited in soils with an EC value below 2.7 dS m^{-1} measured in 1:1 solid/water ratio (Guo, 2020).

Table 1. Effects of sludge and its derived biochar amendments on soil pH. Values are mean ± standard deviation of triplicate measurements.

Treatment	**pH**	**Electric conductivity ($\mathbf{dS\ m^{-1}}$)**
Test Soil*	±0.04	±0.001
Biochar	± 0.001	± 0.009
Test Soil + 1% Biochar*	±0.05	±0.01
Test Soil + 2% Biochar*	±0.02	±0.01
Control*	±0.03	±0.01

*Measured in slurry 1:1 solid/water ratio

Measured in 1:10 solid/water ratio

3.8. Effects of sewage sludge derived biochar amendments on soil biological properties

The effect of sewage sludge derived biochar amendments on soil biological properties is illustrated in Figure 6. As illustrated (a), 1% biochar demonstrated higher respiration rate (0.52 mg CO2 g^{-1} dry soil) compared to 2% biochar (0.45 mg CO2 g^{-1} dry soil) and control treatment (0.43 mg CO2 g^{-1} dry soil). Similarly, Paz-Ferreiro et al. (2012) reported that soils amended with 4% biochar demonstrated lower respiration rate compared to 2% biochar and unamended control treatments. Typically, the addition of biochar into soils significantly increase respiration rate compared to untreated control, and the ideal respiration rate should be >0.7 mg CO_2 g^{1} dry soil (Wang et al., 2017; Moebius-Clune et al., 2017; Slapakova et al., 2018).

The effect of biochar amendments on total organic carbon (b) was not observed in the biochar treatments, as there were no significant differences between biochar treatments and unamended control. As demonstrated (b), control showed 33.34 mg kg^{-1}, followed by 2% biochar (28.44 mg kg^{-1}) and 1% biochar (18.25 mg kg^{-1}). Typically, soils amended with biochar are expected to have higher total organic carbon contents than control (Gasco et al., 2016; Jing et al., 2020). However, OC contents in soils is influenced by several factors including the method of measurement, as it is speculated that 0.5 M of K_2SO_4 may flocculate biochar and cause adsorption of solubilized C onto biochar particles therefore, total organic carbon (TOC) was not detectable.

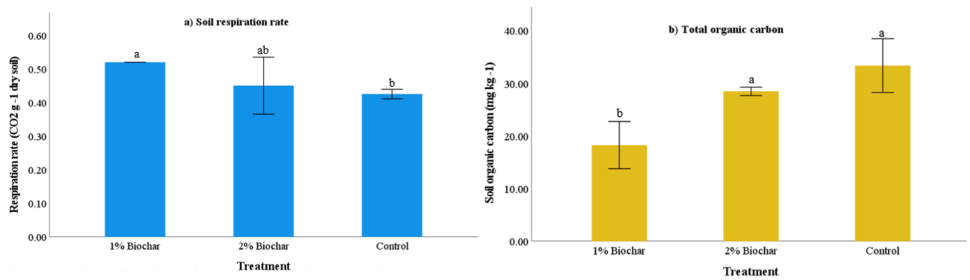

Figure 6. Effect of sludge derived biochar amendments on soil biological properties. Means with common letters are not significantly different (P 0.05).

4.0 Conclusions

Plant biomass of winter wheat and spinach, and mung bean seeds was significantly higher in soils amended with 2% biochar compared to those of unamended control treatments. The effect of sludge biochar was not observed in soil bulk density however, aggregates stability was improved in soils amended with 2% sludge biochar (24.17%) compared to control treatment (21.38%). Soil pH was increased in soils amended with 2% biochar (6.5) compared to unamended control soils (5.8), and soil electric conductivity was higher in 1% biochar (0.25 dS m^{-1}) compared to control (0.20 dS m^{-1}). Respiration rate was higher in 1% biochar treatment (0.52 mg CO2 g^{-1} dry soil) compared to control (0.43 mg CO2 g-1 dry soil), and total organic carbon was lower in soils amended with sludge biochar compared to control owing the limitation of 0.5 M K_2SO_3 (extractant solution) on extracting C adsorbed by biochar particles.

The present study demonstrated that adding sewage sludge derived biochar amendments into soil improves plant growth and enhances soil physical, chemical, and biological properties, and the overall soil health. The conducted research was efficient as it complemented the proposed research goals and hypothesis. Further studies are required to optimize sludge biochar utilization programs in commercial agriculture.

Acknowledgement

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Conflict of Interest

The authors declare no conflict of interest.

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