Characterization and Modification of Biochar from a Combined Heat and Power (CHP) Plant for Amending Sandy Soils Collected from Wild Blueberry Fields

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Wild (or lowbush) blueberries (*Vaccinium angustifolium* Ait.) undergo severe drought impacts due to climate warming because they grow in sandy soils with poor water retention. The feasibility was studied for using biochar in a forest biomass-fueled combined heat and power (CHP) plant to amend the sandy soils. The chemico-physical properties (*e.g.*, bulk density, moisture content, porosity, pH) of the biochar were measured. An acid treatment method (1% to 3% acidic or citric acid solution) was developed to decrease the biochar pH from 11.4 to neutral or lower, aiming to aid in weed control in wild blueberry fields. The water holding capacity (WHC) of sandy soils (S) mixed with biochar (B) (Type I) and sandy soils mixed with both biochar and fertilizer (Type II) at four ratios of 100S:0B (control), 50S:50B, 30S:70B, and 10S:90B were measured. The biochar generated from the CHP plant had comparable physical properties (such as bulk density, porosity, pH, and surface area) with woody biochar made from pyrolysis. The acid treatment method significantly lowered the pH to a range of 5.0 to 6.5. The 50:50 mixing ratio for both Type I and Type II increased the water holding capacity by about 20% compared with control groups.

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Keywords: Biochar; pH modification; Sandy soil; Water Holding Capacity (WHC); Wild blueberry

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INTRODUCTION

The projected increase in climate variability poses a threat to agricultural systems, particularly with crops that reside in sandy soils, where low water retention and inadequate buffering heighten crop susceptibility to drought (Kundu *et al*. 2008; Fernández-Luqueño *et al*. 2010; Chukalla *et al*. 2015; Clément *et al*. 2019). Crops, such as wild (or lowbush) blueberries (*Vaccinium angustifolium* Ait.), may thrive in sandy soils. However, these crops require considerable water and fertilizer to remain productive (Kundu *et al*. 2008; Yarborough 2008; Fernández-Luqueño *et al*. 2010). The severity, duration, and frequency of droughts are predicted to increase in many regions of the world, including the Northeastern United States (Dai *et al*. 2013; Fernandez *et al*. 2020). Wild blueberry crops are an important economic crop primarily grown in the Northeastern United States and Atlantic Canada and are experiencing climate change impacts. Approximately 70% of the wild blueberry farmlands in Maine are not equipped with irrigation systems (Yarborough 2008). Urgent measures are imperative to enhance water and fertilizer efficiencies, reduce water management costs, and ensure stable growth and berry production.

Biochar, a charcoal-like material, is produced through pyrolysis (an oxygen-depleted environment) of biomass such as forest logging, wood processing, agricultural residues, sludge, and municipal solid waste streams (Rehrah *et al*. 2014; Suliman *et al*. 2017; Chen *et al*. 2018). The application of biochar in soils can be traced back to at least 2,500 years ago when Amazonians made biochar and applied it to the soils to increase the organic carbon content and fertility in the Amazon Basin of South America (Bezerra *et al*. 2019). Overall, biochar has a highly porous structure, a relatively large surface area, high carbon content, a wide pH range, and abundant mineral elements (Rehrah *et al*. 2014; Suliman *et al*. 2017; Chen *et al*. 2018). These characteristics can aid in its potential as a prominent soil amendment to bring many agronomic, socioeconomic, and environmental benefits in varying soils and crop systems. For instance, biochar can increase soil water holding capacity through alteration in soil porosity, improve nutrient retention through cation adsorption on biochar surface, enhance soil fertility through soil pH modification and facilitation of microbial growth and enzymatic activities, immobilize heavy metals and other contaminants through surface adsorption, reduce greenhouse gases emissions, and increase carbon storage on the earth (Van Zwieten *et al*. 2010; Atkinson *et al*. 2010; Choppala *et al*. 2012; Jones *et al*. 2012; Rehrah *et al*. 2014; Cayuela *et al*. 2014; Kuppusamy *et al*. 2016; Zhao *et al*. 2017; Xiao *et al*. 2018; Lu and Zong 2018; Kameyama *et al*. 2019; Kapoor *et al*. 2022).

Though many studies have addressed the potential benefits of biochar, as mentioned above, the negative implications associated with biochar technology should also be considered when selecting suitable biochar products and designing application regimes for target soils and crops. For instance, the effects of biochar additions on the improvement of water retention in sandy soils are significant but have little effectiveness in other soil types, such as clay soil (Yu *et al*. 2013). Biomass sources and pyrolysis processes affect the biochar pH, ranging between 5 and 12 (Fig. 1) (Guo *et al*. 2020). When it intends to ameliorate soil acidity for crops, *e.g.*, bean cargamanto mocho (*Phaseolus vulgaris* L), alkaline biochar could be directly used in the soils (Becerra-Agudelo *et al*. 2022). However, some crops like wild blueberries are adapted to acidic environments with an optimum soil pH of 4 to 5, where many other plants, such as weeds, cannot survive (Wood 2008; Yarborough and Calderwood 2019). When the soil pH is above the optimal range, soil pH can be lowered by adding fertilizers with sulfur , pine needle litter, papermill sludge, and soilless substrates (Rosen *et al*. 1990; Starast *et al*. 2007; Imler *et al*. 2019; Guo *et al*. 2020). Therefore, acidic biochar would be more suitable for wild blueberries. In contrast, alkaline biochar might need to be modified to decrease its pH to avoid greatly raising the soil pH after applying it in acidic soils.

Advanced pyrolysis techniques, such as industrial-scale biomass pyrolysis reactors and gasifiers, have been mainly used to produce biochar for agricultural uses as a co-production of bioenergy production. Unlike the traditional earthen brick and steel kilns, modern pyrolysis plants can synergistically produce bioenergy, bio-oils, and biochar products, offering the highest return on efficiency and greenhouse gas abatement potential (Pratt and Moran 2010). In 2018, the US produced an estimated 45,000 tons of biochar, utilizing 125,000 to 250,000 green tons of feedstocks (Groot et al. 2018). However, optimizing biochar output may compromise bio-oil and syngas production, impacting economic viability (Jeffery et al. 2015). Biochar production alone for agriculture may not achieve energy self-sufficiency (Kuppusamy *et al*. 2016), but regions, *e.g.*, the New England region, with ample biomass resources and demand for heat and electricity could overcome this challenge.

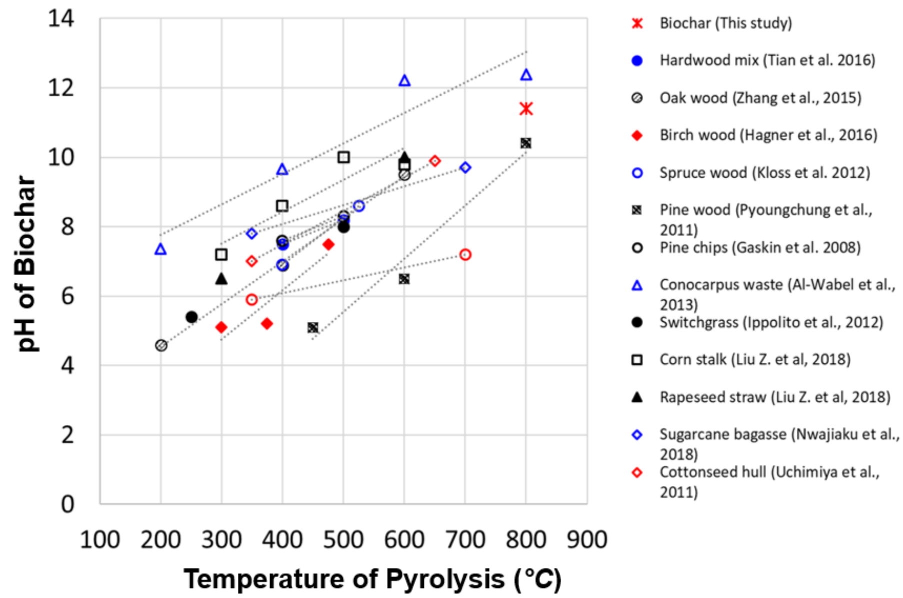


Fig. 1. Relationship between pyrolysis temperature and pH of lignocellulosic biochar. The dashed lines indicate the linear relationship of pH to pyrolysis temperature for each of these studies, with each symbol representing the biochar tested during that study. (Note: Data in this graph was from Guo *et al*. (2020).)

In this study, biochar sourced from a local forest biomass-fueled combined heat and power (CHP) plant was used for amending sandy soils collected from Maine's wild blueberry fields to assist in drought management and crop growth. The biochar mixed with fly ash, as a waste stream was collected from the CHP unit's flue gas cleaning system, called an electrostatic precipitator system. It was estimated that approximately 1,000 tons of biochar are currently disposed of with ash in landfills. The goal of this study was to investigate the characteristics of this biochar type, how it can be modified to be suitable as a soil amendment for wild blueberries, one of the most important crops in Maine, and its influence on soil properties when used as an amendment in sandy soils. The objectives were to 1) characterize the basic physical properties of locally sourced biochar to create a material information database, 2) determine an ideal mixing ratio of sandy soil and woody biochar without fertilizer and with fertilizer mixture to increase the water holding capacity, and 3) develop an effective and efficient post-treatment method to neutralize the pH of alkaline biochar for application to acidic soils. The results will provide essential information for developing a sustainable solution for drought management of crops in acidic sandy soils.

EXPERIMENTAL

Materials

A biochar material, as a byproduct of power generation, collected from a local biomass CHP plant located in the central Maine was derived from low-quality forest biomass (*e.g.*, bark, branches, leaves, and wood chips) generated from forest operations and wood processing on deciduous and coniferous tree species (*e.g.*, spruce, fir, maple, oak). The biochar was produced at a high temperature of approximately 800 °C in the biomass furnace of the CHP unit due to incomplete combustion. The mixture of biochar and ash was transported in barrels to the BioEnergy Lab of the University of Maine. The biochar was separated from the mixture by using a laboratory sifting machine (Gilson Testing Screen, Model TM-3", Gilson Company, Inc., Worthington, OH, USA).

Acetic acid (liquid, pure) and citric acid (solids) were purchased from Fisher Scientific (Hampton, NH, USA), and Research Products International (Mt Prospect, IL, USA) and chosen to neutralize the biochar by considering their environmentally friendly nature, economic feasibility, and accessibility.

Before this study, twenty soil samples were collected from 5 genotype sites that were unmanaged at a local blueberry farm in DownEast Maine. The soils were collected up to 10 cm depth with the organic layer included. They were sent to the Maine Analytical Lab and Maine Soil Testing Service soil lab to analyze the soil composition and pH. The twenty soil samples were classified as sandy (eleven samples), sandy loam (six samples), loamy (two samples), and loamy sand (one sample). The pH of the soil samples ranged between 4.5 to 6.2. Ammonium sulfate [$(NH_4)_2SO_4$] fertilizer is commonly used in blueberry crop management and was purchased from Northeast Agriculture Sales Inc. (Detroit, ME, USA).

Characterization of Biochar

The basic physical and chemical properties and morphology of untreated biochar samples were measured using different methods; these are described as follows. Biochar moisture content was measured using a moisture balance (Ohaus MB23, Hogentogler & Co. Inc, Columbia, MD, USA). The samples had been stored in the lab for a few months before testing the moisture content. Three 5-gram samples were randomly taken from the storage container. Each sample was dried at 120 °C for about 10 minutes to ensure the sample weight reached a constant value. Then the sample's moisture content on a wet basis was reported from the reading of the moisture balance.

The porosity and medium pore diameter of biochar were measured using a Mercury Intrusion Porosimetry (MIP) Autopore IV (Micromeritics Instrument Corporation, Norcross, GA, USA). Two biochar samples were tested. The bulk density of untreated biochar particles was measured following ASTM E873-82(2019) Standard Test Method for Bulk Density of Densified Particulate Biomass Fuels (ASTM 2019). The weight of biochar particles that filled up a graduated cylinder (250 mL) was measured to calculate the bulk density following equation (1). Three replicates were tested.

$$Bulk\ density, gcm^{-3} = \frac{Mass_{dry},\ g}{Volume\ of\ column\ packed\ by\ sample, cm^3} \tag{1}$$

The total surface area of biochar was measured by using a Brunauer-Emmett-Teller (BET) surface analyzer (model: Micromeritics ASAP 2020, Micromeritics Instrument Corporation, Norcross, GA, USA). Two randomly selected biochar samples were tested.

The morphology of untreated biochar was observed using a Scanning Electron Microscope (SEM) (AMRay 18201820; Amray scanning electron microscopes, Bedford, ME, USA). Biochar particles were mounted on stubs using carbon tape, and conductive silver paint was applied to the samples. The regions of interest of the samples were sputter coated with gold and palladium (23 nm) using a Cressington 108 auto sputter coater (Ted Pella Inc., Redding, CA). The images were taken at an accelerating voltage of 3 kV.

Biochar pH Modification

An acid treatment method was developed to modify the alkaline nature of the biochar acquired from the CHP plant, aiming to reduce the high pH to a neutral pH of 7 or lower. A total of three biochar samples were measured for the five treatments that were designed, including two diluted acetic acid (AA) solutions (1% and 2% concentrations by volume), two diluted citric acid (CA) solutions (1.5% and 3% concentrations), and deionized (DI) water (control).

The biochar treatment procedure was described as follows. Approximately 200 mL of 1% of AA, 2% of AA, 1.5% of CA, 3% of CA solutions, and DI water were prepared in five beakers, respectively. 10 g of prewashed biochar were added to each beaker and soaked for 5 minutes. Then, the pH of the biochar slurries was measured and recorded using a pH meter (Hanna Instruments, Smithfield, RI, USA). After that, each beaker's solution was drained using a filtering funnel. About 200 mL of DI water was added into each beaker to wash the biochar, followed by a second pH measurement and recording. This process was repeated an average of five times until the biochar pH reached a constant value, indicating that water-soluble basic mineral compounds were removed from the biochar. After that, the five groups of biochar samples were oven-dried at 103 °C until no water was in the biochar, which ensured all the samples had the same initial moisture contents before doing the final measurement of biochar pH. Then, the oven-dried biochar samples were rewet by soaking them in 200 mL of DI water. The final pH of the five samples was measured and recorded. This process was repeated three times, and each time the raw biochar was randomly picked from the storage containers. Fifteen treated biochar samples were made and tested.

Biochar Ash Content

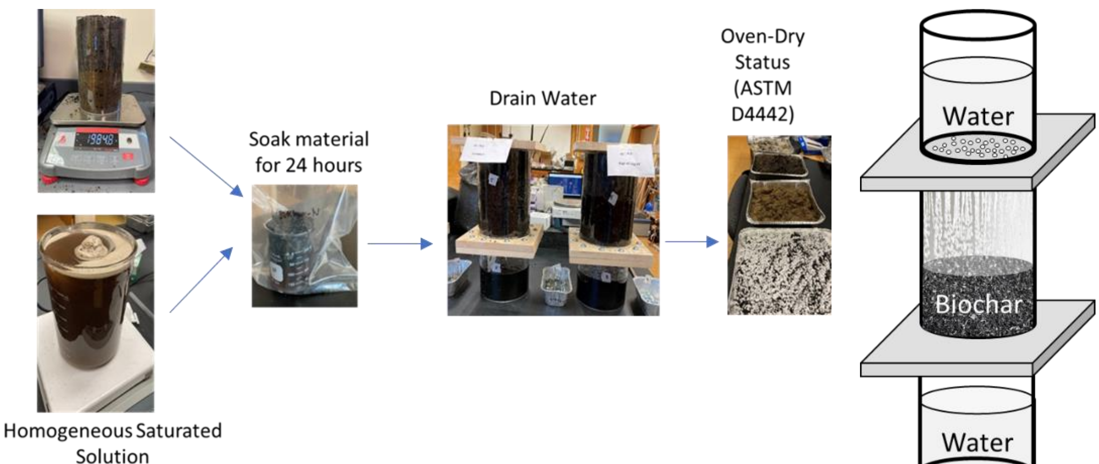
Thermogravimetric analysis (TGA) was conducted to determine whether ash minerals were removed through the DI-water and acid solution treatments. The twelve acid-treated biochar samples, three untreated biochar samples treated with DI water, and three untreated biochar samples (control group) were placed in 18 crucibles in a TGA instrument (LECO 701, St. Joseph, MI, USA). Each crucible had approximately 1 gram of biochar sample. The samples were first dried at 103 °C for 1 hour. Then the temperature of TGA was increased to 600 °C at a rate of 15 °C per minute and kept at 600 °C for 1 hour to burn the samples completely. The remaining inorganic compounds (*i.e.*, ash) were weighed and used to calculate the ash content following the ASTM E1755-01 (2020): Standard Test Method for Ash in Biomass (ASTM 2020) and Eq. 2:

$$Ash\ content, \% = \frac{Mass\ of\ ash,\ g}{Initial\ mass\ of\ biochar\ sample,\ dry\ basis,\ g} \times 100\% \qquad (2)$$

Water Holding Capacity (WHC) of Biochar and Sandy Soil

Two types of untreated biochar and sandy soil mixtures were prepared to test ratios of biochar and the effect of adding fertilizer on soil properties. Type I consisted of sandy soil (S) and biochar particles (B) mixed at four ratios of 100S:0B (control), 50S:50B, 30S:70B, and 10S:90B by volume. Type II was composed of the same mixing ratios of sandy soil (S) and biochar (B) but amended with fertilizer (F). Untreated biochar and sandy soil mixtures were prepared and tested the same but with DI water. Unlike simply blending soil, biochar, and fertilizer granules, an exploratory approach was designed in this study, aiming to ensure a more homogeneous distribution of fertilizer in the biochar and sandy soil mixture and minimize wind-driven losses after applying it in fields. Ammonium sulfate fertilizer granules were firstly dissolved in water to form a saturated solution at room temperature (74.4 grams per 100 grams water at 20 °C). Then, the soil and biochar mixture samples with the four ratios used in Type I were soaked in the solution for 24 hours at room temperature. Afterward, the samples were dried at 50 °C in a conventional laboratory oven to allow the fertilizer to be crystalized on the sandy soil and biochar particles (Fig. 2a). The bulk density of all the soil and biochar mixture samples was measured and calculated using equation (1).

The water-holding capacity (WHC) of these mixture samples was determined using a modified column experiment based on the column test (Yu *et al*. 2013). A water-collecting device was constructed that was 150-mm in diameter (D) by 610-mm in height (H) acrylic column system comprised of three sections: upper column (200-mm H) to supply water, middle column (254-mm H) for holding soil/biochar/fertilizer mixture, and bottom column (150-mm H) (Fig. 2b). The bottoms of the upper and middle columns were drilled to form a perforated plate with forty-eight holes of 3-mm in diameter. A fine 25-mesh size screen was placed at the bottom of the middle column, allowing water to drain off only.



(a) Preparation of biochar/fertilizer composites **(b)** Column system

Fig. 2. Water holding capacity test of biochar/soil mixed samples using a column system. (a) the preparation process of Type II sand soil/biochar/fertilizer samples. The first step was to measure the biochar/soil ratio and create the saturated solution for the material. After that, the material was soaked for 24 hours, drained, and oven-dried to obtain the water holding capacity. (b) the column system was used for the water-holding capacity test. The sample was packed in the middle column; water was poured into the top column, and a waterfall was formed by a perforated plate; and the excess water drained out from the sample was collected in the bottom column.

The sample was packed in the middle column of the custom column system with a thickness of 150 mm, leaving 100 mm of space above the sample. Next, 1000 to 4000 mL of water was poured through the upper column with more solution used for the fertilizer solution due to the dissolved solutes. The water in each sample was drained by gravity until no water dripped into the lower column. Lastly, the sample was collected, weighed ($Mass_{wet}$), and then dried at 103 ºC in an oven until the mass reached a constant value ($Mass_{dry}$). There were a total of twenty-four samples run with three replicates within each combination of 10S:90B, 30S:70B, and 50S:50B. The water holding capacity was calculated using Eq. 3 (Yu *et al*. 2013).

$$Water\ holding\ Capacity, \%\ = \frac{Mass_{wet} - Mass_{dry}}{Mass_{dry}}\ \times\ 100\% \qquad (3)$$

Statistical Analysis

The effects of acid treatments on biochar pH and ash content and the effects of mixing ratios of soil and biochar on water holding capacity and bulk density were analyzed using an analysis of variances (ANOVA) and a paired comparison test using Origin Pro 2021b (Origin Pro 2021). The significance level was 0.05 ($p < 0.05$).

RESULTS AND DISCUSSION

Characteristics of Biochar

Physical properties of biochar

The size of the biochar particles ranged from 1 to 5 mm after sifting (Fig. 3). The moisture content was 29% to 38% (Table 1). The porosity of the two biochar samples was 52.7% and 30.3%. The median pore diameters were 14.5 and 17.5 µm. The surface areas were 302 to 402 m^2g^{-1} (Table 1). The variation in these properties might be caused by the large variation in biomass feedstock, such as species and portions of trees (Zhao *et al*. 2013; Pariyar *et al*. 2020). The biochar's porosity and surface area agreed well with biochar derived from different forest biomass (*e.g.*, pine sawdust, shaving, oak pellets, birch wood chips) through pyrolysis with temperatures ranging from 550 to 650 ºC (Lu and Zong 2018; Guo *et al*. 2020; Ferraro *et al*. 2021). The porosity of coniferous forest biochar was 57%, with pore sizes of 6 to 25 µm (Lu and Zong 2018). The surface area of biochar derived from black pine (*Pinus nigra*), poplar (*Populus*), and willow (*Salix*) is greatly increased with increasing the pyrolysis temperature from 400 to 650 ºC (Ferraro *et al*. 2021).

Table 1. Physical Properties of Untreated Biochar

Property	Method	Sample 1	Sample 2	Sample 3
Moisture Content (MC)	Moisture Analyzer	37.4%	29.7%	32.7%
Porosity of biochar particle	MIP	52.7 %	30.2 %	
Median pore diameter		14.5 µm	17.5 µm	
Bulk density, dry	ASTM E873	0.08 gcm^{-3}	0.09gcm^{-3}	0.08 gcm^{-3}
Total surface area	BET	402.2 m^2g^{-1}	301.9 m^2g^{-1}	

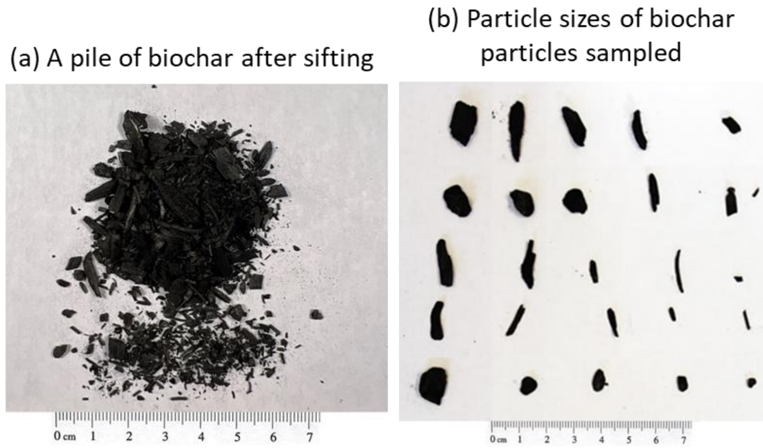


Fig. 3. Untreated biochar particle size and shape. a) A pile of biochar at different sizes and b) the particle sizes of biochar particles sampled

The pore diameter distribution of untreated biochar ranged from 0 to 350 µm (Fig. 4a). The two biochar samples (Fig. 4a, b) showed a substantial increase in the pore volume between 5 and 35 µm, which would be classified primarily as "micropores," as defined by the Soil Science Societies of Americas (Kameyama *et al*. 2019). Micropores play an important role in holding water in place through capillary forces (Kameyama *et al*. 2019). The advantage of woody biochar for holding excess water is that biochar keeps the original wood cell structure, such as tracheids, vessels, and fibers that typically have diameters within this range (Fig. 4a) (Tarmian *et al*. 2009; Salvo *et al*. 2017; Held *et al*. 2021). Moreover, about 60% of the total pores of the two biochar samples are micropores. Amending woody biochar into sandy soils, therefore, would likely increase the number of micropores in the soils to achieve an increase in water-holding capacity (Liu *et al*. 2016).

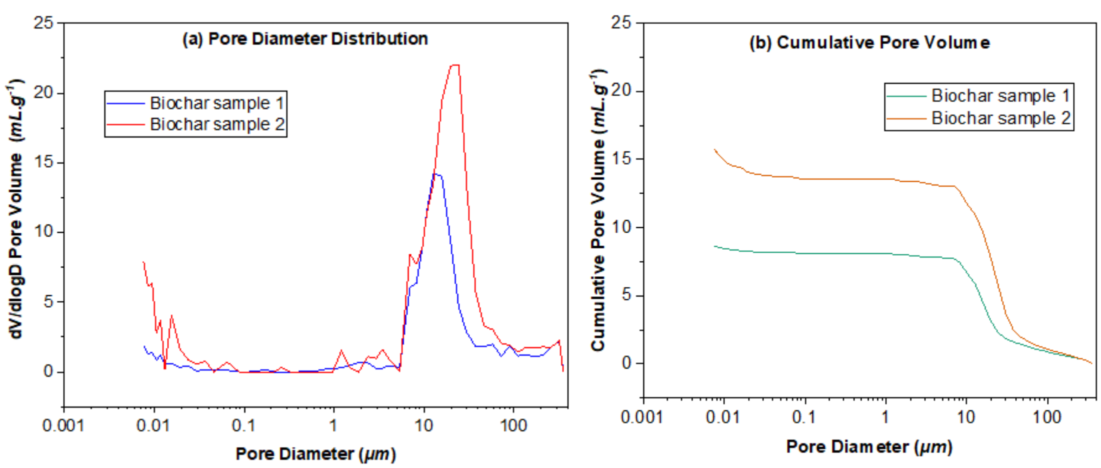


Fig. 4. Pore diameter distribution (a) and cumulative pore volume (b) of biochar samples measured with biochar pore size decreasing from 0 to 350 µm

Morphology of untreated biochar

Biochar scanning electron microscopy (SEM) images showed that the untreated biochar was derived from a mix of forest biomass: xylem (Fig. 5a) and bark sample (Fig. 5b). The biochar material retained the original structure of woody biomass, such as vessels with function of water conduction (Fig. 5a). In combination with Fig. 4, it is apparent that the biochar possessed a hieratical structure from macroscale to nanoscale, allowing for various water transfer activities taking place in biochar, such as relatively quick convection and diffusion, capillary rising, and capillary condensation (Rehrah *et al*. 2014; Suliman *et al*. 2017; Chen *et al*. 2018). Also, ash deposition and agglomeration were observed from the SEM images (Fig. 5c and 5d). Ash in biochar may provide both benefits and negative impacts on the soils. Ash could be a supplementary source for some essential plant nutrients (*i.e.*, mineral nutrients), such as P, K, and Ca (Bieser and Thomas 2019). However, excess ash may block the ultramicropores (pore size in 0.1 to 5 µm) and cryptopores (pore size <0.1 µm) of biochar to decrease the total surface area, which would reduce the adsorption capacity for organic and inorganic pollutants (Zhang *et al*. 2013). Hence, proper ash removal approaches should be considered based on the end uses of the biochar.

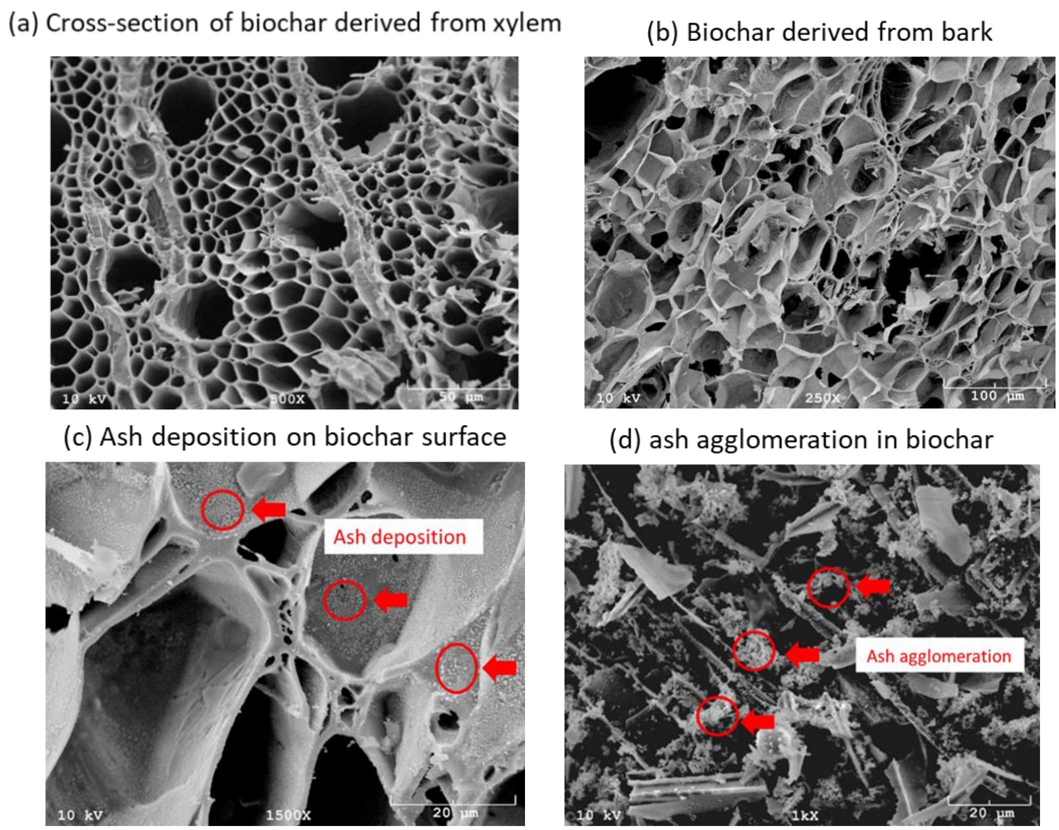


Fig. 5. Scanning Electron Microscopy (SEM) images of selected untreated biochar samples to show the morphological structure of the biochar (a) cross-section of biochar derived from xylem; (b) biochar derived from bark; (c) ash deposition on biochar surface; (d) ash agglomeration in biochar)

Biochar pH and ash content

The mean ± SD values of untreated biochar pH were 11.40 ± 0.08 (Fig. 6a). The biochar washed by water had a slightly lower pH of 10.07 ± 0.05, but this was not statistically significant based on the multiple comparisons analysis. Both acetic acid and citric acid treatments significantly lowered the pH of the biochar relative to raw and washed controls, resulting in pH values ranging from 5 to 6.5. However, there was no statistically significant difference in pH between the different acetic acid-treated biochar and citric acid-treated biochar treatments. Nevertheless, a relatively large variation in pH results was observed in the four groups of biochar samples treated with acetic acid or citric acid but not in the raw biochar and biochar washed by water. The results indicate that the biochar may not provide a lot of pH-buffering ability. At high pH levels, this issue was not significant due to the relatively high concentration of OH- ions. Since the acid treatment of biochar in this study was to help the sandy soils retain the acidic nature, the treated biochar with a lowered pH buffering ability might be a manageable issue. To address this question, it would be helpful to conduct long-term soil pH monitoring.

The ash content of untreated biochar (16.60 ± 3.27 %) was significantly reduced to 8.60 ± 1.00 % when the biochar was washed with water (Fig. 6b). The ash content of the four types of acid-treated biochar samples were also significantly lower than the untreated and water-washed biochar. However, similar to the pH results, the ash content of the acid treatments did not significantly differ from each other (Fig. 6b). Both biochar pH and ash results suggested that the removal of a portion of ash using acid treatments was an effective method to reduce the pH of biochar produced using forest biomass from the high-temperature furnace of the industrial-scale CHP unit. The reasons can be explained by the mechanism of biochar alkalinity, which is attributed to four categories: 1) surface organic functional groups (as conjugate bases), 2) soluble organic compounds (also conjugate bases of weak acids), 3) carbonates (salts of bicarbonate and carbonate), and 4) other inorganic alkalis (oxides, hydroxides, sulfates, sulfides, and orthophosphates) (Singh *et al*. 2010; Yuan *et al*. 2011; Fidel *et al*. 2017). Field *et al*. (2017) quantitively analyzed the contribution of the four categories using biochar samples made of corn stover (*Zea mays*), oak (*Quercus* spp.), and mixed hardwood species (oak (*Quercus* spp.), elm (*Ulmus* spp.), and hickory (*Carya* spp.) through pyrolysis and gasification processes at three temperatures of 300, 500, and 600 °C. For hardwood biochar made at 500 and 600 °C through pyrolysis and gasification, carbonates, and other inorganic compounds (*i.e.*, ash constituents) took about 70% of the total alkalinity. Therefore, the acid treatment method is recommended for forest biomass derived biochar.

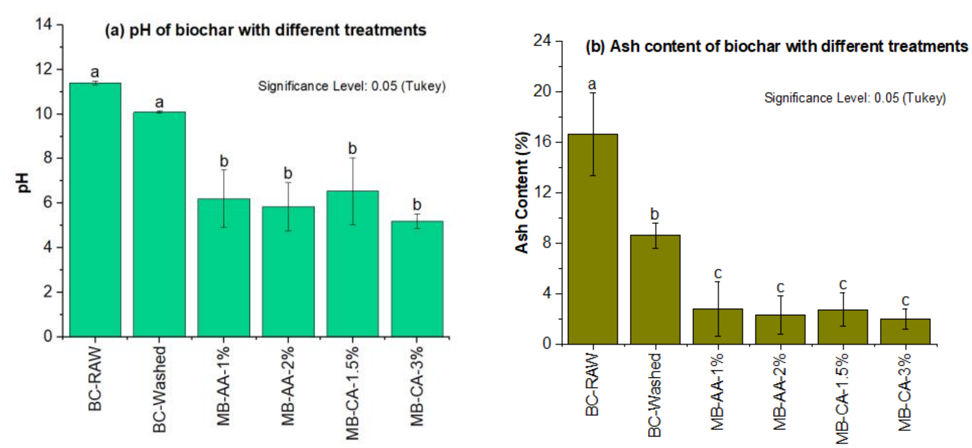


Fig. 6. Effects of wash-treatment and acid-treatment on biochar pH through a paired comparison test (a) and ash content (b) fit with standard error bars (Note: The mean values of biochar pH and ash content were plotted. An error bar was added to each column showing the standard derivation (SD) of results. Different letters on bars indicate statistical significance in a paired comparison analysis. Letters shared in common between the mixing ratios indicate no significant difference.)

Water holding capacity (WHC) of biochar and soil mixed samples

In the Type I group of sand:biochar mixture that did not contain fertilizer (Fig. 7a), the mean ± SD value of WHC of sandy soil (100S:0B, control) was 30.4 ± 1.43%. The averaged WHC of each of the three soil/biochar mixture samples (50S:50B, 30S:70B, and 10S:90B) were all significantly higher than the control and reached as high as 72.2 ± 2.65% for the 10S:90B group (Fig. 7a). However, none of the mixtures containing biochar were significantly different from each other. The Type II soil mixture that also contained fertilizer showed an overall lower WHC than Type I soil mixture by about 30% on average at all mixing ratios. This is likely because the fertilizer filled some of the pore spaces (interpores and intrapores) of the mixture samples. The mean ± SE values of WHC of the Type II 100S:0B group was 12.24 ± 2.23%, while the WHC increased to about 30% (50S:50B), 37 % (30S:70B), and 46 % (10S:90B). In this case, however, there was a statistically significant increase in WHC with each progressive increase in biochar proportion (Fig. 7b), which is in line with other studies done on the WHC of biochar (Basso *et al*. 2012; Liu *et al*. 2016; Fischer *et al*. 2019).

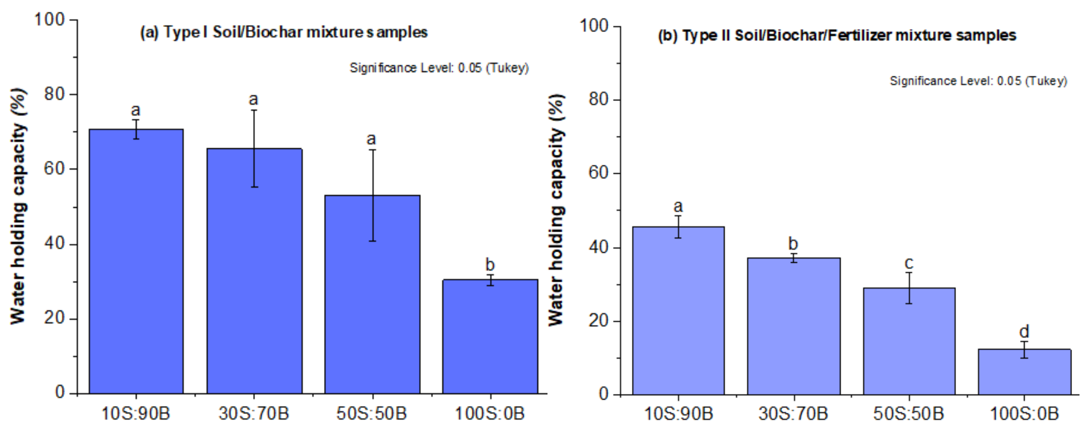


Fig. 7. Water holding capacity (WHC) of soil/biochar samples (a) and soil/biochar/fertilizer samples (b) fit with standard error bars (Note: The mean values of water holding capacity of Type I and Type II samples were plotted. An error bar was added to each column showing the standard derivation (SD) of results. Different letters on bars indicate statistical significance in a paired comparison analysis. Letters shared in common between the mixing ratios indicate no significant difference.)

Bulk density of biochar and soil mixed samples

Amending untreated biochar into sandy soils significantly reduced the bulk density of the soils for Type I and Type II samples from 1.15 ± 0.16 g cm^{-3} (100S:0B Type I, control) to 0.18 ± 0.03 g cm^{-3} (10S:90B Type I; Fig. 8a), and from 1.38 ± 0.10 g cm^{-3} (100S:0B Type II, control) to 0.34 ± 0.05 g cm^{-3} (10S:90B Type II; Fig. 8b). The density for Type II was slightly higher than that of Type I, which was likely because the ammonium sulfate fertilizer has a high density of 1.77 g cm^{-3}.

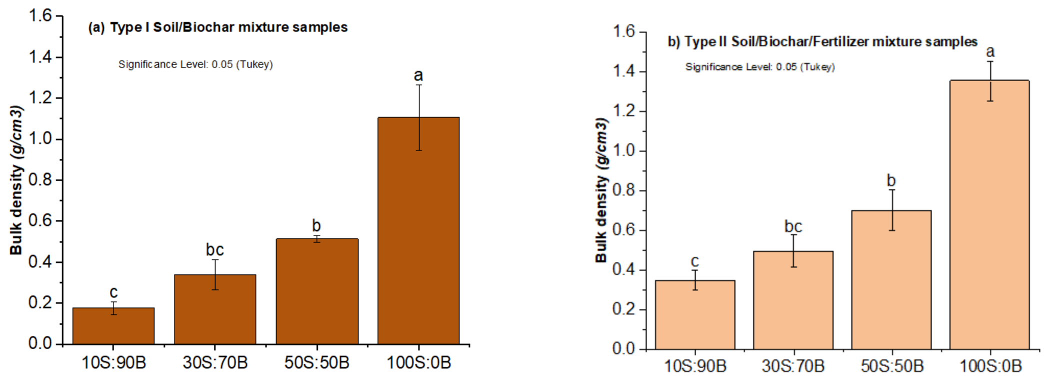


Fig. 8. Bulk density of soil/biochar mixture samples fit with standard error bars (a) and soil/biochar/fertilizer mixture samples (b). Ratios of soil/biochar include 10S:90B, 30S:70B, 50S:50B, and 100S:0B. (Note: The mean values of bulk density of Type I and Type II samples were plotted. An error bar was added to each column showing the standard derivation (SD) of results. Different letters on bars indicate statistical significance in a paired comparison analysis. Letters shared in common between the mixing ratios indicate no significant difference.)

The decline in bulk density of the mixed samples became more significant when more biochar and less sandy soils were mixed together, as biochar has a very low bulk density (0.08 gcm^{-3} in Table 1) due to the highly porous structure (Verheijen *et al*. 2019; Luo *et al*. 2020). When incorporating biochar into sandy soil, like wild blueberry fields, the bulk density will decrease with biochar, which could alter the soil amendment composition of the existing soils.

In this study, the characteristics of biochar sourced from a biomass combined heat and power (CHP) plant in Maine were studied to explore its feasibility of being used as a soil amendment for the sandy soils in wild blueberry fields. Future work will focus on a mid-term (3 to 5 years) biochar field study to study biochar as a cost-effective solution to help conserve water resources (irrigation and precipitation) at the regional scale, to prevent groundwater contamination by reducing the downward movement of agrichemicals and heavy metals, and to sustain crop productivity of wild blueberries.

CONCLUSIONS

1. The bulk density, moisture content, porosity, functional groups, pH, and ash content, showed comparable qualities with other biochar products made of similar feedstocks.
2. An even mixing ratio of soil and biochar (50S:50B) struck a balance that increased the beneficial properties of soils (increased water holding capacity, reduced bulk density). However, the beneficial effects of biochar on soil structural and water-holding properties were partly offset by the addition of fertilizer when using the sample preparation method (*i.e.*, soaking and crystallization) developed in this study.
3. Due to the similar effects of weak acid treatments, a 2% acetic acid solution could be used to decrease the pH of biochar to reduce the risk of increasing the alkalinity of the sandy soils amended with biochar, creating a favorable environment for wild blueberry plants but a hostile environment for weeds and other plants to survive. Overall, these

results suggested that waste biochar recycled from the CHP plant may become an applicable soil amendment to the wild blueberry fields.

4. After refining the operational feasibility of biochar applications in these settings, using pH-modified biochar in the sandy soils of wild blueberry fields could create a mutually sustainable solution to reduce the negative environmental impact of biochar waste in landfills and help wild blueberry plants combat drought.

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