



Use of Biochar Waste from a Biomass Combined Heat and Power Plant as Value-Added Products for Water Retention and Nutrient Management in Sandy Wild Blueberry Soils

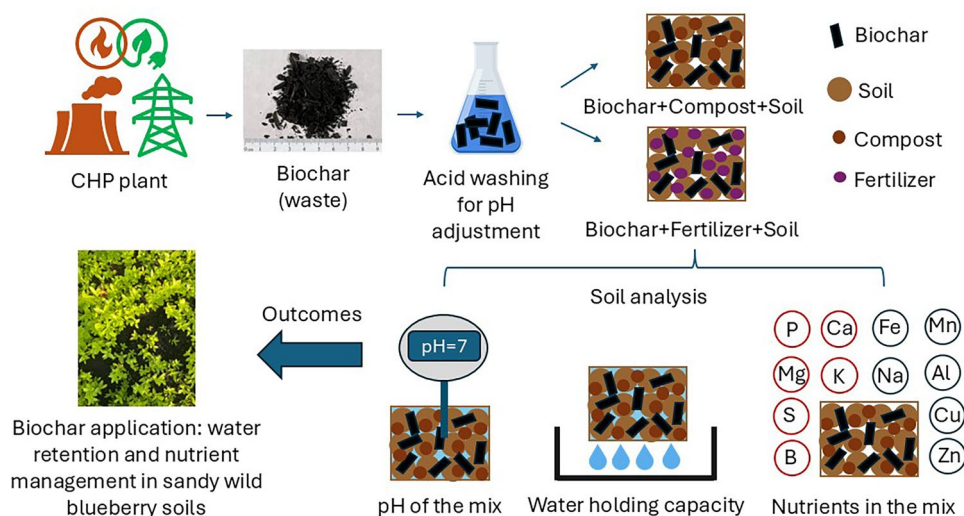
Rafa Tasnim¹ · Ling Li² · Abigail Novak² · Jinwu Wang³ · Yong-Jiang Zhang^{1,4}

Received: 19 November 2022 / Accepted: 13 February 2025 / Published online: 2 March 2025
 © The Author(s), under exclusive licence to Springer Nature B.V. 2025

Abstract

Agronomic benefits of applying biochar into soils, as a sustainable and environment-friendly soil amendment approach, have been well-documented for decades, known for improving soil water and nutrient retention capacity followed by better crop production. Still, research on the effects of certain locally sourced biochar waste and combined use with fertilizer and compost on agricultural lands with sandy soils is rather limited. Therefore, our study attempted to explore the effects of locally produced biochar waste amended with compost and fertilizer on the water retention, pH, and nutrients of the sandy wild blueberry soil in Maine. We found that the studied biochar (either mixed with compost or fertilizer) effectively improved the water holding capacity (WHC) of the sandy wild blueberry field soil, with 15% and 20% application (biochar mix % in soil by weight) showing the highest effect. On the other hand, the studied alkaline biochar caused a significant increase in the soil pH up to 7–8, which would not be favorable for wild blueberry plants naturally growing in acidic soil (pH: 4–5). While our study also attempted to lower the soil pH by treating the studied alkaline biochar with mild acid, it did not lower the soil pH below 7. Our study further revealed that the 50–50 ratio for the biochar-compost/fertilizer mix application could be the most beneficial for the wild blueberry soil. This ratio could enhance WHC significantly while providing the most useful nutrient elements (P, K, Ca, B) for the wild blueberry plants, and keeping the heavy metals (Al, Fe) in check.

Graphical Abstract



Keywords Biochar · New England USA · Soil water holding capacity · Soil pH · Nutrient retention · Maine

Statement of Novelty

This study presents the promising usage of a sustainable and environmental-friendly locally sourced and produced biochar that is currently deemed a waste of bioenergy production in a forest biomass-fueled combined heat and power (CHP) plant as a soil amendment for the commercially important wild blueberry crop in Maine, USA. We also revealed the best biochar-compost/fertilizer mix ratio for wild blueberry soils.

Introduction

Biochar is a charcoal-like material, which can be derived from a variety of organic materials (i.e., biomass), such as forest and agricultural residuals, wood processing residuals, manure, and municipal solid waste, through different thermal conversion processes of pyrolysis, gasification, and incomplete combustion [1–6]. In general, biochar has a highly porous structure, a relatively large surface area, a low bulk density, a wide range of pH (5–12), and abundant mineral elements. These characteristics can aid in its potential as a successful soil amendment to modify the soil texture and properties, increasing water retention and soil moisture content, organic carbon content, nutrients, correction of soil acidification, and immobilization of heavy metals [7–12]. However, the effects of biochar additions on the improvement of soil properties are greatly dependent on soil types, crop types, biochar characteristics, and application methods. For instance, the effects of a high rate (> 10 t/ha) of biochar (particle size > 1 mm) application on the improvement of water retention of coarse-grained soil are significantly greater than other soil types, such as silty clay loam soil [13]. It was reported that the field capacity and plant available water content of sandy soils mixed with biochar particles of medium size (0.85–2 mm) and coarse size (over 2 mm) are greater by 25–35% than the sandy soils mixed with fine biochar particles (0.25–0.85 mm) [14]. In terms of using biochar of different pH levels, alkaline biochar can reduce soil acidification, favored by plants and vegetables preferring a neutral or alkaline soil environment. However, it might disrupt the growth of plants growing in acidic soils, such as wild blueberries, because of the increased competition of weeds in neutral or alkaline soil environments [15]. Therefore, applying any particular biochar in soils needs to be carefully identified based on the targeted soil type and plant species.

On another note, biochar is a material of low bulk density (< 0.6 g/cm³), which implies that cost-effective biochar should come from locally available sources. In Maine and other New England states of the USA, biochar could be obtained from industrial-scale combined heat and power

(CHP) plants, which combust forest and wood processing residuals to generate heat, steam, and electricity for wood products manufacturing and neighboring communities. In the biomass furnace of a CHP unit, biochar mixed with ash is yielded as a byproduct by burning biomass feedstocks under a lean air-to-fuel ratio (i.e., insufficient air supply). For instance, a CHP plant with an annual electricity generation capacity of 7.5 MWe can consume about 100,000 tons of forest biomass and yield approximately 5000 tons of biochar yearly. In addition, auxiliary pyrolysis units can be added to CHP units to utilize thermal energy to produce biochar [16]. Moreover, when local forest resources are accessible, sustainable, and cheap, forest biomass (i.e., residuals of bark, leaves, and branches) and wood processing residuals (i.e., sawdust, wood shavings, and wood chips) can be used to produce cost-effective biochar for large-scale agricultural applications. For instance, biochar produced from local forest and wood processing residuals in Maine could be useful for local commercially important crops such as wild lowbush blueberries.

Wild blueberries naturally grow in sandy soils, usually with low water-holding capacity (WHC). Wild blueberry plants are regarded as drought-resistant plants [17, 18], but their yield is rather sensitive to drought, and the yield of any particular year is greatly influenced by the water conditions of the past four years [19]. Therefore, irrigation could be an effective way to maintain sufficient water availability in soils and to improve wild blueberry production [20]. However, only about 30% of the wild blueberry fields of Maine are irrigated, while the rest relies on rainfall [20]. While annual rainfall is predicted to increase in the New England region of the USA, rainfall in the summer is decreasing, and more rainfall anomalies are predicted [21, 22]. Furthermore, climate warming will also increase crop and soil water loss and reduce soil moisture content, consequently reducing soil nutrient availability [23]. Thus, new techniques of water and nutrient management are of importance for the wild blueberry industry in Maine. For instance, biochar enhancing soil water and nutrient retention for other crops such as rice and maize [24, 25] could be a feasible and affordable solution for wild blueberry farmers to mitigate climate change impacts as locally produced biochar is available.

It has been well documented that biochar could provide a sustainable solution to mitigate the impact of climate disturbances, and thus could potentially secure wild blueberry production under climate change. However, research regarding the applications of locally sourced and produced biochar in sandy wild blueberry soils is still limited. Research is needed to test its applicability on the sandy wild blueberry soil by conducting laboratory, greenhouse, and field tests at large temporal and spatial scales before establishing biochar application guidelines

for the end users. Therefore, the overall goal of this study was to explore the applications of locally produced biochar (from a biomass CHP plant) amended with compost and fertilizer in wild blueberry field soil for water and nutrient management. We hypothesized that the studied biochar-compost and biochar-fertilizer mixes would aid in improving the WHC and nutrient contents of wild blueberry soils. Specific objectives of this study were (1) to characterize physiochemical properties of the CHP biochar, (2) to quantify the effects of different application rates of the studied biochar-compost mix and biochar-fertilizer mix on the WHC of wild blueberry soils, (3) to investigate whether the studied biochar will change soil pH and whether pH treatment of biochar will be effective, and (4) to characterize how biochar-compost mix and biochar-fertilizer mix will change soil nutrient availability.

Materials and Methods

Materials

The biochar used was from a local CHP plant located in the central area of Maine, USA, which is a byproduct of heat and power generation and doesn't have a market value. The biomass was collected from the nearby sawmills, wood products manufacturing plants, and their forest lands. The biomass included a variety of feedstocks, including bark, treetops, branches, sawdust, shavings, and chips. The biochar was produced at a high temperature of approximately 800 °C in the biomass grate furnace of the CHP unit due to incomplete combustion [26, 27]. The mix of dry biochar and fly ash was collected from the electrostatic precipitator (ESP) system in the CHP plant. In the Bioenergy Laboratory at the School of Forest Resources, the biochar was separated from the mix using a laboratory sifting machine (Gilson Testing Screen, Model TM-3, Gilson Company, Inc., Worthington, Ohio, USA). Fine biochar powder and ash passed through the 425- μ m sieve were not used. The estimated ratio of biochar and ash was about 4:6 by volume.

Soil samples were collected from six different genotype sites at the Blueberry Hill Farm in Jonesboro, Maine, USA. The samples were collected up to 15 cm (6 inches) depth from the soil surface with a soil sampler and were mixed thoroughly to minimize the variance caused by the soil texture at different depths. Those soil samples from different genotypes far from each other were studied to consider significant spatial variations in their soil characteristics, and hence, the six soil samples were considered as six replicates. The samples were sent to the Analytical Soil Testing Lab at the University of Maine to test the soil type, pH, and nutrients, which were used as a control in this study. The

soil type of the six samples was sandy loam, consisting of $66 \pm 1.9\%$ sand, $24.4 \pm 1.5\%$ silt, and $9.6 \pm 0.5\%$ clay.

The compost was provided by the University of Maine composting facility, which was composted using local food waste. The compost was air-dried before weighing and mixing with biochar for testing. Air-dried compost samples were also used for nutrient analysis using the methods described in the following subsection of 2.2.4. The nutrient elements included phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), boron (B), sulfur (S), aluminum (Al), copper (Cu), iron (Fe), manganese (Mn), sodium (Na), and zinc (Zn).

Ammonium sulfate $[(\text{NH}_4)_2\text{SO}_4]$ and potassium sulfate $[\text{K}_2\text{SO}_4]$ were purchased from a local store. These two granular chemicals were mixed at a 1:1 ratio by weight as a fertilizer.

Methods

Biochar Characterization

The basic properties of biochar, including morphology, moisture content, bulk density, porosity, pore size and distribution, surface area, surface functional groups, pH, and ash content, were measured and reported in a previous study [27]. The testing methods are briefly described as follows. The morphology of biochar was observed using a Scanning Electron Microscope (SEM) (AMRay 18,201,820; Amray scanning electron microscopes, Bedford, ME, USA). Biochar moisture content was measured using a moisture balance (Ohaus MB23, Hogentogler & Co. Inc, Columbia, MD, USA). The bulk density of biochar particles on a dry basis was measured following ASTM E873-82(2019) Standard Test Method for Bulk Density of Densified Particulate Biomass Fuels [28]. The surface area of biochar was measured using a N_2 gas adsorption by a Brunauer–Emmett–Teller (BET) surface analyzer (model: Micromeritics ASAP 2020, Micromeritics Instrument Corporation, Norcross, GA, USA). The ash content of oven-dried biochar (untreated and acid-treated) particles was measured using a thermogravimetric analysis (TGA) instrument (LECO 701, St. Joseph, MI, USA), following ASTM E1755-01(2020): Standard Test Method for Ash in Biomass [29]. The results were reported on a dry basis. The pH of biochar (untreated and acid-treated) slurry (biochar: deionized water = 1:20 by weight) was measured using a pH meter (Hanna Instruments, Smithfield, RI, USA).

In addition, organic elemental CNHO analysis of oven-dried, untreated biochar was conducted to determine the percentage of carbon (C), nitrogen (N), hydrogen (H), and oxygen (O) by weight using a CHNS/O analyzers (FLASH 2000, Thermo Fisher Scientific, Waltham, MA USA). The inorganic elements (P, K, Ca, Mg, B, S, Al, Cu, Fe, Mn,

Table 1 Experimental design of soil water holding capacity test (water percolation method)

Materials	Mixing ratio of Biochar (B) + Compost (C) & Biochar (B) + Fertilizer (F) (by weight)	Mixing rate (%) with soil (by weight)	Number of tests
Wild blueberry field soil	No soil amendment added (control)		6
Soil + Untreated biochar + Compost	50% B + 50% C	5%, 10%, 15%, 20%	24
	70% B + 30% C		24
Soil + Treated biochar + Compost	50% B + 50% C	5%, 10%, 15%, 20%	24
	70% B + 30% C		24
Soil + Untreated biochar + Fertilizer	50% B + 50% F	5%, 10%, 15%, 20%	24
	70% B + 30% F		24
Soil + Treated biochar + Fertilizer	50% B + 50% F	5%, 10%, 15%, 20%	24
	70% B + 30% F		24

Na, and Zn) analysis of oven-dried, untreated biochar was conducted using the same methods for testing compost and soils. The results were reported as milligram per kilogram on a dry basis.

Biochar pH Treatment

An acid treatment method was used to modify the alkaline nature of the biochar acquired from the CHP plant. A 2% acetic acid solution was used in this study [26]. Bulk biochar was washed three times and then soaked in the 2% acetic acid solution for 5 min. During this time, the biochar slurry was mechanically stirred. After this treatment, the biochar was washed with water 5–10 times until the pH reached 7.

Soil WHC Test: Water Percolation Method

The soil, biochar, compost, and fertilizer were air-dried before weighing, mixing, and testing. The experimental design for the WHC test is detailed in Table 1. Six replicates of the wild blueberry field soil were tested with a biochar-compost mix and biochar-fertilizer mix of two different ratios by weight (50% biochar + 50% compost/fertilizer and

70% biochar + 30% compost/fertilizer). Then the biochar-compost mix, and the biochar-fertilizer mix were added to the soil at 0%, 5%, 10%, 15%, and 20% w/w ratios (based on the soil weight). Both treated biochar and untreated biochar were used in separate tests. The WHC of those samples was tested using a simple water-percolation method [30]. In this method, we used Whatman Grade 1 Qualitative filter paper on a funnel and kept it vertically straight on a measuring cylinder. Then we put the soil and soil mixes with the amendments (biochar-compost mix) on the funnel lined with filter paper and then we poured 50 ml of water on the samples slowly and uniformly. For each of the tests, we used 35 gm of soil and 50 ml of water where only the addition of the amendments (biochar-compost mix and biochar-fertilizer mix) varied based on the studied percentages of soil (5, 10, 15 and 20% by weight). 50 ml of water was determined by conducting a preliminary test which ensured that there was still free water collected from the measuring cylinder when the maximum rate (20%) of soil amendments was added to the soil samples. For each of the tests, the initial water amount that was poured on the sample was H_2O_i (50 ml), and the amount of water percolated through those samples into the measuring cylinder after 8 min (when water pouring

Table 2 Experimental design of soil pH and nutrient testing

Materials	Mixing ratio of Biochar (B) + Compost (C) & Biochar (B) + Fertilizer (F) (by weight)	Mixing rate (%) with soil (by weight)	Number of tests
Wild blueberry field soil	No soil amendment added (control)		6
Soil + Untreated biochar + Compost	50% B + 50% C	20%	6
	70% B + 30% C		6
Soil + Treated biochar + Compost	50% B + 50% C	20%	6
	70% B + 30% C		6
Soil + Untreated biochar + Fertilizer	50% B + 50% F	20%	6
	70% B + 30% F		6
Soil + Treated biochar + Fertilizer	50% B + 50% F	20%	6
	70% B + 30% F		6

started) was H_2O_p . The WHC was calculated using Eq. (1). Six replicates for each combination in Table 1 were tested. Based on those six replicates, the mean and standard error (SE) were used for visual representations of the soil WHC.

$$WHC, \% = \frac{(H_2O_i - H_2O_p)}{H_2O_i} \times 100\% \quad (1)$$

Soil pH and Nutrient Testing

The experimental design for the soil pH and nutrient testing is detailed in Table 2. For soil pH and nutrient testing, wild blueberry field soil samples (as control), soil samples mixed with 20% biochar-compost mix, and 20%

biochar-fertilizer mix at two mixing ratios of 50–50 and 70–30 by weight were prepared and tested. Both treated biochar and untreated biochar were used in separate tests. Six replicates for each combination in Table 2 were tested at the Analytical Soil Testing Lab at the University of Maine, Orono, ME, USA. Before the testing, the samples were ground so that any large biochar particles could pass through the 2-mm sieve for the soil pH and nutrient testing. In the lab, those samples were first air-dried and sieved through a 2-mm sieve. Soil pH was measured using a pH meter with electrodes inserted in the soil slurry, where a dry soil sample was mixed with distilled water. Further, the nutrients of those soil samples were extracted in pH 4.8 ammonium acetate (modified Morgan solution). Phosphorus (P) was determined colorimetrically by Flow Injection Analysis. All other nutrient elements were measured by the inductively coupled plasma – optical emission spectrometry (ICP-OES) technique (Thermo-Fisher model iCAP 6300 radial view ICP-OES, Waltham, MA, USA). After the measurements, major nutrients of P, K, Ca, and Mg were reported as pounds per acre in dry soil because they are generally needed in larger amounts in the soil. Secondary and micronutrients of B, S, Al, Cu, Fe, Mn, Na, and Zn were reported as milligrams per kilogram (parts per million) in dry soil.

Statistical Analysis

JMP Pro 16.2 software was used to conduct the statistical analysis and to prepare the visual representations of the data in this study. A full factorial two-way analysis of variance (ANOVA) test was performed to determine the effects of adding soil amendments on the pH and nutrient levels of the wild blueberry field soil. Here, main effects and interaction



Fig. 1 Particles of the biochar used in the present study after separating from ash. (Biochar source: a local biomass combined heat and power plant in the central area of Maine, USA)

Table 3 Physical properties of the biochar samples used in the present study [26]. (Biochar source: a local biomass combined heat and power plant in the central area of Maine, USA)

Property	Method	Results ⁽¹⁾	Note
Moisture Content	Moisture Analyzer	7–8.5% ⁽²⁾	Untreated biochar used
Porosity of biochar particle	MIP	30–60%	
Median pore diameter		14.5–17.5 μm	
Bulk density, dry	ASTM E873	0.08–0.09 gcm^{-3} ⁽³⁾	
Total surface area	BET	300–400 m^2g^{-1}	
pH of biochar	pH meter	11.3–11.5	Untreated
		6.5–7.5	Treated
Ash content of biochar	TGA	13–20% ⁽⁴⁾	Untreated, oven-dried
		2–3%	Treated, oven-dried

⁽¹⁾ The results were given based on three or six replicates of biochar

⁽²⁾ The moisture content of biochar was tested after the biochar was placed in the ambient environment in the laboratory for one month

⁽³⁾ The bulk density of biochar was tested using oven-dried biochar

⁽⁴⁾ The ash content of oven-dried biochar particles was attributed to the ash bonded on the surface of the biochar pores and loose ash fines

effects were considered using both the ratios of soil amendments used (control, 50–50 biochar-compost/fertilizer, and 70–30 biochar-compost/fertilizer) and types of biochar (treated and untreated biochar).

Results

Biochar Properties

Biochar exhibited a mix of particle sizes (Fig. 1), ranging from medium (0.25–0.85 mm), coarse (0.85–2.00 mm), and very coarse (> 2.00 mm), which were categorized based on a previous study [31]. In our study, we did not reduce the size of the very coarse biochar. Nevertheless, it is evident that fine biochar has a significant impact on increasing the water holding capacity and bulk density of the soil and biochar

mixture compared to coarse biochar. This is primarily due to the differences in how they alter particle packing and tortuosity [32]. The bulk density of biochar on a dry basis varied from 0.08 to 0.09 g cm⁻³ (Table 3). Biochar moisture content was between 7 and 8.5% (Table 3) after being exposed to the ambient environment for about one month. Biochar SEM images revealed that the biochar retained the intrinsic structure of xylem (Fig. 2a) and bark (Fig. 2b) and ash agglomerations in biochar (Fig. 2c).

The porosity of biochar ranged from 30 to 60%, with the median pore diameter of the biochar between 14.50 µm and 17.50 µm (Table 3). The total surface area of the two samples ranged from 300 to 400 m²/g (Table 3). The pH of untreated biochar was over 11, while the pH of treated biochar ranged from 6.5 to 7.5 (Table 3). The ash content of untreated biochar and treated biochar was approximately 13–20% and 2–3%, respectively (Table 3). The high ash content of the

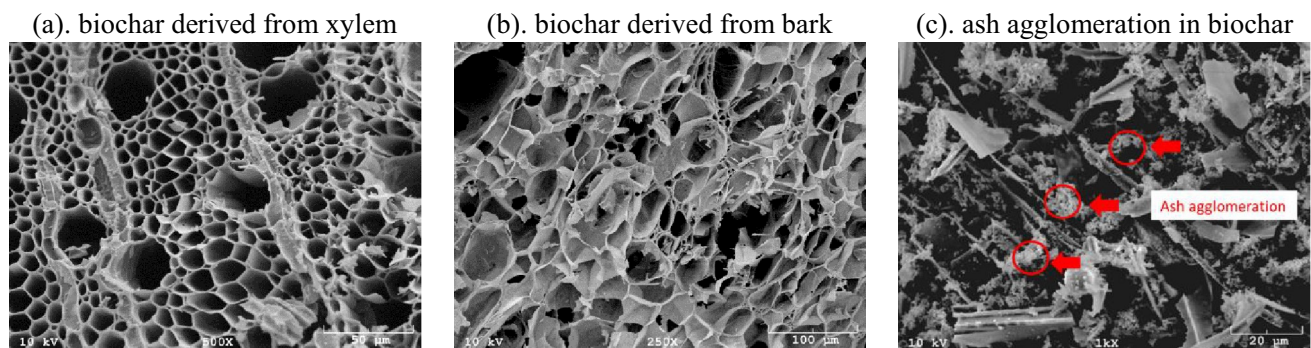


Fig. 2 SEM images of the biochar samples used in the present study after separating from ash. (Biochar source: a local biomass combined heat and power plant in the central area of Maine, USA; Source of images: [26])

Table 4 CHNO results of oven-dried, untreated biochar samples on a dry basis. (Biochar source: a local biomass combined heat and power plant in the central area of Maine, USA)

Organic elements	C	H	O	N	Ash ⁽²⁾
Mean ± SE, % by weight ⁽¹⁾	86.2% ± 1.78%	0.8% ± 0.03%	6.4% ± 0.11%	0.3% ± 0.03%	6.26% ± 1.88

⁽¹⁾ The results were given based on three replicates

⁽²⁾ The ash content represented the individual biochar particles for CHNO analysis, which is listed in Table 4 as a reference

Table 5 Inorganic elemental analysis results of oven-dried, untreated biochar on a dry basis. (Biochar source: a local biomass combined heat and power plant in the central area of Maine, USA)

Inorganic elements	Ca	K	Mg	P				
Mean ± SE, mg/kg ^(1,2)	20,454 ± 3,578	18,708 ± 1,828	1,408 ± 226	532 ± 59				
Inorganic elements	Na	Zn	Al	B	Fe	Cu	S	Mn
Mean ± SE, mg/kg ^(1,2)	268 ± 29	103 ± 27	39 ± 6	30 ± 1.8	7.9 ± 3.1	1.4 ± 0.7	2,135 ± 506	506 ± 28

⁽¹⁾ The results were given based on three replicates

⁽²⁾ mg/kg = mass of each element in mg per 1 kg of oven-dried biochar

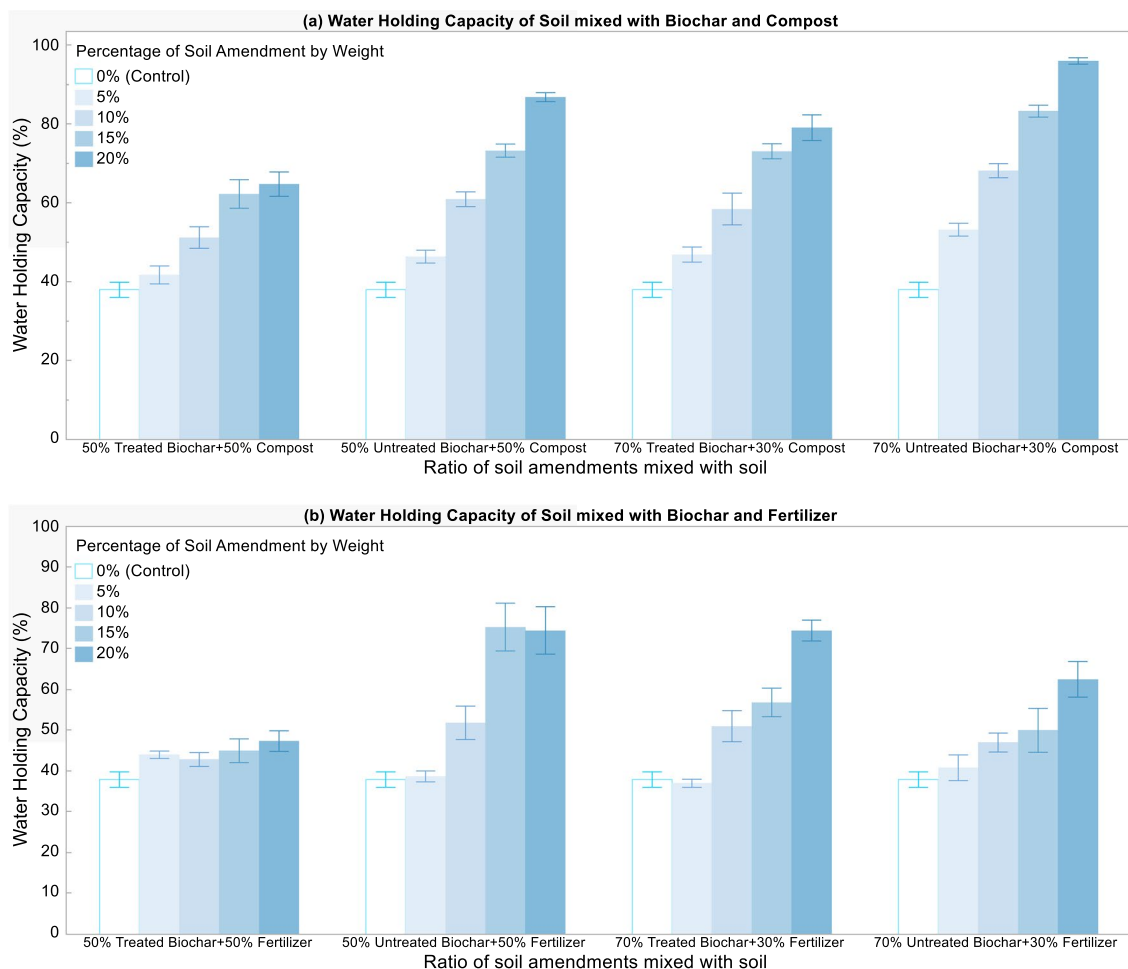


Fig. 3 Water Holding Capacity (WHC) of wild blueberry field soil mixed with different types of soil amendments: **(a)** Treated and untreated biochar mixed with compost at two different ratios, and **(b)** Treated and untreated biochar mixed with fertilizer at two different

ratios. Here, bars of 0–20% represent the percentages of soil amendments added to the soil by weight where 0% means no soil amendments were added to the soil (presented as Control)

untreated biochar samples may be attributed to the presence of ash bonded on the surface of biochar pores and loose ash fines. For the CHNO analysis, individual biochar particles were selected and ground for the testing. The considerable variation of ash content results may be due to the variety of biomass feedstocks, including bark, sawdust, treetops, shavings, and chips. The C content of the biochar was as high as 86% by weight, while the H, O, and N content were 0.8%, 6.4%, and 0.3% by weight, respectively (Table 4). The biochar samples used for CHNO analysis had an average ash content of approximately 6.26%, which was used as a reference. Additionally, biochar exhibited very high concentrations of Ca (20,454 mg/kg) and K (18,708 mg/kg), but extremely low concentrations of Al (39 mg/kg), B (30 mg/kg), Fe (7.9 mg/kg), and Cu (1.4 mg/kg) (Table 5).

Biochar Effects on Soil WHC

Water holding capacity (WHC) of the wild blueberry field soil (Control) was ~35–40% when no soil amendments were added to the soil (Fig. 3). After adding 5–20% biochar-compost mix to the field soil, the soil WHC was gradually increasing from 40 to 98% (Fig. 3a). In fact, the soil WHC was ~50–98% when 70% biochar was used in the biochar-compost mix compared to the ~45–85% WHC when 50% biochar was used in the biochar-compost mix. Also, the WHC was lower (~38–70% in 50–50 biochar-compost mix and ~45–85% in 70–30 biochar-compost mix) when treated biochar was used compared to the untreated biochar (WHC: ~45–88% in 50–50 biochar-compost mix and ~52–98% in 70–30 biochar-compost mix) (Fig. 3a).

Similarly, WHC of the wild blueberry field soil improved when the biochar-fertilizer mix was added to the soil (Fig. 3b), which varied based on the application rates of the

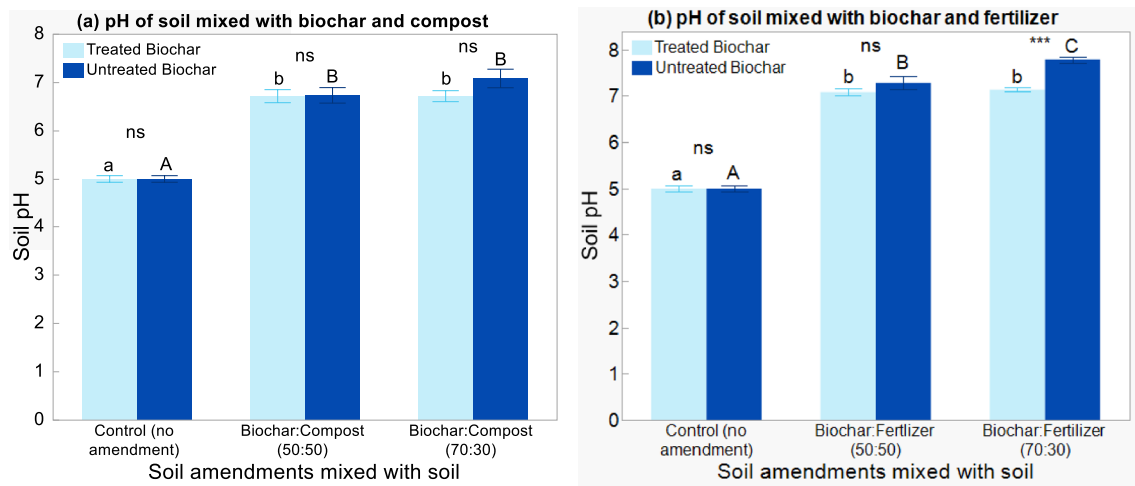


Fig. 4 pH of wild blueberry field soil mixed with soil amendments (20% of soil weight): (a) Treated and untreated biochar mixed with compost at two different ratios, and (b) Treated and untreated biochar mixed with fertilizer at two different ratios. Here, small letters and

capital letters on the bars represent significant differences among the treated biochar and the untreated biochar treatments, respectively at $p < 0.05^*$, $p < 0.01^{**}$, $p < 0.001^{***}$, $p < 0.0001^{****}$, and *ns* not significant

biochar-fertilizer mix. For instance, soil WHC was gradually increased from ~42 to 50% and ~40–82% after adding 5–20% treated and untreated biochar-fertilizer (50–50) mix. Interestingly, the soil WHC range was higher (40–82%) when untreated biochar-fertilizer was added in the same ratio (50–50) compared to that for other ratios. Soil WHC was higher when more treated biochar was used in the soil, for example, soil WHC was 40–80% in the 70–30 treated biochar-fertilizer mix compared to the 42–50% soil WHC in the 50–50 treated biochar-fertilizer mix. On the contrary, soil WHC was lower (40–67% in 70–30 biochar-fertilizer mix) when 70% untreated biochar was used compared to the WHC (40–82% in 50–50 biochar-fertilizer mix) when 50% untreated biochar was used (Fig. 3b).

Biochar Effects on Soil pH

The pH of the wild blueberry field soil (Control) was ~4.9–5.1 when no soil amendments were added to this soil (Fig. 4). The soil pH increased significantly up to 6.5–7.4 after adding 20% biochar-compost mix to the soil regardless of the use of treated or untreated biochar (Fig. 4a). The soil pH did not differ significantly between the 50–50% and 70–30% use of biochar-compost mix with the soil (Fig. 4a).

The soil pH increased significantly up to 6.9–7.8 after adding 20% biochar-fertilizer mix regardless of the use of treated or untreated biochar (Fig. 4b). On average, soil pH was slightly higher (not significant) in the 50–50 untreated biochar-fertilizer mix compared to the pH in the 50–50 treated biochar-fertilizer mix. In contrast, soil pH was significantly higher in the 70–30 untreated biochar-fertilizer

mix compared to the 50–50 treated and untreated biochar-fertilizer mix as well as compared to the 70–30 treated biochar-fertilizer mix.

Effects of Biochar-Compost Mix on Soil Nutrients

The concentrations of macro-nutrients (P, K, Ca, Mg, B and S in Fig. 5) were found to be significantly higher in the wild blueberry field soil when mixed with biochar-compost mix compared to the soil with no amendment (Control; Fig. 5). Comparing between the use of 50–50 biochar-compost mix and 70–30 biochar-compost mix, the average concentration of those macro-nutrients was slightly lower (not significant) in the soil mixed with 70–30 treated biochar-compost mix. On the contrary, the average concentration of those macro-nutrients was slightly higher (not significant) in the soil mixed with 70–30 untreated biochar-compost mix. Interestingly, among those macro-nutrients, the amount of K and S (Fig. 5b,f) was significantly higher in the soil mixed with untreated biochar than in the soil with treated biochar.

The trends observed in the concentration of micro-nutrients (Al, Cu, Fe, Mn, Na, and Zn in Fig. 6) were different in contrast to the trends found in macro-nutrients (Fig. 5). Concentrations of Al and Fe (Fig. 6a,c) were significantly lower in the soil mixed with biochar-compost compared to the soil with no amendment (control) regardless of the use of treated or untreated biochar and different biochar-compost mix ratios. In contrast, the concentrations of Cu and Zn (Fig. 6b,f) were similar in both soil samples without and with soil amendment (biochar-compost mix), except the concentration of Cu was significantly higher in the soil with untreated 70–30 biochar-compost mix. However, the

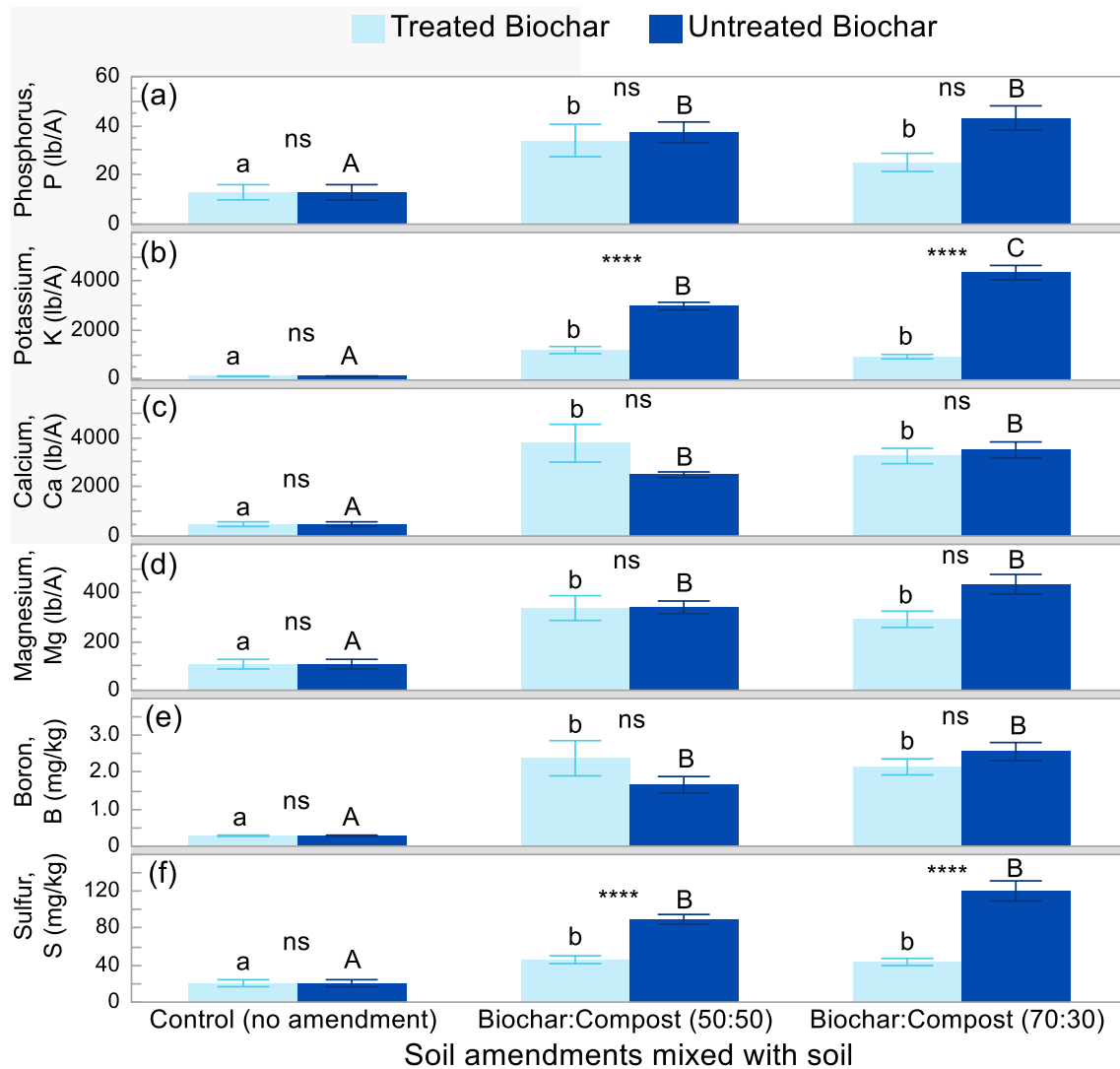


Fig. 5 Concentrations of available macro-nutrients (a) P, (b) K, (c) Ca, (d) Mg, (e) B, and (f) S in the wild blueberry field soil mixed with soil amendments (20% of soil weight): Treated and untreated biochar mixed with compost at two different ratios. Here, small letters

and capital letters on the bars represent significant differences among the treated biochar and the untreated biochar treatments, respectively at $p < 0.05^*$, $p < 0.01^{**}$, $p < 0.001^{***}$, $p < 0.0001^{****}$, and *ns* not significant

average concentration of Zn was slightly higher in the soil with untreated biochar than in treated biochar. The concentration of Mn (Fig. 6d) was significantly higher in the soil with treated biochar-compost mix compared to the soil with no amendment, whereas the concentration of Mn was lower (not significant) in the soil with 70–30 biochar-compost mix than with 50–50 biochar-compost mix. In contrast, the concentration of Mn was significantly higher in the soil with 70–30 biochar-compost mix than with 50–50 biochar-compost mix where biochar was untreated. The concentration of Na (Fig. 6e) was similar in both the soil without and with treated biochar-compost mix, whereas it was significantly higher in the soil with untreated biochar-compost mix than in the soil with no amendment. However, the concentration

of Na was significantly higher in the soil with untreated biochar than with treated biochar. When untreated biochar was used, the concentration of Na was significantly lower in the soil with a 70–30 biochar-compost mix than with a 50–50 biochar-compost mix.

Effects of Biochar-Fertilizer Mix on Soil Nutrients

The concentrations of macro-nutrients (P, K, Ca, Mg, B, and S in Fig. 7) were also significantly higher in the wild blueberry field soil when amended with biochar-fertilizer mix compared to the soil with no amendment (Control; Fig. 7). Comparing the use of 50–50 and 70–70 treated biochar-fertilizer mix, the concentration of K and Mg (Fig. 6b,d)

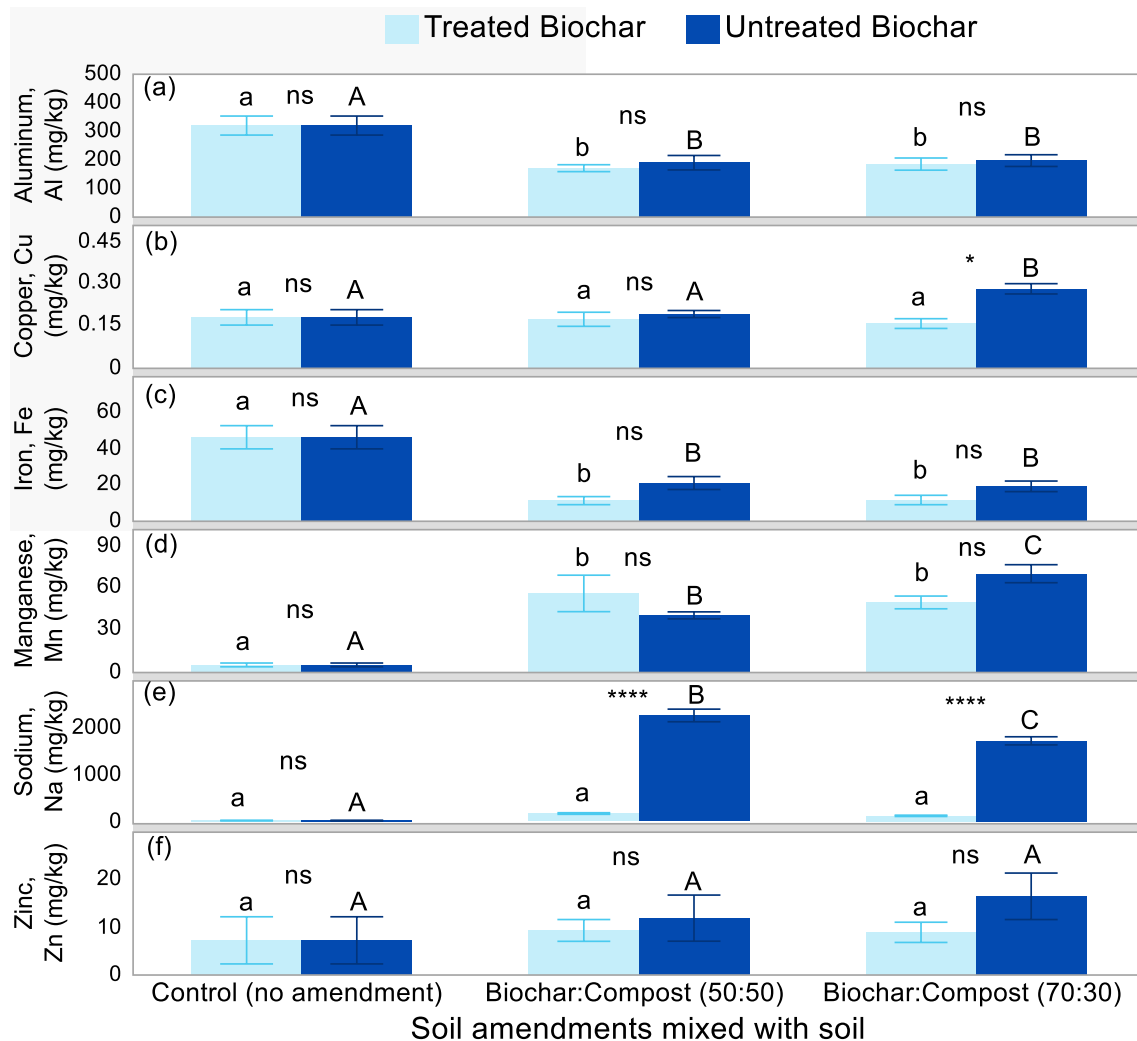


Fig. 6 Concentrations of different micro-nutrients (a) Al, (b) Cu, (c) Fe, (d) Mn, (e) Na, and (f) Zn in the wild blueberry field soil mixed with soil amendments (20% of soil weight): Treated and untreated biochar mixed with compost at two different ratios. Here, small letters

and capital letters on the bars represent significant differences among the treated biochar and the untreated biochar treatments, respectively at $p < 0.05^*$, $p < 0.01^{**}$, $p < 0.001^{***}$, $p < 0.0001^{****}$, and *ns* not significant

was similar in both treatments. In contrast, a significantly higher concentration of P, Ca, and B (Fig. 7a,c,e) and a significantly lower concentration of S (Fig. 7f) were found in the soil with 70–70 treated biochar-fertilizer mix. Comparing the use of 50–50 and 70–70 untreated biochar-fertilizer mix, the concentration of P, K, Mg, and S (Fig. 7a,b,d,f) was similar in both treatments. In contrast, the concentration of Ca and B (Fig. 7c,e) was significantly higher in the soil with 70–70 untreated biochar-fertilizer mix. Comparing the use of treated and untreated biochar, the concentration of K and S (Fig. 7b,f) was similar in both treatments. In contrast, a significantly lower concentration of P, Ca, Mg, and B (Fig. 7a,c,d,e) was found in the 50–50 and 70–30 untreated biochar-fertilizer mix.

The trends observed in the concentrations of micro-nutrients (Al, Cu, Fe, Mn, Na, and Zn in Fig. 8) were different

compared to the trends found in the macro-nutrients (Fig. 7). The concentration of Al and Fe (Fig. 8a,c) was significantly lower in the soil with biochar-fertilizer mix compared to the soil with no amendment regardless of the use of treated or untreated biochar and different biochar-fertilizer mix ratios. In contrast, the concentration of Cu, Mn, Na, and Zn (Fig. 8b,d,e,f) was significantly higher in the soil with biochar-fertilizer mix compared to the soil with no amendment. Especially, the concentration of Cu, Mn, and Zn (Fig. 8b,d,f) was significantly higher in the soil with treated and untreated 70–30 biochar-fertilizer mix compared to the soil with treated and untreated 50–50 biochar-fertilizer mix, respectively. Moreover, the concentration of Cu, Mn, and Zn (Fig. 8b,d,f) was significantly lower in the soil with untreated biochar than with treated biochar, whereas the

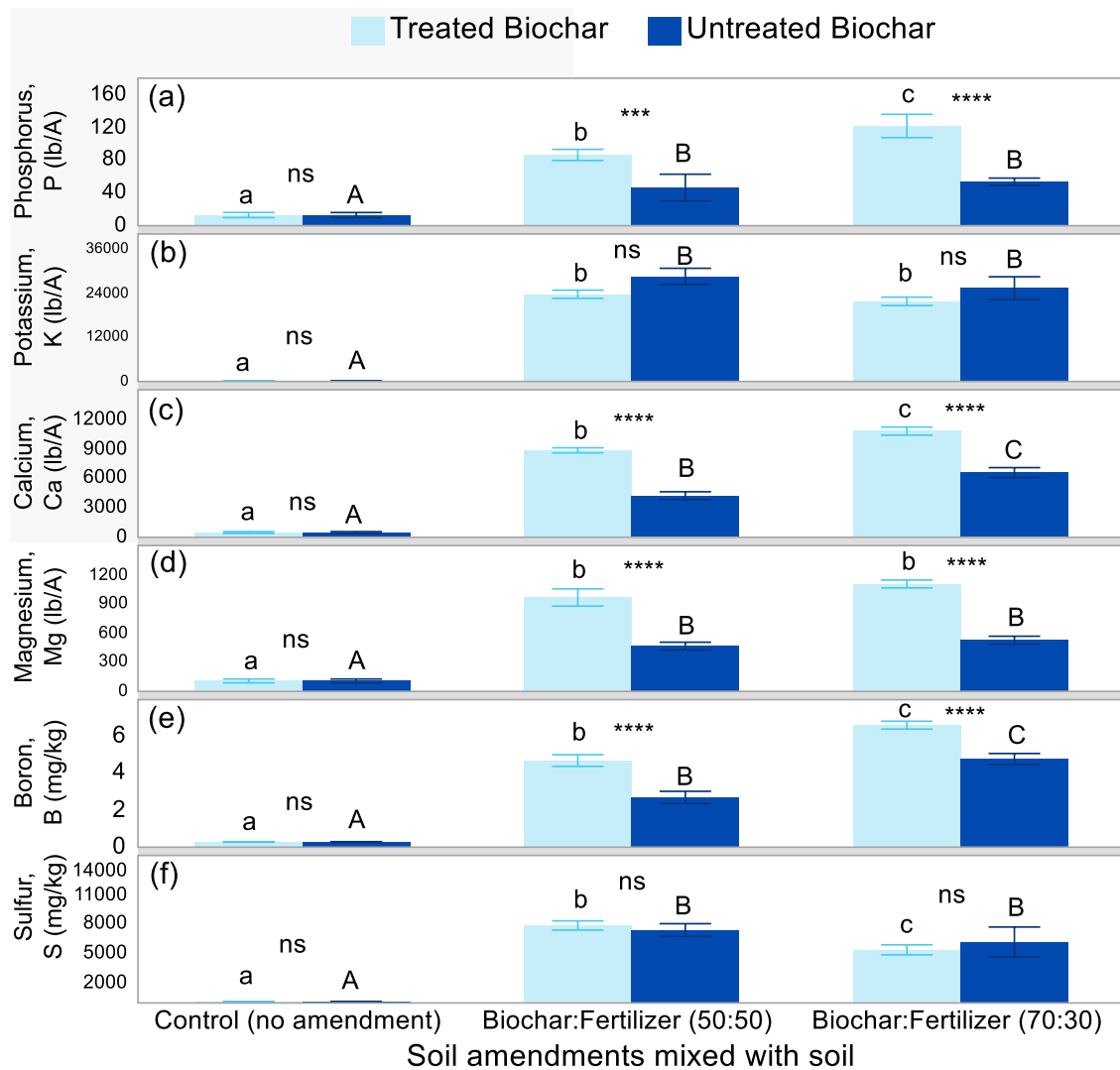


Fig. 7 Concentrations of macro-nutrients (a) P, (b) K, (c) Ca, (d) Mg, (e) B, and (f) S in the wild blueberry field soil mixed with soil amendments (20% of soil weight): Treated and untreated biochar mixed with fertilizer at two different ratios. Here, small letters and

capital letters on the bars represent significant differences among the treated biochar and the untreated biochar treatments, respectively at $p < 0.05^*$, $p < 0.01^{**}$, $p < 0.001^{***}$, $p < 0.0001^{****}$, and *ns* not significant

concentration of Al, Fe, and Na (Fig. 8a,c,e) was similar in the soil with treated and untreated biochar.

Discussion

Our study revealed that amending biochar into the sandy loam soil was an effective approach to increase the water holding capacity (WHC) of sandy wild blueberry field soil regardless of the addition of compost or fertilizer with the untreated or treated biochar. Soil WHC has been observed to be getting higher with the addition of a higher amount of biochar. Additionally, soil WHC was not significantly affected by the pH treatment of biochar when compost or

fertilizer was added to both treated and untreated biochar. The addition of 20% biochar-compost and biochar-fertilizer significantly increased the pH of wild blueberry field soil up to 7–8, regardless of the mixing ratios of 50–50 or 70–30. While improved WHC of the soil would have a significantly positive impact on the wild blueberries, higher soil pH might not be favorable for them in competing with weeds. We also found that a 50–50 biochar-compost/fertilizer mix would be an advantageous ratio to use with wild blueberry field soil for providing the important nutrient elements to the plants as well as keeping the heavy metals of the soil in check. Our study is the first to assess a locally sourced, sustainable, and environment-friendly soil amendment like biochar to improve the WHC of wild blueberry field soil while

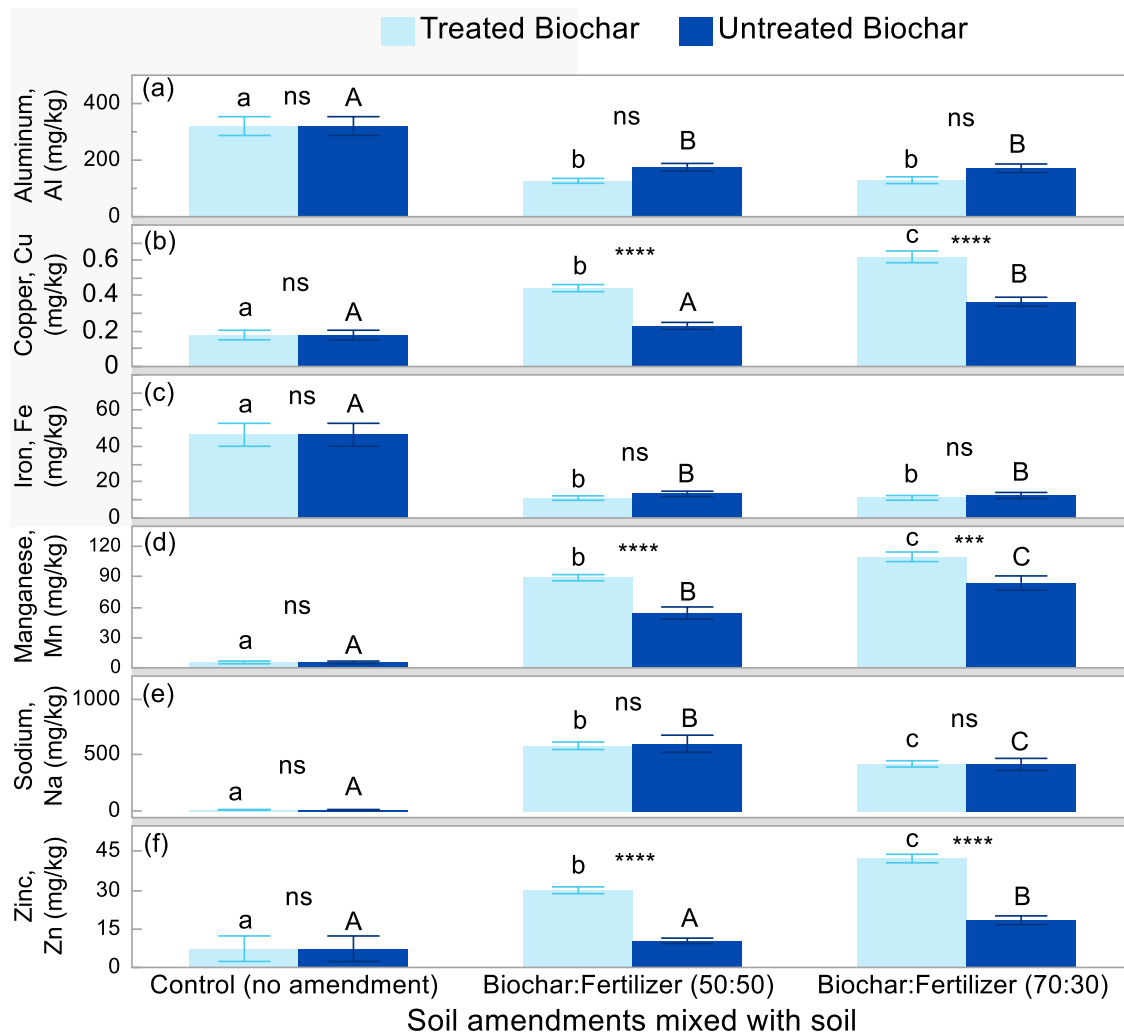


Fig. 8 Concentrations of micro-nutrients (a) Al, (b) Cu, (c) Fe, (d) Mn, (e) Na, and (f) Zn in the wild blueberry field soil mixed with soil amendments (20% of soil weight): Treated and untreated biochar mixed with fertilizer at two different ratios. Here, small letters and

capital letters on the bars represent significant differences among the treated biochar and the untreated biochar treatments, respectively at $p < 0.05^*$, $p < 0.01^{**}$, $p < 0.001^{***}$, $p < 0.0001^{****}$, and ns not significant

maintaining other soil characteristics like pH and nutrient availability for the betterment of wild lowbush blueberries in Maine, USA.

Effects of Biomass Feedstocks and Manufacturing Process on Biochar Properties

The biomass feedstocks used for generating bioenergy and biochar in the CHP plant were a mix of forest logging residues and wood processing residues, including bark, wood shavings, chips, and tree branches from a mixture of hardwood and softwood species. As a result, a large variation in all the measured properties was observed [33, 34].

As listed in Table 3, the very low bulk density of oven-dried biochar ($0.08\text{--}0.09\text{ g cm}^{-3}$) may be attributed to

factors such as the use of low-density feedstocks, high pyrolysis temperature ($\geq 600\text{ }^{\circ}\text{C}$). The porosity (30–60%) and surface area ($300\text{--}400\text{ m}^2\text{g}^{-1}$) of the biochar studied are within the range obtained from biochar derived from various forest biomass sources (e.g., pine sawdust, shavings, oak and birch wood chips) at high pyrolysis temperatures ($\geq 600\text{ }^{\circ}\text{C}$) [35–37]. For instance, coniferous forest biochar showed a porosity of approximately 57%, with most of the pores falling within the size range of 6 to $25\text{ }\mu\text{m}$ [35]. The surface area of biochar derived from black pine (*Pinus nigra*), poplar (*Populus*), and willow (*Salix*) can reach up to $500\text{ m}^2\text{g}^{-1}$ at a pyrolysis temperature of $650\text{ }^{\circ}\text{C}$ [37]. It has been found that biochar's ultra-micropores and micropores, ranging from 0.2 to $9\text{ }\mu\text{m}$, contribute to its available water capacity, achieved

by holding water in place by capillarity [4]. The ultra-micropore and micropore classifications of biochar were based on the classifications of soil pore size by the Soil Science Society of America [38] due to its application of altering soil porosity to enhance the soil water retention. Woody biochar tends to possess more pores within this range compared to biochar produced from agricultural biomass such as rice husk, manure, and biosolid wastes. Furthermore, increasing the pyrolysis temperature can also enhance the percentage of these pores, which is correlated with an increase in surface area resulting from the thermal decomposition of organic material, during which volatiles are driven off and the remaining structure is composed of highly concentrated carbon chains. [4, 39].

Lastly, the low concentration (2%) of acetic acid treatment neutralized biochar pH and significantly decreased the ash content (Table 3). This could be due to the acetic acid solution dissolved ash compounds of carbonates and other inorganic alkalis, which account for approximately 70% of the total biochar alkalinity [40]. The low pH of the biochar may be beneficial for weed control in wild blueberry fields. However, it might impair the fertility of the biochar. Therefore, supplementary nutrients such as compost and fertilizer are often blended with biochar and applied to soils, which is discussed in subsection of 4.4.

WHC of Biochar with Different Treatments (Compost or Fertilizer)

Adding biochar and compost mixes and biochar and fertilizer mixes to the sandy soils improved the WHC of sandy soils collected from the wild blueberry field (Fig. 3). Many previous studies also reported similar findings that biochar from different sources helped to improve WHC of agricultural soil, and tropical soil, especially sandy soil [7, 8, 13, 41–44]. As aforementioned, woody biochar possesses a considerable amount of pores (0.2 μm to 9 μm) that contribute to water retention in biochar pores via capillary forces [4, 38]. Hence, the stored water in those micropores could be easily accessible to the root hairs (10 μm diameter) of plants, meeting their needs, especially under drought conditions. On another note, the weak acidic acid treatment of biochar used in this study was to neutralize the biochar pH by removing the basic ash from the biochar, which had little impact on altering the total volume of pores and pore sizes of biochar. Therefore, the influence of biochar treatment on WHC of soil mixed with biochar-compost, and biochar-fertilizer samples was not significant.

Since biochar is highly recommended to use with compost [45, 46] for better crop production, we investigated two different ratios of biochar-compost mix (50–50% and 70–30% biochar-compost). As a result, 70–30% biochar-compost mix

retained more water in the soil, which implied that biochar rather than compost was regulating the water retention in the soil. Such improved water retention in agricultural sandy soil could further reduce nutrient leaching loss, which in turn can reduce fertilizer needs [43, 44, 47]. Compared to the WHC of biochar-compost mixed soil samples, the biochar-fertilizer mix also increased the WHC of wild blueberry soils to different degrees. However, the WHC values of biochar-fertilizer mixed soil samples showed a relatively larger variation in terms of pH treatment of biochar along with their mixing ratios with fertilizer and their application rates. For instance, increasing application rates of biochar-fertilizer from 5 to 20% did not significantly increase the WHC of soil amended with 50–50 treated biochar-fertilizer. Moreover, the WHC of soil amended with 70–30 biochar-fertilizer mix did not increase much compared with 50–50 biochar-fertilizer mix regardless of pH treatment of biochar and application rates. While the exact reason remains unclear, it is important to mention that the compost used was air-dried before being blended with biochar for testing purposes. It should also be noted that the hydrophilicity of compost allows it to absorb substantial amounts of water, thereby contributing to the increase in water-holding capacity. In contrast, fertilizers are water-soluble, meaning that only the biochar in the mixture of biochar and fertilizers provides benefits for water retention. Further investigation may be required to comprehend the impact of water-soluble fertilizer granules in this particular case.

Influence of Biochar-Compost and Biochar-Fertilizer on Soil pH

The soil pH increased from approximately 5 to 7 or 8 after the biochar-compost and biochar-fertilizer mixes were added to the soil (Fig. 4). Based on our pH testing prior to this study, the average pH of compost, ammonium sulfate fertilizer, and potassium sulfate fertilizer was approximately 8, 5.5, and 7, respectively. The average pH of untreated biochar and treated biochar was approximately 11.4 and 7.5, respectively. When a 20% application rate was used, the increase in pH was mainly due to the alkaline biochar and compost. When increasing the biochar ratio from 50 to 70%, the treated biochar can reduce the pH of the soil with soil amendments (biochar-compost and biochar-fertilizer mixes) by 0.5–1.0 pH unit compared to untreated biochar. This indicates the effectiveness of the biochar treatment method employed in this study. Consequently, if a high application ratio of biochar is necessary in wild blueberry fields, biochar pH treatment can help alleviate the rise in soil pH.

The effect of such alkaline biochar on the modification of soil acidification was also reported in previous studies [48–50]. However, wild blueberry crops in Maine have the adaptability to grow well and compete over weeds in

an acidic soil environment with a pH of 4–5. The low soil pH creates a hostile environment for weeds and other plants while creating a favorable environment for wild blueberry plants and their associated mycorrhizal fungi [15, 51]. In such cases, if the soil pH increases causing undesired soil alkalinity, remedies need to be implemented, such as adding fertilizers with sulfur or gypsum, pine needle litter, papermill sludge, soilless substrates, etc. [52–55]. In addition, using low pyrolysis temperatures of 250–400 °C could produce acidic biochar with a pH of 5–6 [56–60]. Therefore, we suggest conducting long-term field studies to monitor the changes in soil pH to effectively control soil pH as needed if alkaline biochar is added to wild blueberry fields. For instance, applying sulfur in the wild blueberry fields every six years is a recommended efficient technique to maintain the lower pH level [15].

Impacts of Biochar-Compost and Biochar-Fertilizer on Soil Nutrition

The biochar used in this study was derived from forest biomass, while the compost was made from food waste. According to the nutrient testing results, untreated biochar was found to be rich in most nutrient elements (P, K, Ca, Mg, B, Mn, Na, S, Cu, and Zn) and had low concentrations of Al and Fe (Table 5). In comparison, the compost had lower concentrations of Cu, Fe, and Zn, but higher concentrations of other elements (P, K, Ca, Mg, B, Mn, Na, and S) (Table S1). Two fertilizers, namely $(\text{NH}_4)_2\text{SO}_4$ and K_2SO_4 , were used to provide nutrients such as K and S. Biochar-compost and biochar-fertilizer additions improved the availability of six macro-nutrients (P, K, Ca, Mg, B, and S) in the soil for wild blueberries (Figs. 5, 7) and of four micro-nutrients (Cu, Mn, Na, and Zn) (Figs. 6, 8). Previous research has reported that biochar-compost amendment has been effective in significantly increasing the availability of major nutrients in various types of nutrient-deficient agricultural soils [24, 25, 61, 62]. These elements are essential for plant growth and development [63].

In the case of treated biochar usage, a significant reduction of 50–80% in K and S was observed in the soils with biochar-compost additions (Fig. 5). This reduction could be attributed to the mild acidic acid treatment, which removed ash compounds containing K and S. However, in the case of biochar-fertilizer additions, the reduction in K and S concentrations in biochar did not have a significant impact on the overall concentrations of K and S in the soils with biochar-fertilizer additions (Fig. 7). The effect of mild acidic acid treatment on other elements, apart from K and S, did not show consistent results across all elements. The underlying reason for this inconsistency remains unclear and could be attributed, at least in part, to sample variations observed during collection and analysis. In addition, it has

been observed that the overall concentrations of Al and Fe in soil with soil additions (i.e., biochar-compost, and biochar-fertilizer) were lowered to varying degrees compared to the soil samples used as controls (Figs. 6, 8). This reduction can be attributed to the extremely low concentrations of Al and Fe in the biochar, compost, and fertilizer.

Furthermore, there is ample evidence that biochar, especially biochar with a large surface area, has the potential to regulate and reduce nutrient uptake by plants through physicochemical adsorption on its surface [10, 60, 64, 65]. In addition to improving water retention in sandy soils, biochar may also serve as a nutrient sorbent, enabling a slow release of nutrients into the soil. The optimization of nutrient availability and concentrations in soil-biochar mixtures for optimal plant uptake should be further investigated to maximize their benefits in agricultural systems and promote improved plant growth [66–70].

Conclusion

We found that the locally sourced and produced biochar from a biomass CHP plant in Maine effectively increases the water holding capacity (WHC) of sandy wild blueberry field soils. Out of the studied four different application rates (5, 10, 15, and 20%) of biochar-compost and biochar-fertilizer amendments, the 20% rate resulted in the highest soil WHC. On the other hand, the addition of 20% biochar-compost and biochar-fertilizer amendments significantly increased the pH of wild blueberry field soil up to 7–8 because our studied biochar was alkaline. Raised pH could be a issue for wild blueberry plants, which are typically growing in acidic soil. Thus, other techniques to maintain a lower soil pH need to be implemented when applying alkaline biochar. For instance, modifying or treating the biochar to be acidic or applying other additional amendments, such as sulfur is a recommended technique to maintain a soil pH of 4–5 in wild blueberry fields. However, our study also revealed that the mild acidic treatment of biochar did not lower the soil pH, and the reason is unclear, calling for further investigation. Our study also concludes that a 50–50 biochar-compost/fertilizer mix could be a promising ratio to apply in the wild blueberry soil for providing the important nutrient elements (P, K, Ca, B) to the plants as well as keeping the heavy metals (Al, Fe) of the soil in check. Following this study, we further recommend conducting large-scale, long-term field trials to investigate the impacts of biochar-compost and biochar-fertilizer additions on soil properties (water content and nutrient levels) and their effects on wild blueberry crops' physiological performance and berry yield and quality during normal conditions and abnormal conditions, like drought and warming.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s12649-025-02977-y>.

Acknowledgements We thank undergraduate students Zachary Maynor and Ava Ardito from the Zhang Lab, School of Biology and Ecology as well as Alexandra Koretsky and Evan Dickson from the BioEnergy Lab, School of Forest Resources at the University of Maine to assist with the sample preparation and testing for this study.

Author Contributions Concept and design of this study was planned by Rafa Tasnim and Yong-Jiang Zhang. Material preparation, data collection and analysis were performed by Rafa Tasnim and Abigail Novak. The first draft of the manuscript was written by Rafa Tasnim, Ling Li and Yong-Jiang Zhang. All authors commented and contributed on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This project is supported by a Maine ADG grant, USDA National Institute of Food and Agriculture (NIFA), McIntire-Stennis Project Number ME0-42205, Hatch Project Number ME0-22021 through the Maine Agricultural and Forest Experiment Station, Wild Blueberry Commission of Maine, U.S. Department of Agriculture's (USDA) Agricultural Research Service [grant number 58-0204-9-166]. R.T. is supported by the Janet Waldron Doctoral Research Fellowship and A.N. is supported by the Ellen Keough Hodosh Fellowship. Undergraduate students are supported by the University of Maine Research Reinvestment Fund for Rural Health and Wellbeing Grand Challenge Grant Program (FY21-22, FY22-23).

Data Availability Datasets of this study are available from the corresponding authors.

Declarations

Competing interests The authors have not disclosed any competing interests.

References

1. Braghiroli, F.L., Passarini, L.: Valorization of biomass residues from forest operations and wood manufacturing presents a wide range of sustainable and innovative possibilities. *Curr. Forestry Rep.* **6**(2), 172–183 (2020). <https://doi.org/10.1007/s40725-020-00112-9>
2. Suliman, W., Harsh, J.B., Abu-Lail, N.I., Fortuna, A.-M., Dallmeyer, I., Garcia-Perez, M.: Influence of feedstock source and pyrolysis temperature on biochar bulk and surface properties. *Biomass Bioenerg.* **84**, 34–48 (2016). <https://doi.org/10.1016/j.biombioe.2015.11.010>
3. Rehrah, D., Reddy, M.R., Novak, J.M., Bansode, R.R., Schimmel, K.A., Yu, J., Watts, D.W., Ahmedna, M.: Production and characterization of biochars from agricultural by-products for use in soil quality enhancement. *J. Anal. Appl. Pyrol.* **108**, 301–309 (2014). <https://doi.org/10.1016/j.jaap.2014.03.008>
4. Kameyama, K., Miyamoto, T., Iwata, Y.: The preliminary study of water-retention related properties of biochar produced from various feedstock at different pyrolysis temperatures. *Materials* **12**, 1732 (2019). <https://doi.org/10.3390/ma12111732>
5. Lu, S., Zong, Y.: Pore structure and environmental serves of biochars derived from different feedstocks and pyrolysis conditions. *Environ. Sci. Pollut. Res.* **25**(30), 30401–30409 (2018). <https://doi.org/10.1007/s11356-018-3018-7>
6. Xiao, F., Bedane, A., Zhao, J., Mann, M., Pignatello, J.: Thermal air oxidation changes surface and adsorptive properties of black carbon (char/biochar). *Sci. Total. Environ.* **618**, 276–283 (2018). <https://doi.org/10.1016/j.scitotenv.2017.11.008>
7. Basso, A.S., Miguez, F.E., Laird, D.A., Horton, R., Westgate, M.: Assessing potential of biochar for increasing water-holding capacity of sandy soils. *Gcb Bioenergy* **5**(2), 132–143 (2013)
8. Yu, O.Y., Raichle, B., Sink, S.: Impact of biochar on the water holding capacity of loamy sand soil. *Int. J. Energy Environ. Eng.* **4**(1), 1–9 (2013). <https://doi.org/10.1186/2251-6832-4-44>
9. Mukherjee, A., Zimmerman, A.R.: Organic carbon and nutrient release from a range of laboratory-produced biochars and biochar–soil mixtures. *Geoderma* **193**, 122–130 (2013)
10. He, L., Zhong, H., Liu, G., Dai, Z., Brookes, P.C., Xu, J.: Remediation of heavy metal contaminated soils by biochar: mechanisms, potential risks and applications in China. *Environ. Pollut.* **252**, 846–855 (2019)
11. Zhang, X., Wang, H., He, L., Lu, K., Sarmah, A., Li, J., Bolan, N.S., Pei, J., Huang, H.: Using biochar for remediation of soils contaminated with heavy metals and organic pollutants. *Environ. Sci. Pollut. Res.* **20**(12), 8472–8483 (2013)
12. Berek, A.K., Hue, N., Ahmad, A.: Beneficial use of biochar to correct soil acidity. *The food provider*, pp. 1–3. (2011)
13. Wang, D., Li, C., Parikh, S.J., Scow, K.M.: Impact of biochar on water retention of two agricultural soils—A multi-scale analysis. *Geoderma* **340**, 185–191 (2019). <https://doi.org/10.1016/j.geoderma.2019.01.012>
14. Liu, Z., Dugan, B., Masiello, C.A., Gonnermann, H.M.: Biochar particle size, shape, and porosity act together to influence soil water properties. *PLoS ONE* **12**, e0179079 (2017)
15. Yarborough, D., Calderwood, L.: 254-Soil pH Management - Cooperative Extension: Maine Wild Blueberries - University of Maine Cooperative Extension. Cooperative Extension: Maine Wild Blueberries. <https://extension.umaine.edu/blueberries/factsheets/management/254-cultural-management-ph/> (2019)
16. Kohl, T., Laukkanen, T.P., Järvinen, M.P.: Integration of biomass fast pyrolysis and precedent feedstock steam drying with a municipal combined heat and power plant. *Biomass Bioenerg.* **71**, 413–430 (2014)
17. Glass, V.M.: Drought stress effects in wild blueberries. Master's Thesis, Dalhousie University, Halifax, NS, Canada, p. 164. (2000)
18. Percival, D., Murray, A., Stevens, D.: Drought stress dynamics of wild blueberry (*Vaccinium angustifolium* Aiton). *Acta Hort.* **618**, 353–362 (2003)
19. Barai, K., Tasnim, R., Hall, B., Rahimzadeh-Bajgiran, P., Zhang, Y.J.: Is drought increasing in Maine and hurting wild blueberry production? *Climate* **9**(12), 178 (2021)
20. Yarborough, D.E.: Factors contributing to the increase in productivity in the wild blueberry industry. *Small Fruits Rev.* **3**(1–2), 33–43 (2004)
21. Janowiak, M.K., D'Amato, A.W., Swanston, C.W., Iverson, L., Thompson, F.R., Diak, W.D., Matthews, S., Peters, M.P., Prasad, A., Fraser, J.S., Brandt, L.A.: New England and northern New York forest ecosystem vulnerability assessment and synthesis: a report from the New England Climate Change Response Framework project. Gen. Tech. Rep. NRS-173. Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station 173, pp. 1–234. (2018)
22. Dai, A.G.: Increasing drought under global warming in observations and models. *Nat. Clim. Chang.* **3**, 52–58 (2013)
23. Tasnim, R., Calderwood, L., Annis, S., Drummond, F.A., Zhang, Y.J. The future of wild blueberries: Testing warming impacts using open-top chambers. *Spire Maine J. Conserv. Sustain* **4** (2020)
24. Agegnehu, G., Bass, A.M., Nelson, P.N., Bird, M.I.: Benefits of biochar, compost and biochar–compost for soil quality, maize

- yield and greenhouse gas emissions in a tropical agricultural soil. *Sci. Total. Environ.* **543**, 295–306 (2016)
25. Manolikiaki, I., Diamadopoulos, E.: Positive effects of biochar and biochar-compost on maize growth and nutrient availability in two agricultural soils. *Commun. Soil Sci. Plant Anal.* **50**(5), 512–526 (2019)
 26. Novak, A., Li, L., Wason, J., Wang, J., Zhang, Y.J.: Characterization and modification of biochar from a combined heat and power (CHP) plant for amending sandy soils collected from wild blueberry fields. *BioResources* **19**(1), 228–244 (2024)
 27. Novak, A.: Influence of biochar as a soil amendment on soil water content and wild blueberry physiology. Unpublished Master's thesis. University of Maine. (2023)
 28. ASTM Standard E873: Standard Test Method for Bulk Density of Densified Particulate Biomass Fuels. ASTM International, West Conshohocken, PA (2019). <https://doi.org/10.1520/E0873-82R19>. www.astm.org
 29. ASTM Standard E1755-01: Standard Test Method for Ash in Biomass. ASTM International, West Conshohocken, PA, (2020). <https://doi.org/10.1520/E1755-01R20>. www.astm.org
 30. Water holding capacity of garden soil and roadside soil. https://www.brainkart.com/article/Water-holding-capacity-of-garden-soil-and-roadside-soil_38350/. Accessed 05 Oct 2020
 31. Liu, Z., Dugan, B., Masiello, C.A., Gonnermann, H.M.: Biochar particle size, shape, and porosity act together to influence soil water properties. *PLoS ONE* **12**(6), e0179079 (2017). <https://doi.org/10.1371/journal.pone.0179079>
 32. Alghamdi, A.G., Alkhasha, A., Ibrahim, H.M.: Effect of biochar particle size on water retention and availability in a sandy loam soil. *J. Saudi Chem. Soc.* **24**(12), 1042–1050 (2020). <https://doi.org/10.1016/j.jscs.2020.11.003>
 33. Pariyar, P., Kumari, K., Jain, M.K., Jadhao, P.S.: Evaluation of change in biochar properties derived from different feedstock and pyrolysis temperature for environmental and agricultural application. *Sci. Total. Environ.* **713**, 136433 (2020). <https://doi.org/10.1016/j.scitotenv.2019.136433>
 34. Zhao, L., Cao, X., Mašek, O., Zimmerman, A.: Heterogeneity of biochar properties as a function of feedstock sources and production temperatures. *J. Hazard. Mater.* **256–257**, 1–9 (2013). <https://doi.org/10.1016/j.jhazmat.2013.04.015>
 35. Lu, S., Zong, Y.: Pore structure and environmental serves of biochars derived from different feedstocks and pyrolysis conditions. *Environ. Sci. Pollut. Res.* **25**, 30401–30409 (2018). <https://doi.org/10.1007/s11356-018-3018-7>
 36. Guo, M., Song, W., Tian, J.: Biochar-facilitated soil remediation: mechanisms and efficacy variations. *Front. Environ. Sci.* (2020). <https://doi.org/10.3389/fenvs.2020.52151>
 37. Ferraro, G., Pecori, G., Rosi, L., Bettucci, L., Fratini, E., Casini, D., Rizzo, A.M., Chiaramonti, D.: Biochar from lab-scale pyrolysis: influence of feedstock and operational temperature. *Biomass Conv. Bioref.* (2021). <https://doi.org/10.1007/s13399-021-01303-5>
 38. Soil Science Society of America: Glossary of Soil Science Terms; SSSA: Madison, WI, USA. (1997)
 39. Yu, O.Y., Raichle, B., Sink, S.: Impact of biochar on the water holding capacity of loamy sand soil. *Int. J. Energy Environ. Eng.* **4**, 1–9 (2013)
 40. Fidel, R.B., Laird, D.A., Thompson, M.L., Lawrinenko, M.: Characterization and quantification of biochar alkalinity. *Chemosphere* **167**, 367–373 (2017). <https://doi.org/10.1016/j.chemosphere.2016.09.151>
 41. Lustosa Carvalho, M., de Moraes, M.T., Cerri, C.E.P., Cherubin, M.R.: Biochar amendment enhances water retention in a tropical sandy soil. *Agriculture* **10**(3), 62 (2020)
 42. Li, L., Zhang, Y.J., Novak, A., Yang, Y., Wang, J.: Role of biochar in improving sandy soil water retention and resilience to drought. *Water* **13**(4), 407 (2021)
 43. Laird, D.A., Fleming, P., Davis, D.D., Horton, R., Wang, B., Karlen, D.L.: Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. *Geoderma* **158**, 443–449 (2010)
 44. Laird, D., Fleming, P., Wang, B., Horton, R., Karlen, D.: Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma* **158**, 436–442 (2010)
 45. Hunt, J., DuPont, M., Sato, D., Kawabata, A.: The basics of biochar: A natural soil amendment. *Soil Crop Manag.* **30**(7), 1–6 (2010)
 46. Dias, B.O., Silva, C.A., Higashikawa, F.S., Roig, A., Sánchez-Monedero, M.A.: Use of biochar as bulking agent for the composting of poultry manure: effect on organic matter degradation and humification. *Biores. Technol.* **101**(4), 1239–1246 (2010)
 47. Liang, B., Lehmann, J., Solomon, D., et al.: Black carbon increases cation exchange capacity in soils. *Soil Sci. Soc. Am. J.* **70**, 1719–1730 (2006)
 48. Dai, Z., Zhang, X., Tang, C., Muhammad, N., Wu, J., Brookes, P.C., Xu, J.: Potential role of biochars in decreasing soil acidification—a critical review. *Sci. Total. Environ.* **581**, 601–611 (2017)
 49. Shi, R.Y., Ni, N., Nkoh, J.N., Dong, Y., Zhao, W.R., Pan, X.Y., Li, J.Y., Xu, R.K., Qian, W.: Biochar retards Al toxicity to maize (*Zea mays* L.) during soil acidification: the effects and mechanisms. *Sci. Total. Environ.* **719**, 137448 (2020)
 50. Zhao, X., Wang, S., Xing, G.: Nitrification, acidification, and nitrogen leaching from subtropical cropland soils as affected by rice straw-based biochar: laboratory incubation and column leaching studies. *J. Soils Sediments* **14**(3), 471–482 (2014)
 51. Wood, G.W.: The wild blueberry industry—past. *Small Fruits Rev.* (2008). https://doi.org/10.1300/J301v03n01_03
 52. Starast, M., Karp, K., Vool, E.: Effect of NPK fertilization and elemental sulphur on growth and yield of lowbush blueberry. *Agricult. Food Sci.* (2007). <https://doi.org/10.2137/145960607781635859>
 53. Rosen, C.J., Allan, D.L., Luby, J.J.: Nitrogen form and solution pH influence growth and nutrition of two vaccinium clones. *J. Am. Soc. Hortic. Sci.* **115**(1), 83–89 (1990). <https://doi.org/10.21273/JASHS.115.1.83>
 54. Imler, C.S., Arzola, C.I., Nunez, G.H.: Ammonium uptake is the main driver of Rhizosphere pH in Southern highbush blueberry. *HortScience* **54**(5), 955–959 (2019). <https://doi.org/10.21273/HORTSCI13764-18>
 55. Drummond, F., Smagula, J., Annis, S., Yarborough, D.E. B852: Organic Wild Blueberry Production. Maine Agricultural and Forest Experiment Station, The University of Maine. https://digitalcommons.library.umaine.edu/cgi/viewcontent.cgi?article=1002&context=aes_bulletin. (2009)
 56. Zhang, H., Voroney, R.P., Price, G.W.: Effects of temperature and processing conditions on biochar chemical properties and their influence on soil C and N transformations. *Soil Biol. Biochem.* **83**, 19–28 (2015)
 57. Hagner, M., Kemppainen, R., Jauhiainen, L., Tiilikkala, K., Setälä, H.: The effects of birch (*Betula* spp.) biochar and pyrolysis temperature on soil properties and plant growth. *Soil Tillage Res.* **163**, 224–234 (2016)
 58. Kim, P., Johnson, A., Edmunds, C.W., Radosevich, M., Vogt, F., Rials, T.G., Labbé, N.: Surface functionality and carbon structures in lignocellulosic-derived biochars produced by fast pyrolysis. *Energy Fuels* **25**(10), 4693–4703 (2011)
 59. Windeatt, J.H., Ross, A.B., Williams, P.T., Forster, P.M., Nahil, M.A., Singh, S.: Characteristics of biochars from crop residues:

- potential for carbon sequestration and soil amendment. *J. Environ. Manage.* **146**, 189–197 (2014)
60. Askeland, M., Clarke, B., Paz-Ferreiro, J.: Comparative characterization of biochars produced at three selected pyrolysis temperatures from common woody and herbaceous waste streams. *PeerJ* **7**, e6784 (2019)
 61. Agegnehu, G., Srivastava, A.K., Bird, M.I.: The role of biochar and biochar-compost in improving soil quality and crop performance: a review. *Appl. Soil Ecol.* **119**, 156–170 (2017)
 62. Oldfield, T.L., Sikirica, N., Mondini, C., López, G., Kuikman, P.J., Holden, N.M.: Biochar, compost and biochar-compost blend as options to recover nutrients and sequester carbon. *J. Environ. Manage.* **218**, 465–476 (2018)
 63. Taiz, L., Zeiger, E., Møller, I.M., Murphy, A.: Plant physiology and development. 7th edition. Sinauer Associates. (2022)
 64. Paz-Ferreiro, J., Lu, H., Fu, S., Mendez, A., Gasco, G.: Use of phytoremediation and biochar to remediate heavy metal polluted soils: a review. *Solid Earth* **5**(1), 65–75 (2014)
 65. Xu, Q., Xu, Q., Zhu, H., Li, H., Yin, W., Feng, K., Wang, S., Wang, X.: Does biochar application in heavy metal-contaminated soils affect soil micronutrient dynamics? *Chemosphere* **290**, 133349 (2022)
 66. Glaser, B., Lehmann, J., Zech, W.: Ameliorating physical and chemical properties of highly weathered soils in the tropics with bio-char – a review. *Biol. Fertil. Soils* **35**, 219–230 (2002)
 67. Marris, E.: Black is the new green. *Nature* **442**, 624–626 (2006)
 68. Warnock, D.D., Lehmann, J., Kuyper, T.W., Rilling, M.C.: Mycorrhizal responses to biochar in soil – concepts and mechanisms. *Plant Soil* **300**, 9–20 (2007)
 69. Asai, H., Samson, B.K., Stephan, H.M.: Biochar amendment techniques for upland rice production in northern Laos. *Field Crop Res* **111**, 81–84 (2009)
 70. Graber, E.R., Meller-Harel, Y., Kolton, M., et al.: Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media. *Plant Soil* **337**, 481–496 (2010)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Authors and Affiliations

Rafa Tasnim¹ · Ling Li² · Abigayl Novak² · Jinwu Wang³ · Yong-Jiang Zhang^{1,4}

✉ Rafa Tasnim
rafa.tasnim@maine.edu

✉ Ling Li
ling.li@maine.edu

¹ School of Biology and Ecology, University of Maine, Orono, ME 04469, USA

² School of Forest Resources, University of Maine, Orono, ME 04469, USA

³ U.S. Forest Service – Forest Products Laboratory, Madison, WI 53726, USA

⁴ Climate Change Institute, University of Maine, Orono, ME 04469, USA