agronomy

MDPI

Article

Biochars Improve Nutrient Phyto-Availability of Hawai'i's Highly Weathered Soils

Arnoldus Klau Berek [1,*], Nguyen V. Hue [2], Theodore J. K. Radovich [2] and Amjad A. Ahmad [2]

[1] Program Studi Agroteknologi, Universitas Timor, Jl. Km 9, Kel. Sasi, Kec. Kota, Kefamenanu, TTU, NTT 85613, Indonesia

[2] Department of Tropical Plant and Soil Sciences, University of Hawaii at Manoa, Honolulu, HI 96822, USA; nvhue@hawaii.edu (N.V.H.); theodore@hawaii.edu (T.J.K.R.); alobady@hawaii.edu (A.A.A.)

* Correspondence: b3r3kkl4u@gmail.com; Tel.: +62-813-3933-7111

Received: 15 August 2018; Accepted: 21 September 2018; Published: 23 September 2018

check for updates

Abstract: Highly weathered soils in Hawai'i are low in fertility, negatively affecting plant growth. The potential of biochar for improving soil nutrient availability to crops is promising, and prompts this study. Two biochars at 2% (*w*/*w*) made of lac tree (*Schleichera oleosa* (Lour.) Oken) wood and mixed wood (scrapped wood and tree trimmings) with and without vermicompost or thermocompost at 2% (*w*/*w*) were added to an Ultisol (Ustic Kanhaplohumult, Leilehua series) and an Oxisol (Rhodic haplustox, Wahiawa series) of Hawai'i. In each soil two additional treatments—lime + compost and un-amended soil—served as the control. Chinese cabbage (*Brassica rapa* cv. Bonsai) was used as the test plant in two greenhouse plantings, which had a factorial completely randomized design with three replicates per treatment. The results indicated that soil acidity, nutrient in the soils, plant growth and nutrient uptake were improved by the amendments compared to the control. The combined additions of biochar and compost significantly increased pH and EC; reduced exchangeable Al; reduced Mn and Fe in the Oxisol; increased P, K, and Ca content of the soils; and increased Ca, Mg and Fe uptake. Exchangeable aluminum in the Ultisol decreased from 2.5 cmol+/kg to nil; Mehlich-3 extractable P, K, Ca, Mg, Fe, and Mn in the Ultisol increased by 1478%, 2257%, 1457%, 258%, 125% and 72%, respectively compared to the un-amended soil, while the same nutrients increased or decreased in the Oxisol by 180%, 59%, 308%, −14%, and −36%, respectively. Shoot and total cabbage fresh and dry matters increased by 94%, 96%, 107%, and 112%, respectively, as compared to the lime plus compost treatment. Cabbage growth in the Ultisol amended with the lac tree wood biochar and vermicompost was almost twice over the lime and vermicompost treatment. Essential nutrients in the plant tissues, except for N and K, were sufficient for the cabbage growth, suggesting increases in nutrients and reduced soil acidity by the additions of biochar combined with compost were the probable cause. It is recommended that locally produced biochars and composts be used to improve plant nutrient availability in the highly weathered soils.

Keywords: biochar; compost; nutrient availability; highly weathered soil; Chinese cabbage

1. Introduction

Highly weathered soils are generally old soils in moist climates where weathering over the years has resulted in low activity clays and leaching of many cations. These soils are typically acidic and suffer from nutrient deficiencies. Low soil fertility necessitates fertilizer applications which increase cost of crop production and can result in environmental issues such as algal bloom and contamination of water bodies [1]. Biochar reportedly has good capacity to retain nutrients and improve their phyto-availability due to its numerous pores and large surface area and charge [2,3]. Recent research has shown that additions of biochar reduced nutrient losses from agricultural lands [4–10]. Other observed benefits were: increased soil water retention [11,12], raised soil pH [13] and cation exchange capacity (CEC) [14,15], improved beneficial soil microbial population and activities [16,17], and consequently, enhanced plant growth. In the tropics, biochar increased crop yield through liming and fertilization, of low soil pH, and low fertility, typical of tropical soils [18]. More specifically, Panditt et al. [19] reported increasing soil moisture, available K and P by addition of biochars in a moderately acidic low-input Nepalese soil. Application of pine-chip and poultry litter (50:50) biochar blend significantly increased soil concentrations of K, P, Na, Mg, and Ca by 830%, 669%, 2315%, 687%, and 307%, respectively, relative to the control [20].

The nutrient regulating capacity of biochar could be attributed to its large surface area, porosity, surface charge, organic coating, and other factors, such as pH and ionic competition [2,3,21]. For example, NH_4-N adsorption is due to cation exchange of the surface functional (e.g., phenolic and carboxylic) groups of biochar produced at relatively low (300–400 °C) temperature [22] and physical entrapment in biochars pores [23]. Furthermore, NO_3-N adsorption on the basic functional groups can be increased by increasing pyrolysis temperature [22]. Immobilization of N by microorganisms has also been observed in low temperature-produced biochars [24]. Phosphorus ions were specifically adsorbed at certain sites of biochar or precipitated by Ca [25].

The objective of this study was to evaluate the nutrient regulation or enhancement role of two biochars applied in combination with two composts to two highly weathered soils of Hawai'i as measured by the nutrient uptake and growth of Chinese cabbage (Brassica rapa subsp. *pekinensis* (Lour.) Rupr.)

2. Materials and Methods

The nutrient regulation and enhanced availability of biochars were studied in a greenhouse, at the Magoon research facility, University of Hawai'i at Manoa, Honolulu, Hawai'i, using two acid soils, an Ultisol (Ustic Kanhaplohumult, Leilehua series) and an Oxisol (Rhodic haplustox, Wahiawa series). Soil samples were air-dried, crushed and screened to pass a 4 mm sieve for the pot experiment. Finer (<0.5 mm) soil particles were used in chemical analysis. The lac tree (*Schleichera oleosa* (Luhr.) Oken) wood biochar was produced at approximately 450 °C in an open fire traditional charcoal making process in West Timor, Indonesia. The mixed wood (scrapped wood and tree trimmings) derived biochar was produced by the Landscape Ecology Corp., Hilo, Hawai'i, also at 400–450 °C. These biochars were chosen due to their availability and usability to people of Indonesia and Hawai'i. Vermicompost was a local earthworm compost produced by one of the authors (T. Radovich) in Honolulu, Hawai'i, USA, and the thermocompost was a commercial product available in Honolulu, Hawai'i. The biochars were oven dried at 70 °C for 48 h, ground and sieved to pass a 60 mesh (0.25 mm) sieve and stored before use. Selected properties of these biochars are listed in Table 1. Surface structure and porosity of biochars were measured with a scanning electron microscope (SEM) (HITACHI; Hitachi High-technologies, Corp., Tokyo, Japan). Pore diameters were measured from 2000-time magnified SEM images. The pH (H_2O) of the soils, biochars and composts were measured with a pH meter in a mixture of soil, biochar, compost, and deionized water in ratios of 1:1, 1:5 and 1:5, respectively, after 30 minutes of equilibrium time. The EC of the soil, biochars and composts were measured using a pH/EC meter in a mixture of soil, biochar, compost, and deionized water in ratios of 1:1, 1:5, and 1:10, respectively, after 2 h standing. The surface functional groups (carboxylic and phenolic) of biochars were quantified using the Boehm titration method [26]. Water soluble salts and carbonates in biochar were removed before the titration. Briefly, 0.50 g of fine biochar was added to 50 mL of each of the three 0.05 M bases: $NaHCO_3$, Na_2CO_3, and NaOH. The mixtures, along with a control solution without biochar, were shaken for 24 h and then filtered to remove particles. Then, 5 mL of each filtrate were mixed with 10 mL of 0.05 M HCl and back-titrated with 0.05 M NaOH. The endpoint was determined using a pH meter and phenolphthalein color indicator. The total surface acidity was calculated as the quantity neutralized by NaOH, the carboxylic acid fraction as that neutralized by $NaHCO_3$, and the lactonic fraction as that neutralized by Na_2CO_3. The difference between the consumed quantities of NaOH and Na_2CO_3 is assumed to be the phenolic group content [27].

Table 1. Selected chemical properties of the soils, biochars and composts used in the experiment.

Selected Properties	Leilehua Ultisol	Wahiawa Oxisol	Lac Tree Wood Biochar	Hilo Mixed Wood Biochar	Vermicompost	Thermocompost
pH (H_2O)	4.5	5.6	9.2	9.5	7.2	8.3
EC (dS/m)	0.08 ± 0.00	0.13 ± 0.00	1.93 ± 0.01	2.42 ± 0.01	2.28 ± 0.03	3.23 ± 0.02
CEC (cmol+/kg)	16.8 ± 0.45	12.1 ± 0.23	18.0 ± 1.75	14.7 ± 0.20	44.8 ± 3.50	44.5 ± 1.00
Total N (%)	0.21 ± 0.00	0.15 ± 0.00	0.40 ± 0.02	0.50 ± 0.09	1.42 ± 00.0	1.90 ± 0.00
Mehlich-3 extractable P (mg/kg)	1.95 ± 0.03	51.52 ± 0.08	0.06 ± 0.00	0.09 ± 0.00	1.48 ± 0.00	0.17 ± 0.01
Mehlich-3 extractable K (mg/kg)	49.15 ± 0.53	140.70 ± 1.08	0.33 ± 0.00	0.47 ± 0.00	0.04 ± 0.00	1.37 ± 0.01
Mehlich-3 extractable Ca (mg/kg)	111.84 ± 5.09	715.88 ± 5.68	3.13 ± 0.00	1.6 ± 0.01	2.11 ± 0.67	2.39 ± 0.05
Mehlich-3 extractable Mg (mg/kg)	53.93 ± 1.06	232.60 ± 0.07	0.13 ± 0.00	0.22 ± 0.00	0.36 ± 0.00	0.36 ± 0.00
Mehlich-3 extractable Fe (mg/kg)	98.14 ± 1.41	63.95 ± 0.59	684 ± 0.00	12,259.5 ± 233.65	2407.90 ± 30.94	8345.20 ± 103.11
Mehlich-3 extractable Mn (mg/kg)	11.41 ± 0.05	805.80 ± 5.35	55 ± 0.00	153.8 ± 2.32	606.00 ± 0.68	239.20 ± 1.23
Exchangeable Al (cmolc+/kg)	2.16 ± 0.02	0.17 ± 0.01	-	-	-	-
Total functional groups (mmol/g)	-	-	0.38 ± 0.02	0.58 ± 0.03	-	-
Carboxylic functional group (mmol/g)	-	-	0.12 ± 0.02	0.22 ± 0.02	-	-
Phenolic functional groups (mmol/g)	-	-	0.20 ± 0.04	0.27 ± 0.03	-	-
Lactonic functional group (mmol/g)	-	-	0.07 ± 0.02	0.10 ± 0.03	-	-

EC: soil electrical conductivity; CEC: cation exchange capacity.

Vermicompost and thermocompost were oven dried at 70 °C for 72 h, screened to pass a 0.5 mm sieve for chemical analysis. Nutrient content of the composts were determined with an Inductively Coupled Plasma (ICP) spectrometer after a 0.20 g sample was burned at 500 °C for 4 h. The ash was dissolved with 15 mL of 0.1 M HCl. Soil exchangeable aluminum was measured with 1 M KCl leaching/titration method. The measured pH, EC, and nutrient content in the soils, biochars, and composts are listed in Table 1. Hydrated lime (Bandini®) with the $CaCO_3$ equivalent of 108 was dried and screened through a 60-mesh sieve before use.

The treatments, consisting of soil, biochar, and compost, were arranged in a 2 × 2 × 2 factorial completely randomized design with 3 replicates, and a 2 cmolc+/kg lime + compost treatment was included for comparison along with the un-amended soil. Two biochars, namely lac tree wood and Hilo mixed wood, were applied at 2% (*w*/*w*). The compost treatments were a local vermicompost and a commercial thermocompost applied at 2% (*w*/*w*). Biochars were added alone or in combination with composts. The biochar, lime, and compost were mixed with the soil thoroughly, watered and incubated. After three weeks of incubation, all pots (1 kg soil/pot) were planted with Chinese cabbage (*Brassica rapa*) cv. Bonsai Chinensis group, which was harvested after 34 days of growth. The cabbage roots were removed, and the soils were remixed and potted again. The cabbage planting was repeated (second planting) using the same soil in same pot without additional inputs. Shoots and roots were carefully removed from the soil, washed, and the fresh weight was measured before oven-drying at 70 °C for 48 h. Soil samples were collected from each pot 16 days after the treatment additions (a week before the first planting) and 52 days (a week after the harvest of the first planting), air-dried, crushed, and passed through a 0.5 mm sieve before chemical analysis. Soil pH and EC were measured using a pH meter in a 1:1 mixture of soil and deionized water. Total carbon and nitrogen content was measured by dry combustion with a LECO CN-2000 elemental analyzer (Leco Corp., St. Joseph, MI, USA). Soil nutrients quantified with an ICP spectrometer after extraction with the Mehlich-3 solution [28]. Dry weights of shoots and roots were recorded. Plant nutrients were quantified with an ICP spectrometer after dry digestion (at 500 °C for 4 h) and dissolution in dilute HCl (0.20 g tissue in 20 mL of 0.1 M HCl).

Statistical Analysis

Means and standard errors were calculated from two or three replicates of the measured soil pH, electrical conductivity, plant dry weight, and nutrient content in soils and plant tissues. The relationship between nutrient uptake and plant dry matter was analyzed using regression analysis in Microsoft Excel 2010 (Microsoft Corp., Redmond, WA, USA). Bar graphs of soil aluminum changes and plant growth differences resulting from the biochar application were drawn using Microsoft Excel 2010 software. The effects of treatments on soil properties and cabbage growth were analyzed by a two-way Analysis of Variance using PROC Analysis of Variance (ANOVA) GLM) of the SAS 9.2 software (SAS Institute Inc., SAS Campus Drive, Cary, NC, USA), and the orthogonal contrast and the Tukey and *t* tests at $p \leq 0.05$ were used to identify the significant differences of soil and plant parameters, respectively.

3. Results

3.1. Soil pH, EC and Exchangeable Al

The soil pH was raised by 1 and 0.9 units compared to the control in the Ultisol and Oxisol, respectively, 2 weeks after treatment application, and further increased 0.4 and 0.2 units 7 weeks thereafter. The effect of biochar in combination with compost on the increasing of soil pH was not significantly different from the respective lime + compost treatment ($p > 0.05$) (Table 2). Among the biochar + compost treatments, the lac tree wood or Hilo mixed wood biochar in combination with the vermicompost increased pH the most. The data strongly demonstrate the liming capacity of both biochar and compost, especially for low pH soils. Similarly, the lime + vermicompost treatment increased the soil pH 1.5 and 1.4 units in the Ultisol and Oxisol, respectively, 2 weeks after application.

Table 2. The results of the ANOVA and the contrast on soil pH, EC, and nutrients 2 and 7 weeks after being treated with biochar or lime and compost.

Mean Comparisons	pH 2	pH 7	EC 2	EC 7	P 2	P 7	K 2	K 7	Ca 2	Ca 7	Mg 2	Mg 7	Fe 2	Fe 7	Mn 2	Mn 7
Leilehua Ultisol																
Control vs. Amended soil	**	**	**	**	*	*	**	**	**	**	*	*	ns	ns	*	*
B + C vs. L + C	ns	ns	ns	ns	ns	ns	*	*	ns	ns	*	*	ns	ns	ns	ns
B + C vs. B	*	*	*	ns	**	**	*	*	**	**	**	**	ns	ns	*	*
B + C vs. C	*	*	ns	ns	ns	ns	*	*	ns	ns	ns	ns	ns	ns	ns	ns
L + C vs. C	*	ns	ns	ns	ns	ns	ns	ns	*	*	ns	*	ns	ns	ns	ns
B vs. C	ns	ns	*	ns	**	**	**	**	**	**	**	**	ns	ns	**	**
S vs. H	*	*	ns	ns	ns	ns	*	*	**	**	ns	ns	ns	ns	ns	ns
V vs. T	*	*	*	*	**	**	**	**	**	**	*	*	ns	ns	ns	ns
Wahiawa Oxisol																
Control vs. Amended soil	**	**	**	**	*	*	ns	ns	**	**	*	*	ns	ns	*	*
B + C vs. L + C	ns	ns	ns	ns	ns	ns	*	*	ns	ns	ns	ns	ns	ns	*	*
B + C vs. B	*	*	*	*	**	**	**	**	**	**	**	**	ns	ns	ns	ns
B + C vs. C	*	*	ns	ns	ns	ns	*	*	ns	ns	ns	ns	ns	ns	ns	ns
L + C vs. C	**	**	ns	ns	ns	ns	*	*	*	*	ns	ns	ns	ns	ns	*
B vs. C	*	*	*	*	**	**	**	**	**	**	*	*	ns	ns	ns	ns
S vs. H	*	*	ns	ns	ns	ns	**	**	**	**	ns	ns	ns	ns	ns	ns
V vs. T	*	*	ns	ns	**	**	**	**	**	**	ns	ns	ns	ns	ns	ns

ANOVA significant codes: ** < 0.01; * < 0.05; ns > 0.05; ns: not significant; B: biochar, C: compost, L: lime, S: lac tree wood biochar, H: Hilo mixed wood biochar, V: vermicompost, T: thermocompost; 2 and 7: weeks after treatment application; control: un-amended soil, amended soil: general mean of all the treatments; B + C: biochar + compost; L + C: lime + compost.

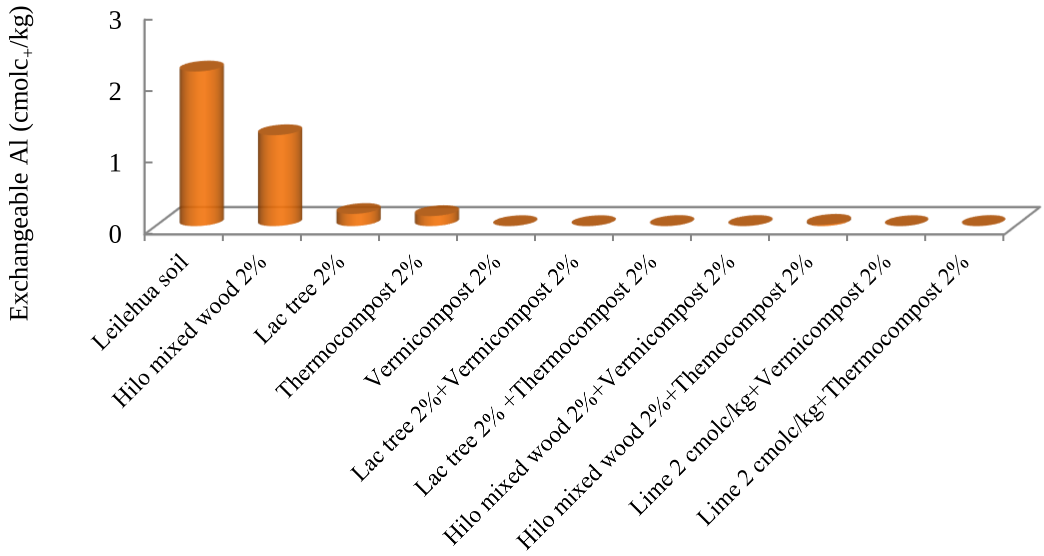
Soil EC increased after 2 weeks of incubation and then decreased after the first harvest (Table 3), perhaps due to the removal of nutrients from the soil by cabbage plants. The effect of biochar + compost on soil EC was not significantly different from the lime + compost ($p > 0.05$) (Table 2). Among the combination of biochar or lime with compost, Hilo mixed wood biochar and thermocompost increased EC the most. Such soil EC increases were attributed mainly to the basic cations (K, Ca, Mg) enrichment by both biochar and compost.

Soil exchangeable Al was significantly reduced by the treatments compared to the control (un-amended soil). More interestingly, the effect of biochar + compost was not significantly different from the lime + compost ($p > 0.05$). The combination of lac tree or Hilo mixed wood biochar at 2% with either vermicompost or thermocompost at 2% decreased soil exchangeable Al from 2.16 cmolc+/kg and 0.12 cmolc+/kg to undetectable in the Ultisol and Oxisol, respectively (Figure 1a,b). Similarly, lime at 2 cmolc+/kg + composts reduced exchangeable Al to an undetectable level in both soils.

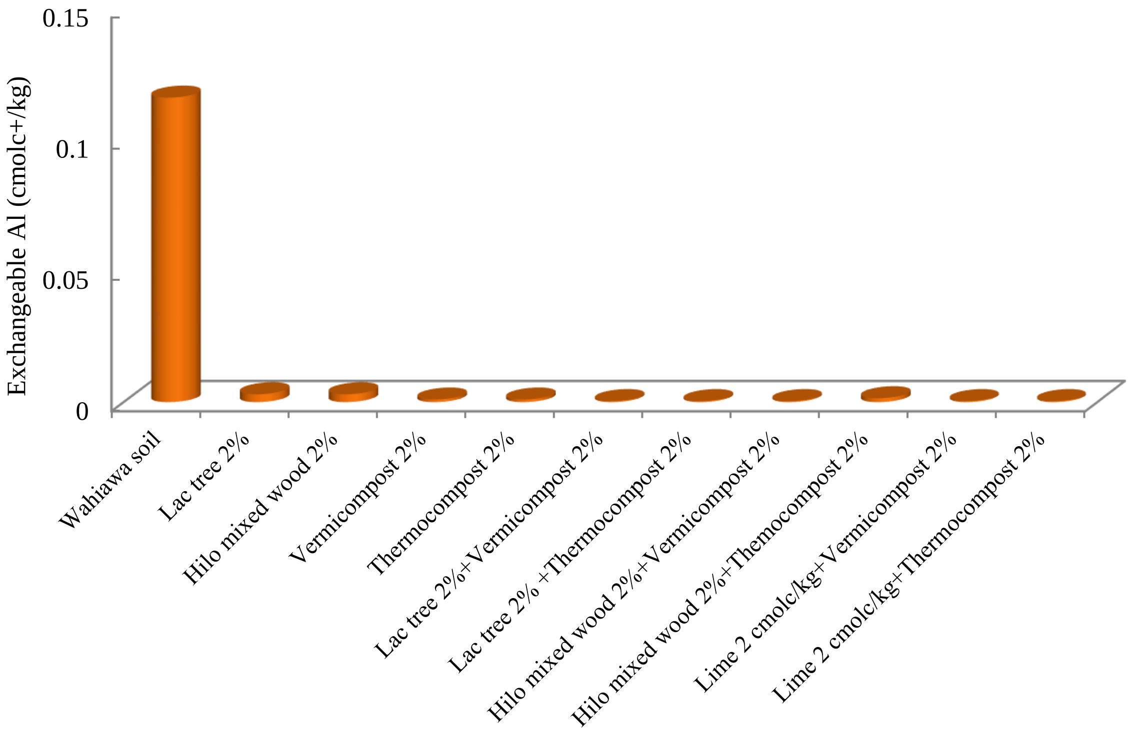
Table 3. Means and standard errors of pH and EC of the soils 2 and 7 weeks after being incubated with the biochars, lime and/or composts ($n = 3$).

Treatment	pH 2	pH 7	EC 2	EC 7
			dS/m	
Ultisol soil				
Control (un-amended soil)	4.6 c	4.6 c	0.09 d	0.09 c
Lac tree wood biochar 2%	5.8 a	5.8 a	0.20 c	0.26 b
Hilo mixed wood biochar 2%	4.8 c	4.8 c	0.22 c	0.25 b
Vermicompost 2%	5.7 ab	6.3 a	0.51 a	0.38 a
Thermocompost 2%	5.1 b	5.5 b	0.39 b	0.27 b
Lac tree wood biochar 2% + Vermicompost 2%	5.9 a	6.5 a	0.51 a	0.38 a
Lac tree wood biochar 2% + thermocompost 2%	5.8 a	6.1 ab	0.43 b	0.29 b
Hilo mixed wood biochar 2% + vermicompost 2%	5.8 a	6.5 a	0.55 a	0.36 a
Hilo mixed wood biochar 2% + thermocompost 2%	5.4 b	5.8 b	0.46 b	0.29 b
Lime 2 cmolc+/kg + Vermicompost 2%	6.1 a	6.6 a	0.50 a	0.38 a
Lime 2 cmolc+/kg + thermocompost 2%	5.6 ab	6.1 ab	0.47 b	0.25 b
Oxisol soil				
Control (un-amended soil)	5.7 d	5.8 d	0.14 d	0.14 c
Lac tree wood biochar 2%	6.5 b	6.6 b	0.27 c	0.34 b
Hilo mixed wood biochar 2%	6.0 c	6.0 c	0.26 c	0.35 b
Vermicompost 2%	6.4 b	6.9 a	0.47 b	0.42 a
Thermocompost 2%	6.3 bc	6.5 b	0.47 b	0.49 a
Lac tree wood biochar 2% + Vermicompost 2%	6.8 a	7.2 a	0.43 b	0.40 a
Lac tree wood biochar 2% + thermocompost 2%	6.7 ab	7.1 a	0.46 b	0.44 a
Hilo mixed wood biochar 2% + vermicompost 2%	6.9 a	7.2 a	0.49 a	0.44 a
Hilo mixed wood biochar 2% + thermocompost 2%	6.3 b	6.8 ab	0.58 a	0.44 a
Lime 2 cmolc+/kg + Vermicompost 2%	7.1 a	7.3 a	0.45 b	0.44 a
Lime 2 cmolc+/kg + thermocompost 2%	6.8 a	7.1 a	0.52 a	0.41 a

Means within a column followed by the same letter(s) were not significantly different by Tukey's test at $\alpha = 5\%$; 2 and 7: weeks after treatment application; EC: soil electrical conductivity.



(a)



(b)

Figure 1. Exchangeable Al in the Leilehua Ultisol (**a**) and Wahiawa Oxisol (**b**) as affected by biochar, lime and/or compost additions.

3.2. Plant Nutrient Content in Soils

Plant nutrients, with exception of Fe in the Ultisol and Mn in the Oxisol soils, were significantly increased by the treatment compared to the control ($p < 0.01$) (Table 2). The Mn in the Oxisol was significantly decreased by the treatment ($p < 0.01$), while Fe in the Ultisol was not significantly affected ($p > 0.05$) by the treatment (Table 4a,b). Effect of biochar + compost was not significantly different on P, Ca, Fe and Mn in the Ultisol and on P in the Oxisol from the lime + compost ($p < 0.05$). The effect of biochar in combination with compost on soil nutrient was varied, depending on the nutrient, soil, compost, or biochar. For example, Lac tree biochar + vermicompost significantly increased P, Ca, Fe and Mn in the Ultisol, and P and Ca in the Oxisol due to the high content of P and Ca in the vermicompost and high Ca in the lac tree biochar, in addition to the high liming effect of the lac tree biochar; and K was significantly increased ($p < 0.01$) in both soils by lac tree or Hilo mixed wood biochar + thermocompost mostly due to the high K content in the thermocompost. In contrast, Mn and Fe in the Oxisol was significantly reduced ($p < 0.01$) by the lac tree + vermicompost. It seemed that increasing nutrient content by biochar and compost indicated that these amendments contribute more nutrients or make nutrients more available. For example, Ca increased by the application of the lac tree wood biochar alone at 2% from 111.8 mg/kg to 816.9 mg/kg in the Ultisol and from 715.9 mg/kg to 1514.4 mg/kg in the Oxisol. Such increases in Ca were more than twice of those increases resulted from the Hilo mixed wood biochar. This might be related to the higher Ca content in the lac tree wood than in the Hilo mixed wood biochar. The combined lac tree wood biochar and vermicompost increased soil Ca the most. In contrast to Ca, K increased more than twice by the thermocompost in combination with either biochar than by the vermicompost, probably due to the higher K content of the thermocompost. Extractable Mn and Fe in the Oxisol soil were sharply decreased by the lac tree wood biochar + vermicompost from 805.8 mg/kg and 63.9 mg/kg to 361.2 mg/kg and 36.9 mg/kg, respectively, perhaps due to the higher liming potential of the lac tree wood biochar that raised pH of the Oxisol, and precipitated Mn and Fe.

Table 4. (a). Means and standard errors of Mehlich-3 extractable P, K and Ca in the soils as affected by the additions of biochars, lime, and/or composts ($n = 3$). (b). Means and standard errors of Mehlich-3 extractable Mg, Fe and Mn in the Hawaiian soils as affected by the additions of biochars, lime, and/or composts ($n = 3$).

(a)

Treatments	P 2	P 7	K 2	K 7	Ca 2	Ca 7
	mg/kg					
Ultisol soil						
Control (un-amended soil)	1.9 b	1.8 b	5.2 b	5.6 b	151.3 b	124.6 b
Lac tree wood biochar 2%	0.8 b	1.0 b	25.5 a	70.2 a	816.9 a	1112.7 a
Hilo mixed wood biochar 2%	1.1 b	0.9 b	8.7 b	48.2 b	315.5 b	411.3 b
Vermicompost 2%	75.6 a	133.4 a	0.0 b	0.0 b	4038.5 a	4408.9 a
Thermocompost 2%	3.4 b	4.1 b	82.1 a	204.2 a	1044.9 b	1076.5 b
Lac tree wood biochar 2% + Vermicompost 2%	68.0 a	146.2 a	0.0 b	63.2 b	4166.5 a	5021.0 a
Lac tree wood biochar 2% + thermocompost 2%	3.1 b	5.8 b	140.7 a	312.6 a	1044.9 b	2009.9 b
Hilo mixed wood biochar 2% + vermicompost 2%	61.8 a	125.4 a	0.0 b	50.0 b	3548.6 a	4615.8 a
Hilo mixed wood biochar 2% + thermocompost 2%	3.7 b	6.5 b	114.8 a	274.6 a	1230.1 b	1337.4 c
Lime 2 cmolc+/kg + Vermicompost 2%	72.9 a	128.5 a	0.0 b	0.0 c	4171.2 a	5004.5 a
Lime 2 cmolc+/kg + thermocompost 2%	2.3 b	5.5 b	93.7 a	209.4 a	1529.1 b	1899.6 bc
Oxisol soil						
Control (un-amended soil)	53.5 b	50.4 b	145.2 b	130.4 b	721.3 c	652.1 d
Lac tree wood biochar 2%	37.7 b	40.2 b	106.3 b	136.5 b	1514.4 b	1695.1 a
Hilo mixed wood biochar 2%	35.8 b	36.7 b	64.3 b	119.9 b	864.2 c	939.3 d
Vermicompost 2%	285.1 a	365.4 a	65.6 b	117.4 b	4367.9 a	4609.8 a
Thermocompost 2%	56.8 b	68.8 b	241.5 a	356.2 a	1556.4 b	1962.2 c
Lac tree wood biochar 2% + Vermicompost 2%	327.4 a	341.6 a	73.9 b	162.5 b	4869.6 a	5504.8 a
Lac tree wood biochar 2% + thermocompost 2%	60.5 b	68.8 b	313.9 a	406.7 a	2528.5 ab	2770.6 c
Hilo mixed wood biochar 2% + vermicompost 2%	270.9 a	367.9 a	93.6 b	174.7 b	4178.1 a	4682.6 b
Hilo mixed wood biochar 2% + thermocompost 2%	64.6 b	70.2 b	271.6 a	419.3 a	1708.2 b	1896.0 c
Lime 2 cmolc+/kg + Vermicompost 2%	295.6 a	353.0 a	52.9 b	76.1 c	4738.2 a	5512.5 a
Lime 2 cmolc+/kg + thermocompost 2%	57.5 b	32.7 b	186.5 ab	304.7 ab	2138.3 ab	2608.4 c

Table 4. *Cont.*

Treatment	(b)					
	Mg 2	Mg 7	Fe 2	Fe 7	Mn 2	Mn 7
	mg/kg					
Ultisol soil						
Control (un-amended soil)	57.3 c	42.7 c	99.8 a	96.5 a	11.7 c	11.4 c
Lac tree wood biochar 2%	136.2 b	92.5 c	106.1 a	109.2 a	8.1 c	8.1 c
Hilo mixed wood biochar 2%	134.6 b	70.9 c	103.9 a	103.9 a	7.7 c	8.8 c
Vermicompost 2%	211.1 a	185.8 b	108.9 a	97.4 a	24.0 a	19.6 a
Thermocompost 2%	211.9 a	156.1 bc	115.7 a	103.6 a	18.8 b	14.6 b
Lac tree wood biochar 2% + Vermicompost 2%	183.1 ab	209.5 ab	113.0 a	115.1 a	23.1 a	20.3 a
Lac tree wood biochar 2% + thermocompost 2%	209.9 ab	183.9 bc	109.3 a	118.6 a	24.9 a	14.7 b
Hilo mixed wood biochar 2% + vermicompost 2%	195.6 ab	192.4 ab	105.9 a	111.3 a	26.9 a	18.4 ab
Hilo mixed wood biochar 2% + thermocompost 2%	198.4 ab	168.9 b	122.4 a	117.2 a	24.2 a	14.4 b
Lime 2 cmolc+/kg + Vermicompost 2%	240.0 a	248.0 a	99.0 a	99.0 a	23.0 a	18.4 ab
Lime 2 cmolc+/kg + thermocompost 2%	230.6 a	232.0 a	101.0 a	103.5 a	16.9 b	14.4 b
Oxisol soil						
Control (un-amended soil)	214.1 c	230.7 c	63.5 a	51.9 b	815.4 a	741.1 a
Lac tree wood biochar 2%	284.6 c	250.8 c	47.3 b	40.9 c	517.2 c	428.7 c
Hilo mixed wood biochar 2%	266.2 c	232.1 c	47.0 b	46.4 c	526.3 c	506.1 b
Vermicompost 2%	351.6 b	358.3 a	43.4 b	39.2 c	422.7 c	336.3 d
Thermocompost 2%	343.9 b	357.5 a	54.6 a	45.9 c	526.3 c	449.0 c
Lac tree wood biochar 2% + Vermicompost 2%	369.1 b	365.3 b	44.8 b	40.5 c	419.3 c	360.9 d
Lac tree wood biochar 2% + thermocompost 2%	401.1 a	353.8 b	60.8 a	47.3 c	634.0 b	481.6 bc
Hilo mixed wood biochar 2% + vermicompost 2%	335.2 b	361.5 b	49.0 b	41.6 c	464.0 c	425.9 c
Hilo mixed wood biochar 2% + thermocompost 2%	350.0 b	342.0 b	58.5 a	54.9 b	593.4 b	557.1 b
Lime 2 cmolc+/kg + Vermicompost 2%	422.0 a	406.8 a	47.1 b	48.1 b	467.4 c	415.2 c
Lime 2 cmolc+/kg + thermocompost 2%	391.4 ab	402.8 a	59.9 a	73.2 a	611.4 b	636.6 b

Means within a column followed by the same letter(s) were not significantly different by Tukey's test at α = 5%; 2 and 7: weeks after treatment application.

3.3. Plant Growth

The growth of Chinese cabbage ((*Brassica rapa* subsp. *pekinensis (Lour.) Rupr.)*) in the Ultisol expressed in shoot dry matter in the second planting was significantly ($p < 0.05$) affected by the interaction of the biochar and compost. For example, the shoot fresh weights of cabbage at the first planting in the Ultisol ranged from 4.9 to 29.5 g, and the best growth expressed in shoot or total fresh and dry weights was obtained from the application of the lac tree wood biochar + vermicompost (Figure 2). Shoot, root, and total fresh and dry weights in the first planting in the Oxisol were significantly increased by the interaction between biochars and composts; however, there were no significant differences among the treatments.

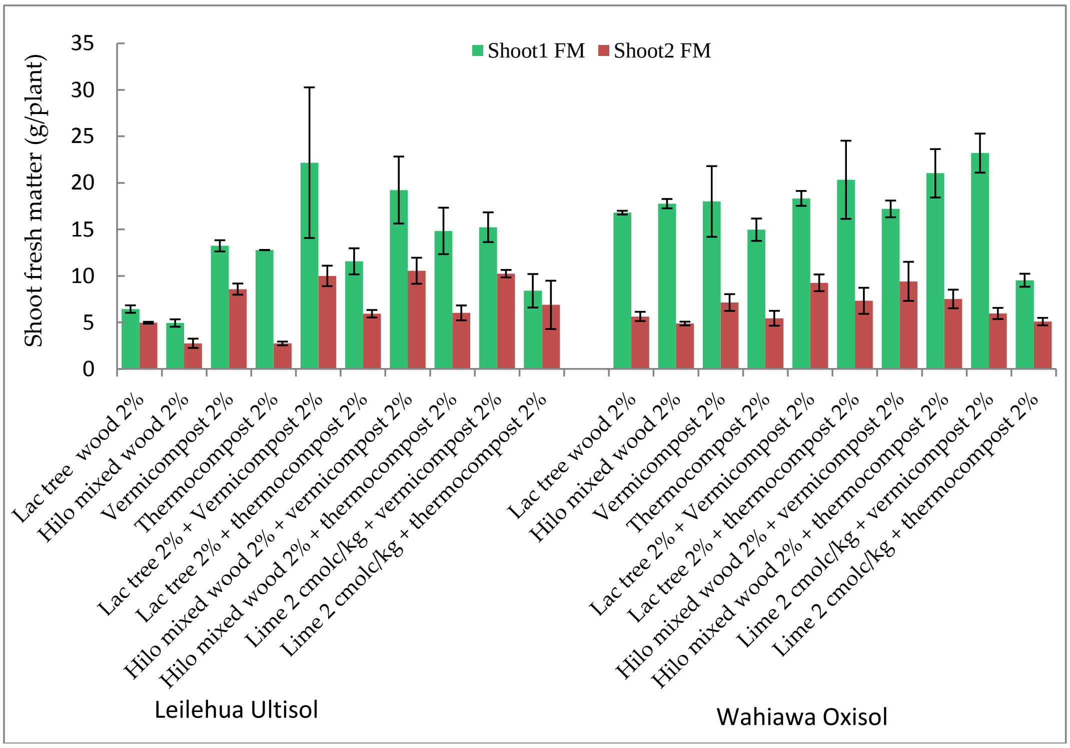


Figure 2. Chinese cabbage shoot fresh weight as affected by biochar, lime, and/or compost additions. FM = fresh matter, 1 and 2: first and second plantings; Error bars: standard error of the mean ($n = 3$).

3.4. Plant Nutrients

Nitrogen, P, K, and Mn concentrations in the Chinese cabbage tissues of both plantings in the Ultisol were significantly affected by the biochar and compost additions ($p < 0.05$) (Tables 5 and 6a). For example, N concentration was significantly higher in plant tissue received the thermocompost treatment than the vermicompost. P concentration in plant was higher in the biochar + compost or compost alone treatments than the biochar alone ($p < 0.01$) probably due to the lower P initial content in the biochars. This might be also the reason P in plants treated with the biochar alone was lower than 0.4% (a deemed critical level for cabbage growth). It was likely that the added biochar contributed more to the liming effect than to P addition.

Phosphor, K, Ca, and Mg concentrations of the cabbage grown in the Oxisol were significantly affected by the biochar + compost ($p < 0.05$) (Tables 5 and 6b) although the concentration of almost all nutrients with exception of N and K was in the sufficiency range for the normal growth of the Chinese cabbage. For example, plant K treated with biochar + compost in the second planting was higher than K in plants treated with biochar + lime or biochar alone. This could be attributed to the higher K content in the composts, thermocompost in particular.

Nitrogen, P, K, and Mg uptake by Chinese cabbage in the Ultisol was significantly improved by the lac tree biochar in combination with the vermicompost, while P, K, and Mg uptake in the Oxisol was not significantly different among the treatments (Table 7, Figure 3a,b).

Table 5. The results of the ANOVA and pair-wise t probabilities on plant nutrients in the first and second plantings as affected by biochar or lime and compost applications.

Mean Comparison	N 1st	N 2nd	P 1st	P 2nd	K 1st	K 2nd	Ca 1st	Ca 2nd	Mg 1st	Mg 2nd	Fe 1st	Fe 2nd	Mn 1st	Mn 2nd
Leilehua Ultisol														
B + C vs. L + C	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns
B + C vs. B	ns	ns	**	*	ns	ns	*	*	ns	ns	*	ns	*	ns
B + C vs. C	ns	ns	*	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns
L + C vs. C	ns	ns	*	ns	ns	*	ns	ns	ns	ns	ns	ns	*	ns
B vs. C	ns	ns	*	*	ns	ns	ns	ns	ns	ns	ns	ns	*	ns
S vs. H	ns	ns	*	*	ns	*	ns	ns	ns	ns	ns	ns	*	ns
V vs. T	*	ns	*	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Wahiawa Oxisol														
B + C vs. L + C	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
B + C vs. B	ns	ns	*	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns
B + C vs. C	ns	ns	*	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
L + C vs. C	ns	ns	*	*	*	*	*	ns	*	ns	ns	ns	ns	ns
B vs. C	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
S vs. H	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	*	ns	ns	ns
V vs. T	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	**	ns	ns

ANOVA significant codes: ** $p < 0.01$; * $p < 0.05$; ns, $p > 0.05$; ns: not significant; B: biochar, C: compost, L: lime, S: lac tree wood biochar, H: Hilo mixed wood biochar, V: vermicompost, T: thermocompost; 1st and 2nd: first and second plantings; control: un-amended soil, amended soil: general mean of all the treatments; B + C: biochar + compost; L + C: lime + compost.

Table 6. (a). Means of N, P and K concentration in Chinese cabbage tissues as affected by biochar, lime, and/or compost additions (n = 3). (b). Means and standard errors of Ca, Mg, Fe and Mn concentration in Chinese cabbage tissues as affected by biochar, lime, and/or compost additions (n = 3).

(a)						
	N		P		K	
Treatments	**1st planting**	**2nd planting**	**1st planting**	**2nd planting**	**1st planting**	**2nd planting**
			%			
Leilehua Ultisol						
Lac tree wood biochar 2%	1.15 ab	1.75 a	0.25 e	0.20 de	3.65 abc	3.50 abc
Hilo mixed wood biochar 2%	1.65 ab	1.50 a	0.30 de	0.05 e	2.50 bc	1.55 d
Vermicompost 2%	1.00 b	1.50 a	0.35 cde	0.60 ab	3.05 bc	2.65 cd
Thermocompost 2%	1.85 a	1.65 a	0.65 ab	0.10 de	2.65 bc	2.40 cd
Lac tree wood 2% + vermicompost 2%	1.30 ab	1.75 a	0.55 abcd	0.45 bc	2.90 bc	3.45 abc
Lac tree wood 2% + thermocompost 2%	1.15 ab	1.60 a	0.60 abc	0.20 de	3.60 abc	4.25 ab
Hilo mixed wood 2% + vermicompost 2%	1.65 ab	1.40 a	0.80 a	0.60 ab	2.85 bc	3.15 bc
Hilo mixed wood 2% + thermocompost 2%	1.05 b	1.80 a	0.50 bcde	0.20 de	3.85 ab	3.45 abc
Lime 2 $cmol_+$/kg + vermicompost 2%	1.30 ab	1.95 a	0.65 ab	0.70 a	2.10 c	3.25 abc
Lime 2 $cmol_+$/kg + thermocompost 2%	1.15 ab	1.35 a	0.50 bcde	0.30 cd	5.00 a	4.75 a
Wahiawa Oxisol						
Lac tree wood biochar 2%	1.60 ab	1.10 ab	0.65 abc	0.60 ab	4.85 a	3.70 ab
Hilo mixed wood biochar 2%	1.25 ab	1.30 ab	0.40 c	0.60 ab	4.55 a	4.05 ab
Vermicompost 2%	1.30 ab	1.45 ab	0.55 bc	0.95 a	2.70 b	3.40 ab
Thermocompost 2%	1.35 ab	2.35 a	0.55 bc	0.90 a	3.10 ab	4.90 a
Lac tree wood 2% + vermicompost 2%	1.30 ab	1.35 a	0.80 ab	0.75 ab	3.40 ab	3.95 ab
Lac tree wood 2% + thermocompost 2%	1.35 ab	1.60 ab	0.70 abc	0.60 ab	2.95 ab	4.05 ab
Hilo mixed wood 2% + vermicompost 2%	1.80 a	1.85 ab	0.60 abc	0.75 ab	4.25 ab	4.90 a
Hilo mixed wood 2% + thermocompost 2%	1.15 b	1.75 ab	0.70 abc	0.85 ab	3.40 ab	4.60 a
Lime 2 $cmol_+$/kg + vermicompost 2%	1.40 ab	1.45 ab	0.90 a	0.50 b	3.75 ab	2.55 b
Lime 2 $cmol_+$/kg + thermocompost 2%	1.65 ab	1.50 ab	0.75 ab	0.50 b	3.50 ab	3.00 ab
Sufficiency level for *Brassica rapa* (%)	3–4		0.4–0.7		4.5–7.5	

Table 6. *Cont.*

(b)

Treatments	Ca		Mg		Fe		Mn	
	1st planting	2nd planting	1st planting	2nd planting	1st planting	2nd planting	1st planting	2nd planting
	%		%		mg/kg		mg/kg	
Leilehua Ultisol								
Lac tree wood biochar 2%	3.40 abc	3.90 ab	0.55 ab	0.95 a	120.00 ab	81.60 a	42.80 abc	64.70 a
Hilo mixed wood biochar 2%	2.30 c	2.05 c	0.60 ab	0.95 a	192.80 a	77.70 a	79.00 a	72.00 a
Vermicompost 2%	2.55 abc	3.25 abc	0.60 ab	0.85 a	104.10 ab	71.20 a	31.10 bc	75.50 a
Thermocompost 2%	3.60 abc	2.20 c	0.50 b	0.55 a	118.00 ab	59.30 a	25.80 c	42.80 a
Lac tree wood 2% + vermicompost 2%	3.90 a	4.10 ab	0.45 b	0.65 a	69.60 b	50.90 a	14.20 c	61.70 a
Lac tree wood 2% + thermocompost 2%	2.70 abc	3.55 abc	0.55 ab	0.70 a	119.60 ab	83.00 a	41.70 abc	73.10 a
Hilo mixed wood 2% + vermicompost 2%	3.50 abc	4.20 ab	0.40 b	0.70 a	88.50 b	64.10 a	16.30 c	50.90 a
Hilo mixed wood 2% + thermocompost 2%	2.45 bc	2.60 bc	0.50 b	0.60 a	92.60 b	144.90 a	36.00 abc	61.40 a
Lime 2 cmol+/kg + vermicompost 2%	3.50 abc	2.55 bc	0.50 b	0.75 a	126.40 ab	69.60 a	26.40 c	82.80 a
Lime 2 cmol+/kg + thermocompost 2%	3.85 ab	4.40 a	0.75 a	0.95 a	146.00 ab	92.00 a	74.30 ab	78.60 a
Wahiawa Oxisol								
Lac tree wood biochar 2%	3.05 bc	3.55 a	0.55 abc	0.80 ab	197.40 a	108.45 b	113.65 a	145.90 abc
Hilo mixed wood biochar 2%	2.30 bc	3.15 a	0.65 a	1.10 a	81.20 b	108.45 b	103.70 a	120.35 bc
Vermicompost 2%	2.10 c	3.80 a	0.40 c	0.70 ba	106.55 a	57.65 b	73.30 a	163.50 abc
Thermocompost 2%	3.05 bc	3.55 a	0.65 a	0.95 ab	165.15 ab	380.90 a	75.75 a	113.90 bc
Lac tree wood 2% + vermicompost 2%	3.00 bc	2.35 a	0.50 abc	0.90 ab	133.35 ab	74.10 b	115.85 a	196.65 a
Lac tree wood 2% + thermocompost 2%	2.70 bc	3.25 a	0.45 bc	0.80 ab	67.40 c	80.30 b	122.50 a	160.10 abc
Hilo mixed wood 2% + vermicompost 2%	3.25 b	3.90 a	0.45 bc	0.70 b	120.15 ab	83.40 b	113.15 a	181.25 ab
Hilo mixed wood 2% + thermocompost 2%	2.20 bc	3.75 a	0.45 bc	0.85 ab	80.30 b	100.90 b	81.00 a	108.25 c
Lime 2 cmol+/kg + vermicompost 2%	4.35 a	3.35 a	0.60 ab	0.60 b	140.05 ab	70.75 b	125.95 a	159.70 abc
Lime 2 cmol+/kg + thermocompost 2%	2.75 bc	3.05 a	0.50 abc	0.85 ab	119.55 ab	64.55 b	125.20 a	116.95 bc
Sufficiency level for *Brassica rapa*	1.9–6.0		0.23–0.75		40–300		25–200	

Means within a column followed by the same letter(s) were not significantly different by Tukey's test at α = 5%.

Table 7. Total nutrient uptake by Chinese cabbage in the Leilehua Ultisol as affected by biochar, lime, and/or compost additions (n = 3).

Treatments	N	P	K	Ca	Mg	Fe	Mn
	mg/plant						
Leilehua Ultisol							
Lac tree wood biochar 2%	20.7 bc	4.0 b	54.4 bcd	3.91 a	11.1 dc	0.17 a	0.08 a
Hilo mixed wood biochar 2%	11.4 c	11.4 b	17.6 d	2.08 a	5.7 d	0.1 a	0.06 a
Vermicompost 2%	35.9 abc	12.6 ab	85.6 abcd	3.29 a	20.5 ab	0.27 a	0.14 a
Thermocompost 2%	28.4 bc	8.5 ab	39.2 cd	2.21 a	7.2 d	0.16 a	0.05 a
Lac tree wood 2% + Vermicompost 2%	66.5 a	26.6 a	139.7 a	4.09 a	22.9 a	0.31 a	0.12 a
Lac tree wood 2% + Thermocompost 2%	28.1 bc	9.2 ab	82.4 abcd	3.58 a	13.2 bcd	0.23 a	0.12 a
Hilo mixed wood 2% + vermicompost 2%	52.9 ab	25.9 a	110.9 abc	4.16 a	19.8 abc	0.27 a	0.11 a
Hilo mixed wood 2% + Thermocompost 2%	39.7 abc	13.1 ab	122.2 ab	2.57 a	18.2 abc	0.29 a	0.14 a
Lime 2 $cmol_+$/kg + vermicompost 2%	30.8 bc	14.5 ab	55.7 bcd	2.51 a	12.7 bcd	0.24 a	0.09 a
Lime 2 $cmol_+$/kg + thermocompost 2%	25.6 bc	9.0 ab	104.2 abc	4.38 a	17.1 abc	0.26 a	0.15 a
Wahiawa Oxisol							
Lac tree wood biochar 2%	39.7 ab	17.2 a	124.7 a	88.7 ab	16.6 a	0.47 a	0.34 abc
Hilo mixed wood biochar 2%	32.8 ab	11.7 a	117.1 a	64.9 ab	19.4 a	0.22 a	0.28 bc
Vermicompost 2%	41.1 ab	19.6 a	88.0 a	80.2 ab	15.1 a	0.27 a	0.29abc
Thermocompost 2%	32.9 ab	15.0 a	85.3 a	71.6 ab	16.4 a	0.41 a	0.20 c
Lac tree wood 2% + Vermicompost 2%	43.9 ab	25.9 a	124.5 a	91.9 ab	20.9 a	0.37 a	0.47 a
Lac tree wood 2% + Thermocompost 2%	41.1 ab	20.9 a	105.9 a	88.2 ab	16.7 a	0.21 a	0.42 ab
Hilo mixed wood 2% + vermicompost 2%	58.2 a	21.8 a	148.5 a	113.7 ab	18.2 a	0.34 a	0.45 ab
Hilo mixed wood 2% + Thermocompost 2%	46.4 ab	25.5 a	134.2 a	93.7 ab	19.7 a	0.29 a	0.32abc
Lime 2 cmol+/kg + vermicompost 2%	48.5 ab	27.7 a	117.5 a	144.5 a	22.2 a	0.41 a	0.45 ab
Lime 2 cmol+/kg + thermocompost 2%	26.3 b	10.a	55.6 a	47.7 b	10.2 a	0.17 a	0.20 c

Means within a column followed by the same letter(s) were not significantly different by Tukey's test at α = 5%.

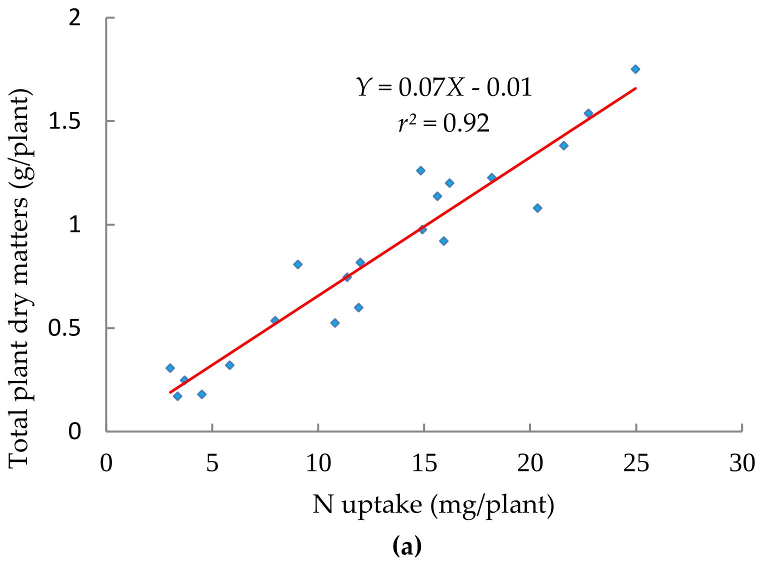


Figure 3. Relationship between N uptake and total dry matter of Chinese cabbage of the second planting in the Leilehua Ultisol soil (**a**). Relationship between K uptake and total dry matter of Chinese cabbage of the second planting in the Leilehua Ultisol soil (**b**).

4. Discussion

Additions of biochars in combination with composts increased acid soils pH and decreased exchangeable Al in the Ultisol and Oxisol soils and decreased the Mehlich-3 extractable Mn and Fe in the Oxisol. Such effects could be attributed to the alkalinity or liming capacity of biochar. The basic cations, such as Ca^{2+}, Mg^{2+}, K^{+}, in the form of oxides or carbonates contained in most biochars can dissolve in water and produce OH^{-} which in turn increased the soil pH and precipitated "active" Al [29,30]. Carbonate content is responsible for the biochar alkalinity [31,32] particularly in biochars produced at high temperature [33]. The close correlation (r^2 = 0.84) between alkalinity and basic cations in biochars has also been shown by Fidel et al. [34], and the carbonate content is closely correlated (r^2 = 90) with the basic cations [30]. Soil EC was also increased with the additions of biochars and/or composts. Such EC increases could be attributed to the release of basic cations from both biochars and composts. A similar result was reported by Chintala et al. [35].

Incorporation of biochar and compost into acid soils would increase nutrients content in the soils. The increase of soil nutrients is attributed to: (1) the release of such nutrients directly from the compost or biochar (as nutrient sources); nutrients such as N, P and K were released by composts and some nutrients (especially K) were released by biochars [2,36]; (2) Changes in soil properties by biochar, e.g., the increase of soil pH that can solubilize nutrients such as P or precipitate Al and Fe [30]; (3) adsorption of nutrients by surface charge or micropore of biochar and the complexation of Al and Fe by organic acids and functional groups of composts and/or biochars [37]; (4) decreasing of nutrient leaching such as NO_3^- and P by improving water-holding capacity of the amended soils [6,38,39], and (5) the formation of organic coating in the outer and inner pores of biochar when it is co-composted or added in combination with compost which could act as a glue for water and nutrient retention [21,40].

The Chinese cabbage growth in the highly weathered soils of Hawai'i treated with the biochars and/or composts was enhanced. The likely reasons for the increased growth especially in the Ultisol, would be the pH increase from 4.6 to 6.6, decreased Al from 2.17 cmol+/kg to 0.17 cmol+/kg, in addition to the release of nutrients into the soil and subsequently uptake by the plants as reported by Ahmad et al. [36] for ten composts. Similar result was reported by [41] who showed that the application of biochar in combination with compost and low rate of inorganic nitrogen fertilizer increased barley yield 54–60% as compared to yield obtained from the maximum inorganic nitrogen fertilizer rate. In the second planting of our experiments, the fresh and dry weights of cabbage in both soils decreased to almost 50% of the first planting (Figure 2) perhaps due to the deficiency of nutrients, especially N and K. The tight linear relationship between total dry matters and N and K uptake suggested such deficiencies (Figure 3a,b).

Nutrients in the plant tissue, except N and K (Table 4a,b), were in the adequate range for the normal growth of cabbage in both plantings [42]. The sufficiency of P, Ca, Mg, Fe, and Mn in cabbage plant tissues in both plantings indicated an improved availability of such nutrients—supply and retention—in these highly weathered soils by the addition of biochars and/or composts.

5. Conclusions

The capacity of biochars in combination with composts to enhance the availability of plant nutrients was assessed in two highly weathered soils of Hawai'i (Oxisol, Wahiawa series; and Ultisol, Leilehua series). The interaction between biochar and compost additions significantly increased the pH of both soils, EC, P and K content in the Oxisol, cabbage shoot and total fresh and dry matter in the Oxisol, plant tissue Ca concentration in both soils, Ca and Mg uptake in the Oxisol, and Fe uptake in the Ultisol. Chinese cabbage growth in the Ultisol was enhanced by the addition of the lac tree wood biochar and vermicompost as a source of nutrients. Increased soil nutrients by compost, extractable Ca and K by biochar, increased soil pH and decreased exchangeable Al, were likely the reasons for the better cabbage growth in the acid Ultisol. The cabbage growth in the Oxisol was also enhanced by the application of biochars in combination with composts. However, there were no significant differences among the treatments with respect to the plant growth. The sufficiency of many nutrients in the plant tissue, with exception of N and K, for the cabbage growth in both plantings indicated an improvement of nutrients supply and availability in these highly weathered soils by a combination of biochar and compost.

Author Contributions: Conceptualization—A.K.B. and N.V.H.; Methodology—A.K.B. and N.V.H.; Software—A.K.B., N.V.H.; Validation—N.V.H., T.J.K.R. and A.A.A.; Formal Analysis-A.K.B.; Investigation—A.K.B.; Resources—A.K.B., N.V.H., A.A.A.; Data Curation—A.K.B.; Writing-Original Draft Preparation—A.K.B.; Writing-Review and Editing—N.V.H., T.J.K.R., A.A.A.; Funding Acquisition—N.V.H.

Funding: This research was funded by the Indonesian Higher Education Directorate General (DIKTI) overseas studies scholarship, NIFA (USDA) and Western SARE grants to Nguyen V. Hue.

Acknowledgments: The authors would like to thank Robert Huang for ICP analysis.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Van Meter, K.J.; Basu, N.B.; Veenstra, J.J.; Burras, C.L. The nitrogen legacy: Emerging evidence of nitrogen accumulation in anthropogenic landscapes. *Environ. Res. Lett.* **2016**, *11*, 1–12. [CrossRef]
2. Zheng, H.; Wang, Z.; Deng, X.; Zhao, J.; Luo, Y.; Novak, J.; Herbert, S.; Xing, B. Characteristics and nutrient values of biochars produced from giant reed at different temperatures. *Bioresour. Technol.* **2013**, *130*, 463–471. [CrossRef] [PubMed]
3. Liu, Z.; He, T.; Cao, T.; Yang, T.; Meng, J.; Chen, W. Effects of biochar application on nitrogen leaching, ammonia volatilization and nitrogen use efficiency in two distinct soils. *J. Soil Sci. Plant Nutr.* **2017**, *17*, 515–528. [CrossRef]
4. Laird, D.A.; Fleming, P.; Wang, B.; Horton, R.; Karlen, D. Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma* **2010**, *158*, 436–442. [CrossRef]
5. Singh, B.P.; Hatton, B.J.; Singh, B.; Cowie, A.L.; Kathuria, A. Influence of biochars on nitrous oxide emission and nitrogen leaching from two contrasting soils. *J. Environ. Qual.* **2010**, *39*, 1224–1235. [CrossRef] [PubMed]
6. Major, J.; Rondon, M.; Molina, D.; Riha, S.J.; Lehmann, J. Nutrient leaching in a Colombian savanna Oxisol amended with biochar. *J. Environ. Qual.* **2012**, *41*, 1076–1086. [CrossRef] [PubMed]
7. Ventura, M.; Sorrenti, G.; Panzacchi, P.; George, E.; Tonon, G. Biochar reduces short-term nitrate leaching from A horizon in an Apple Orchard. *J. Environ. Qual.* **2013**, *42*, 76–82. [CrossRef] [PubMed]
8. Liu, L.; Shen, G.; Sun, M.; Cao, X.; Shang, G.; Chen, P. Effect of biochar on nitrous oxide emission and its potential mechanisms. *J. Air Waste Manage.* **2014**, *64*, 894–902. [CrossRef]
9. Bai, S.H.; Reverchon, F.; Xu, C.-Y.; Xu, Z.; Blumfield, T.J.; Zhao, H.; Van Zwieten, L.; Wallace, H.M. Wood biochar increases nitrogen retention in field settings mainly through abiotic processes. *Soil Biol. Biochem.* **2015**, *90*, 232–240. [CrossRef]
10. Haider, G.; Steffens, D.; Moser, G.; Müller, C.; Kammann, C.I. Biochar reduced nitrate leaching and improved soil moisture content without yield improvements in a four-year field study. *Agric. Ecosyst. Environ.* **2017**, *237*, 80–94. [CrossRef]
11. Novak, J.M.; Lima, I.; Xing, B.; Gaskin, J.M.; Steiner, C.; Das, K.C.; Ahmedna, A.M.; Rehrah, D.; Watts, D.W.; Busscher, W.J.; Schomberg, H. Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. *Ann. Environ. Sci.* **2009**, *3*, 195–206.
12. Laird, D.A.; Fleming, P.D.; Davis, D.D.; Horton, R.; Wang, B.; Karlen, D.L. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. *Geoderma* **2010**, *158*, 443–449. [CrossRef]
13. Yuan, J.H.; Xu, R.K. The amelioration effects of low temperature biochar generated from nine crop residues on an acidic Ultisol. *Soil Use Manage.* **2011**, *27*, 110–115. [CrossRef]
14. Hossain, M.K.; Strezov, V.; Chan, K.Y.; Nelson, P.F. Agronomic properties of wastewater sludge biochar and bioavailability of metals in production of cherry tomato (*Lycopersicon esculentum*). *Chemosphere* **2010**, *78*, 1167–1171. [CrossRef] [PubMed]
15. Silber, A.; Levkovitch, I.; Graber, E.R. pH-dependent mineral release and surface properties of corn straw biochar: Agronomic implications. *Environ. Sci. Technol.* **2010**, *44*, 9318–9323. [CrossRef] [PubMed]
16. Graber, E.R.; Meller-Harel, Y.; Kolton, M.; Cytryn, E.; Silber, A.; David, D.R.; Tsechansky, L.; Borenshtein, M.; Elad, Y. Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media. *Plant Soil* **2010**, *337*, 481–496. [CrossRef]
17. Kolton, M.; Harel, Y.M.; Pasternak, Z.; Graber, E.R.; Elad, Y.; Cytryn, E. Impact of biochar application to soil on the root-associated bacterial community structure of fully developed greenhouse pepper plants. *Appl. Environ. Microbiol.* **2011**, *77*, 4924–4930. [CrossRef] [PubMed]
18. Jeffery, S.; Abalos, D.; Prodana, M.; Bastos, A.; van Groenigen, J.W.; Hungate, B.; Verheijen, F. Biochar boosts tropical but not temperate crop yields. *Environ. Res. Lett.* **2017**, *12*, 5. [CrossRef]
19. Pandit, N.R.; Mulder, J.; Hale, S.E.; Martinsen, V.; Schmidt, H.P.; Cornelissen, G. Biochar improves maize growth by alleviation of nutrient stress in a moderately acidic low-input Nepalese soil. *Sci. Tot. Environ.* **2018**, *625*, 1380–1389. [CrossRef] [PubMed]
20. Sigua, G.C.; Stone, K.C.; Hunt, P.G.; Cantrell, K.B.; Novak, J.M. Increasing biomass of winter wheat using sorghum biochars. *Agron. Sustain. Dev.* **2014**, *35*, 739–748. [CrossRef]
21. Conte, P.; Laudicina, V.A. Mechanisms of organic coating on the surface of a poplar biochar. *Curr. Org. Chem.* **2017**, *21*, 559–565. [CrossRef]

22. Wang, Z.; Guo, H.; Shen, F.; Yang, G.; Zhang, Y.; Zeng, Y.; Wang, L.; Xiao, H.; Deng, S. Biochar produced from oak sawdust by Lanthanum (La)-involved pyrolysis for adsorption of ammonium (NH_4^+), nitrate (NO_3^-), and phosphate (PO_4^{3-}). *Chemosphere* **2015**, *119*, 646–653. [CrossRef] [PubMed]
23. Saleh, M.E.; Mahmoud, A.H.; Rashad, M. Peanut biochar as a stable adsorbent for removing NH4-N from wastewater: A preliminary study. *Adv. Environ. Biol.* **2012**, *6*, 2170–2176.
24. Deenik, J.L.; McClellan, M.; Uehara, G.; Antal, M.J.; Campbell, S. Charcoal volatile matter content influences plant growth and soil nitrogen transformations. *Soil Sci. Soc. Am. J.* **2010**, *74*, 1259–1270. [CrossRef]
25. Xu, G.; Sun, J.; Shao, H.B.; Chang, S.X. Biochar had effects on phosphorus sorption and desorption in three soils with differing acidity. *Ecol. Eng.* **2014**, *62*, 54–60. [CrossRef]
26. Boehm, H.P. Some aspects of surface chemistry of carbon blacks and other carbons. *Carbon* **1994**, *32*, 759–769. [CrossRef]
27. Rutherford, D.W.; Wershaw, R.L.; Reeves, J.B., III. Development of acid functional groups and lactones during the thermal degradation of wood and wood components. *US Geol. Surv. Sci. Investig. Rep.* **2008**, 43. [CrossRef]
28. Mehlich, A. Mehlich III soil test extractant: A modification of the Mehlich II extractant. *Commun. Soil Sci. Plant Anal.* **1984**, *15*, 1409–1416. [CrossRef]
29. Smider, B.; Singh, B. Agronomic performance of a high ash biochar in two contrasting soils. *Agric. Ecosyst. Environ.* **2014**, *191*, 99–107. [CrossRef]
30. Berek, A.K.; Hue, N.V. Characterization of biochars and their use as an amendment to acid soils. *Soil Sci.* **2016**, *181*, 412–426. [CrossRef]
31. Hass, A.; Gonzalez, J.M.; Lima, I.M.; Godwin, H.W.; Halvorson, J.J.; Boyer, D.G. Chicken manure biochar as liming and nutrient spurce for acid Appalachian soil. *J. Environ. Qual.* **2012**, *41*, 1096–1106. [CrossRef] [PubMed]
32. Mukome, F.N.D.; Zhang, X.; Silva, L.C.R.; Six, J.; Parikh, S.J. Use of chemical and physical characteristics to investigate trends in biochar feedstocks. *J. Agric. Food Chem.* **2013**, *61*, 2196–2204. [CrossRef] [PubMed]
33. Yuan, J.H.; Xu, R.K.; Zhang, H. The forms of alkalis in the biochar produced from crop residues at different temperatures. *Bioresour. Technol.* **2011**, *102*, 3488–3497. [CrossRef] [PubMed]
34. Fidel, R.B.; Laird, D.A.; Thompson, M.L.; Lawarinenko, M. Characterization and quantification of biochar alkalinity. *Chemosphere* **2017**, *167*, 367–373. [CrossRef] [PubMed]
35. Chintala, R.; Mollinedo, J.; Schumacher, T.E.; Malo, D.D.; Julson, J.L. Effect of biochars on chemical properties of acidic soil. *Arch. Agron. Soil Sci.* **2013**, *60*, 1–12. [CrossRef]
36. Ahmad, A.; Hue, N.; Radovich, T. Nitrogen release patterns of some locally made composts and their effects on the growth of Chinese cabbage (*Brassica rapa*, Chinensis group) when used as soil amendments. *Compost Sci. Util.* **2014**, *22*, 199–206. [CrossRef]
37. Hue, N.V. Alleviating soil acidity with crop residues. *Soil Sci.* **2011**, *176*, 543–549. [CrossRef]
38. Andrenelli, M.C.; Maienza, A.; Genesio, L.; Miglietta, F.; Pellegrini, S.; Vaccari, F.P.; Vignozzi, N. Field application of pelletized biochar: Short term effect on the hydrological properties of a silty clay loam soil. *Agric. Water Manag.* **2016**, *163*, 190–196. [CrossRef]
39. 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.* **2017**, *119*, 156–170. [CrossRef]
40. Hagemann, N.; Joseph, S.; Schmidt, H.-P.; Kammann, C.I.; Harter, J.; Borch, T.; Young, R.B.; Varga, K.; Taherymoosavi, S.; Elliot, K.W.; et al. Organic coating on biochar explains its nutrient retention and stimulation of soil fertility. *Nat. Cummun.* **2017**, *8*, 1–11. [CrossRef] [PubMed]
41. Agegnehu, G.; Nelson, P.N.; Bird, M.I. The effects of biochar, compost and their mixture and nitrogen fertilizer on yield and nitrogen use efficiency of barley grown on a Nitisol in the highlands of Ethiopia. *Sci. Total Environ.* **2016**, *569–570*, 869–879. [CrossRef] [PubMed]
42. Uchida, R. Recommended plant tissue nutrient levels for some vegetable, fruit, and ornamental foliage and flowering plants in Hawai'i. In *Plant Nutrient Management in Hawai'i's Soils, Approaches for Tropical and Subtropical Agriculture*; Silva, J.A., Uchida, R., Eds.; CTAHR: Honolulu, HI, USA, 2010; pp. 57–65.