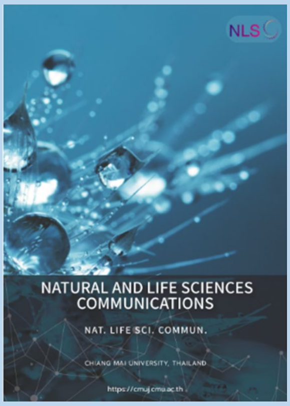
Research article



Effects of Biochar and Poultry Manure Amendments on Soil Physical and Chemical Properties, Growth and Sweet Potato Yield in Degraded Alfisols of Humid Tropics

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ABSTRACT

Information on the impact of biochar and poultry manure on soil characteristics and sweet potato productivity in the humid tropics is lacking. Hence, field experiments were conducted at two locations during the 2019 and 2020 cropping seasons to assess the effects of biochar (B), poultry manure (PM), and their mixture on soil physical and chemical properties, growth and tuber yield of sweet potato (*Ipomoea batatas* L.) Each year, the experiment consisted of 4 × 3 factorial combinations of biochar (0, 10.0, 20.0 and 30.0 t ha^{-1}) and poultry manure (0, 5.0 and 10.0 t ha^{-1}). The findings revealed that using B and PM alone, as well as in combination, improved soil physical and chemical qualities, as well as sweet potato performance. Significant interactions of B and PM (B × PM) were observed on soil characteristics and sweet potato variables that were measured in both years, showing B's potential in enhancing PM use efficiency. Pooled over two years, application of the highest dosage of 30.0 t ha^{-1} B + 10.0 t ha^{-1} PM significantly increased tuber yield of sweet potato compared with other treatments. The multiple regressions showed that both soil physical (bulk density, porosity and moisture content) and chemical (pH, OC, TN, P, K, Ca, and Mg) properties had a significant impact on sweet potato leaf area and tuber yield. The findings indicated that B and PM have the ability to improve soil quality and sweet potato production.

Keywords: Biochar; Poultry manure; Soil properties; Sweet potato; Alfisols

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INTRODUCTION

Sweet potato (*Ipomoea batatas* L.) is widely cultivated in many tropical and subtropical countries in various ecological zones. Sweet potato is the world's seventh most important staple food crop, growing in tropical, subtropical, and warm temperate climates, and it ranks fifth among developing countries, after rice, wheat, maize, and cassava (Mohanraj and Sivasankar, 2014). The crop is especially important in Southeast Asia, Oceania, and Latin America, with China accounting for over 90% of global production (Chandrasekara and Kumar, 2016). Before being consumed, sweet potato tubers are processed in a variety of ways, including hydrothermal treatments such as boiling, frying, baking, and roasting, dehydration, and fermentation. The tuber also provides raw materials for starch, glucose, and alcohol production (Bovell-Benjamin, 2007; Chandrasekara and Kumar, 2016; Ray and Sivakumar, 2009). The leaves are also eaten as vegetables in some Nigerian villages and are frequently utilized as livestock fodder. The tuber is high in anti-oxidants and carotenes, especially in the orange flesh colour varieties, making it a cheap and plentiful source of vitamin A for low-income populations (Bovell-Benjamin, 2007; Mohanraj and Sivasankar, 2014; van Jaarsveld et al., 2006). Nevertheless, the average yield of sweet potato per hectare in Nigeria farmers' fields are as low as 8 t ha^{-1} (Udemezue, 2019). The main cause for this low yield was poor soil fertility as a result of poor plant nutrient management. According to Lal (1986) and Agbede (2010), because tropical soils are deficient in organic matter and available nutrients, productivity and sustainability decrease over time. This is caused by the repeated cultivation of the same land, which results in soil nutrient exhaustion, physical deterioration, and low yield, necessitating the use of soil amendments to correct the anomalies or reverse the negative nutrient imbalances and preserve productivity. As a result, addition of organic matter, manure or a combination of both could be used to restore nutrients and improve the quality of tropical soils. Sweet potato, like any other tuber crop, is a heavy feeder, requiring a large amount of nutrients and water from the soil (Osundare, 2004). Due to the fragile nature of tropical soils, appropriate agronomic techniques and integrated soil management are required for sustainable soil utilization and high crop yields. There has been little research into an appropriate soil management package for increased sweet potato productivity.

Biochar is one the agricultural soil amendments that can improve agricultural production, soil quality and long-term viability. Biochar is the result of high-temperature pyrolysis of organic materials in the absence of oxygen. Organic materials such as manures, mulches and composts were previously employed to improve soil fertility and productivity, but these organic substances have only a transient effect since they decompose quickly, especially in tropical climates with high temperatures and aeration. Biochar amendment is superior to other organic materials in two ways: first, it has a strong resistance to decay, allowing it to stay in the soil for longer periods of time, offering long-term advantages to the soil, and second, it has a greater ability to retain nutrients. Biochar increases soil pH, moisture-holding ability, cation-exchange capacity, and microbial flora, all of which improve soil quality (Gul et al., 2015; Oni et al., 2019). In studies, biochar has been shown to boost crop production by improving physical, chemical and biological qualities. Although biochar has lately sparkled interest as a sustainable technology for improving soil fertility in the tropics, there is currently little evidence on its ability to amend degraded sandy soil and sandy loam soil under sweet potato farming systems in the humid tropics of southwestern Nigeria. Where such research was done, it was in the form of pot experiments in a greenhouse (Nigussie et al., 2012; Basso et al., 2013; Jien and Wang, 2013; Laghari et al., 2015; Frimpong et al., 2016; Sarfraza et al., 2017). Due to low nutrient concentrations and great resistance to biodegradation, biochar may be limited as nutrient source alone (Partey et al., 2014; Frimpong et al., 2021). As a result, application of poultry manure in combination with biochar may be one of the greatest solutions for improving soil sustainability and sweet potato yield. Poultry manure is a valuable organic fertilizer that is produced by the decomposition of chicken droppings (Adekiya et al., 2019; Hoover et al., 2019). Poultry manure is abundant in organic matter and includes nutrients that are essential for crop productivity. The use of poultry manure as an organic fertilizer is still prevalent around the world, and agricultural use of poultry dung has been shown to improve soil quality. The addition of poultry manure to the soil increased soil organic matter and other plant nutrients, improving soil physical and chemical qualities, as well as crop yields (Agbede and Ojeniyi, 2009; Agbede et al., 2017; Adekiya et al., 2019; Hoover et al., 2019).

Few studies have been undertaken in Nigeria to assess the impact of applying biochar to soil in combination with organic fertilizer or inorganic fertilizer on crop productivity. Phares et al. (2020) and Frimpong et al. (2021) reported that biochar, whether used in conjunction with either organic or inorganic fertilizer, has a significant effect on plant development and productivity. Some researchers (Lentz et al., 2014; Agegnehu et al., 2016; Bass et al., 2016; Naeem et al., 2017; Phares et al., 2017; Mensah and Frimpong, 2018; Adekiya et al., 2019; Amoah-Antwi et al., 2020) suggested that biochar could be used in soils in conjunction with other organic residues like manure or compost to boost crop yields in severely degraded soils. In this study, the working hypothesis was that applying sole biochar or poultry manure, or a combination of the two, would improve soil physical and chemical characteristics, growth, and sweet potato yield significantly when compared to the untreated control. Hence, the objective of this study was to assess the synergistic effects of biochar and poultry manure on soil physical and chemical properties, sweet potato growth, and yield in degraded sandy soil and sandy loam soil in southwest Nigeria's forest-savanna transition zone.

MATERIALS AND METHODS

Site description and treatments

Field experiments were conducted at the Teaching and Research Farm of Rufus Giwa Polytechnic (Site A - 7°13′N and longitude 5°32′E, with elevation varying from 314 to 320 m above sea level) and Obasooto village (Site B - 7°12′N and longitude 5°32′E, with elevation varying from 272 to 280 m above sea level), in Owo, Ondo State, Nigeria during the 2019 and 2020 cropping seasons. Obasooto is about 10 km from Owo and is located in the western part of the Owo area. Both sites are located within the forest-savanna transition zone of southwest Nigeria. The soils at Owo and Obasooto have a basement complex texture belonging to the Alfisols, classified as Oxic Tropuldalf (Soil Survey Staff, 2014) or Luvisol (IUSS Working Group WRB, 2015) and locally classified as Okemesi Series (Smyth and Montgomery, 1962). Table 1 shows the physical and chemical properties of the soils at both sites (A and B) prior to the start of the experiment. The soil texture at site A was purely sand, whereas the soil texture at site B was sandy loam (Table 1). Both sites' soils were high in bulk density and moderately acidic, with low levels of organic carbon (OC), total N, available P, exchangeable K, Ca and Mg. This could be related to soil degradation caused by continuous cropping of the experimentation sites' soils. The monthly rainfall, water evaporation and air temperature data for Owo area for the 2 years of trials are shown in Table 2. Evaporation was measured over 24 h period from 09:00 a.m. to 09:00 a.m. second day, and the measurement was credited to the previous day. For 2019 and 2020, the annual rainfall totals were 1093 and 1154 mm, respectively. The rainy season starts in March and lasts until October, while the dry season lasts from November to February, with temperatures varying between 26 and 32°C. The sites had been fallowed for a year after arable cropping, and none of the sites had received fertilizer application in the previous 6 years.

Table 1. Mean ± standard deviation of soil physical and chemical properties (0-15 cm depth) of the site A and site B prior to experimentation in 2019.

Property	Site A	Class	Site B	Class
Sand (%)	92 ± 5.8		76 ± 4.3	
Silt (%)	3 ± 0.1		13 ± 0.5	
Clay (%)	5 ± 0.2		11 ± 0.4	
Textural class	Sand		Sandy loam	
Bulk density (Mg m^{-3})	1.61 ± 0.04	High	1.58 ± 0.03	High
pH (water)	5.51 ± 0.2	Moderately acidic	5.52 ± 0.3	Moderately acidic
Organic carbon (%)	1.23 ± 0.02	Low	1.34 ± 0.02	Low
Total N (%)	0.12 ± 0.01	Low	0.14 ± 0.01	Low
Available P (mg kg^{-1})	6.75 ± 0.3	Low	8.12 ± 0.4	Low
Exchangeable K (cmol kg^{-1})	0.11 ± 0.01	Low	0.12 ± 0.01	Low
Exchangeable Ca (cmol kg^{-1})	1.35 ± 0.02	Low	1.51 ± 0.02	Low
Exchangeable Mg (cmol kg^{-1})	0.37 ± 0.01	Low	0.39 ± 0.01	Low

Table 2. Meteorological data for Owo area 2019-2020.

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Total	Mean
2019														
Rainfall (mm)	0	2	31	104	205	182	196	135	171	52	15	0	1093	91
Pan evaporation (mm)	138	147	128	124	103	98	86	88	79	105	114	122	1332	111
Air temperature (°C)	29	30	31	29	28	28	26	27	29	30	30	31	348	29
2020														
Rainfall (mm)	0	1	35	116	218	194	205	153	186	35	11	0	1154	96
Pan evaporation (mm)	135	143	132	128	108	101	78	83	75	99	108	120	1310	109
Air temperature (°C)	29	31	32	30	28	27	26	27	28	30	31	32	351	29

The treatments consisted of four levels of biochar (B): 0, 10.0, 20.0 and 30.0 t ha^{-1} and three levels of poultry manure (PM): 0, 5.0 and 10.0 t ha^{-1}, which were combined in a 4 × 3 factorial layout to form a total of twelve treatments. The twelve (12) treatments were: (i) B0+PM0 (Control) (ii) B0+PM5 (iii) B0+PM10 (iv) B10+PM0 (v) B10+PM5 (vi) B10+PM10 (vii) B20+PM0 (viii) B20+PM5 (ix) B20+PM10 (x) B30+PM0 (xi) B30+PM5 (xii) B30+PM10.

where;

B0+PM0 = No biochar + No poultry manure (Control); B0+PM5 = No biochar + 5 t ha^{-1} poultry manure; B0+PM10 = No biochar + 10 t ha^{-1} poultry manure; B10+PM0 = 10 t ha^{-1} biochar + No poultry manure; B10+PM5 = 10 t ha^{-1} biochar + 5 t ha^{-1} poultry manure; B10+PM10 = 10 t ha^{-1} biochar + 10 t ha^{-1} poultry manure; B20+PM0 = 20 t ha^{-1} biochar + No poultry manure; B20+PM5 = 20 t ha^{-1} biochar + 5 t ha^{-1} poultry manure; B20+PM10 = 20 t ha^{-1} biochar + 10 t ha^{-1} poultry manure; B30+PM0 = 30 t ha^{-1} biochar + No poultry manure; B30+PM5 = 30 t ha^{-1} biochar + 5 t ha^{-1} poultry manure; B30+PM10 = 30 t ha^{-1} biochar + 10 t ha^{-1} poultry manure.

The twelve treatments were factorially arranged in a randomized complete block design with three replications, making a total of 36 plots. Each block consisted of 12 plots, each measuring 5 × 4 m. The blocks were 1 m apart and the plots were 0.5 m apart. Every year in April, crop establishments were carried out. Each site used the same location for the entire two-year investigation.

Biochar and poultry manure preparation

Biochar was obtained from a local commercial charcoal producer in Owo, Ondo State, Nigeria who produces charcoal for domestic use using hardwood such as *Parkis biglosa, Khaya senegalensis, Prosopis africana* and *Terminalia glaucescens* in traditional kilns. A thermocouple thermometer was used to monitor the temperature within the kiln, which averaged 580°C after 24 h of carbonizing. Before use, the biochar was crushed and sieved through a 2 mm sieve. The poultry manure (PM) was obtained from the poultry unit of Rufus Giwa Polytechnic's Teaching and Research Farm in Owo, Ondo State. To allow for mineralization, the poultry manure was composted for 3 weeks.

Land preparation, incorporation of biochar and poultry manure and planting of sweet potato vines

The experimental sites were manually cleared, then weeds were removed. The trial locations were then laid out according to the specified plot size of 5 × 4 m. A hand-held hoe was then used to till the soils to a depth of 20 cm. The biochar (B) and poultry manure (PM) were weighed and spread evenly on the plots according to the required rates (B: 0, 10.0, 20.0 and 30.0 t ha^{-1}; PM: 0, 5.0 and 10.0 t ha^{-1}) over the soil. The amendments were incorporated into the soil to a depth of about 10 cm using a hand-held hoe. Two (2) weeks before planting sweet potato vines, the biochar and poultry manure were incorporated into the soil.

After tilling the soil, sweet potato (*Ipoemea batatas* L. local variety) vines about 40 cm long were planted in April each year of the experiment. At a spacing of 1 m × 1 m, one sweet potato vine was planted per hole, giving sweet potato population of 10,000 plants ha^{-1}. The field plot was manually weeded twice at 3 and 8 weeks after planting (WAP). No irrigation water was applied during the trial.

Determination of soil physical and chemical properties

The determination of certain soil physical properties in all plots started two months after sweet potato planting, and was repeated four times at 1-month intervals. Steel coring tubes were used to collect five samples (4 cm diameter, 15 cm high) at 0-15 cm depth from the center of each plot at random and about 15 cm away from each sweet potato stand; the samples were used to evaluate bulk density, total porosity, and gravimetric moisture content after oven-drying at 100°C for 24 h. The bulk density and particle density of 2.65 Mg m^{-3} were used to compute total porosity.

Soil samples were collected from 0-15 cm depth at 10 distinct spots chosen at random from the experimental sites prior to the start of the experiment in 2019. At harvest in 2019 and 2020, disturbed soil samples were taken at five different spots per plot at a depth of 0-15 cm from the center of each plot. The soil samples collected were bulked, air-dried and sieved using a 2-mm sieve for routine chemical analysis, as described by Carter and Gregorich (2007). The hydrometer method was used to determine particle size (Gee and Or, 2002). A textural triangle was used to define the textural class. A digital electronic pH meter was used to determine the pH of the soil in a soil/water (1:2) solution. The Walkley and Black procedure was used to determine soil organic carbon using dichromate wet oxidation method (Nelson and Sommers, 1996). Total N was determined using micro-Kjeldahl digestion and distillation procedures (Bremner, 1996), while available P was determined using Bray-1 extraction and colorimetry with molybdenum blue (Frank et al., 1998). A 1 M ammonium acetate (NH4OAC), pH 7 solution was used to extract exchangeable K, Ca, and Mg (Hendershot et al., 2007). After that, a flame photometer was used to determine exchangeable K, and an atomic absorption spectrophotometer was used to estimate exchangeable Ca and Mg.

Analysis of biochar and poultry manure used for the experiment

Standard procedures were employed to determine the chemical properties/characteristics of the biochar and poultry manure used in the trials (International Biochar Initiative, 2011; Tel and Hagarty, 1984). The biochar was slightly alkaline, whereas the poultry manure was slightly acidic. When compared to poultry manure, biochar had higher concentrations of OC, K, Ca, Mg, and a high C:N ratio, whereas poultry manure had higher concentrations of N and P, as well as micronutrients (Table 3).

Table 3. Chemical composition of biochar and poultry manure used in the experiment.

Property	Biochar		Poultry manure	
	2019	2020	2019	2020
Electrical conductivity (dS m^{-1})	3.84	3.86	0.98	0.97
pH (water)	7.86	7.89	6.25	6.28
Ash (%)	8.32	8.29	12.1	12.2
Organic C (%)	55.7	55.5	22.3	22.1
Nitrogen (%)	0.85	0.86	2.89	2.88
C/N	65.5	64.5	7.72	7.67
Phosphorous (%)	0.38	0.35	1.34	1.32
Potassium (%)	1.92	1.89	1.57	1.59
Calcium (%)	4.63	4.60	0.92	0.94
Magnesium (%)	3.78	3.75	0.46	0.47
Copper (mg kg^{-1})	130	131	3700	3710
Iron (mg kg^{-1})	104	105	112	114
Manganese (mg kg^{-1})	680	670	2100	2086
Sulphur (mg kg^{-1})	1000	1100	3300	3290
Zinc (mg kg^{-1})	80	78	2400	2380
Sodium (mg kg^{-1})	2100	2100	2700	2710

Determination of sweet potato vine length, leaf area and tuber yield

At 90 days after planting (DAP), when the sweet potato plant attained its maximal development, ten plants were randomly picked per plot to determine vine length and leaf area. The length of the vines was estimated using the meter rule. The leaf area was calculated using a graphical method (Agbede, 2010). The quantity of tubers, tuber weight (kg $plant^{-1}$), and tuber yield were all quantified as yield parameters (t ha^{-1}). Harvesting 10 sweet potato plants per plot at 5 months after planting (MAP) was used to determine these. The total number of tubers produced by each plant was physically counted and recorded as the number of tubers; the weights of the tubers were calculated and recorded as the tuber weight, and thereafter converted to tuber yield in tons per hectare.

Statistical analysis

The experiments were carried out in a randomized complete block design, with factorial layouts to test the main effects of year (Y), site (S), biochar (B) and poultry manure (PM), as well as the interactions of Y × S, Y × B, Y × PM, B × PM, B × S, PM × S and Y × S × B × PM on soil physical and chemical properties, sweet potato growth, and yield. The data collected from each experiment was subjected to a two-way analysis of variance (ANOVA) using the Genstat statistical package (Genstat, 2005). At $P \leq 0.05$ probability level, Fisher's least significant difference (LSD) test was used to separate the means. Multiple regressions were used to determine the relationship between soil properties and leaf area and tuber yield.

RESULTS

Effect of year, site, biochar and poultry manure and their combined application on soil physical properties

Table 4 shows the influence of year, site, and biochar and poultry manure applications, as well as their combined application, on soil physical properties. When examined as individual factors, the site (S), biochar (B), and poultry manure (PM) all played a major role in determining the physical qualities of the soil. When examined as individual factors, the year (Y) has no effect. When compared to the control, biochar and poultry manure treatments significantly reduced bulk density, improved porosity, and moisture content in both years (Figure 1, Table 4). Moreover, the bulk density reduced, while the porosity and moisture content increased with the rate of biochar and poultry manure treatment (Figure 1, Table 4). When compared to the control, biochar application significantly ($P \leq 0.05$) affected soil physical characteristics - decreased bulk density and increased porosity and moisture content (Table 4). Similarly, as compared to the control, poultry manure as an individual factor considerably improved soil physical properties. The interactive effect of Y × S, B × S, PM × S and B × PM for soil physical properties were significant. On the other hand, the interactive effect of Y × S, Y × B and Y × PM were not significant. When all four factors (Y × S × B × PM) were considered together, interactions were not significant.

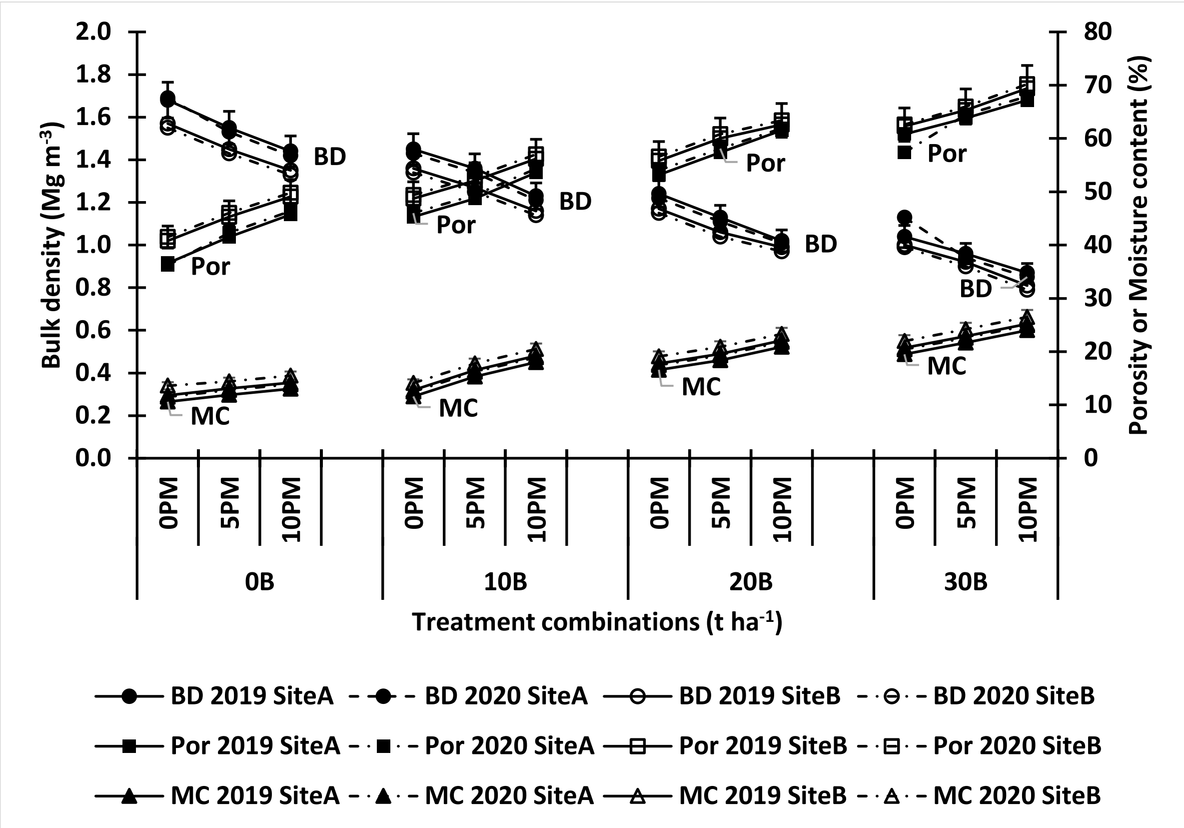

Figure 1. Effect of site, biochar and poultry manure on soil bulk density (BD), porosity (Por) and moisture content (MC).

Table 4. Effect of year, site, biochar and poultry manure and their combined application on soil physical properties (0-15 cm depth) when averaged across four sampling periods (2, 3, 4 and 5 months after planting).

Year/site	Biochar ($t\ ha^{-1}$)	Poultry manure ($t\ ha^{-1}$)	Bulk density ($Mg\ m^{-3}$)	Porosity (%)	Moisture content (%)
2019					
A	0.0	0.0	1.68	36.6	10.6
	0.0	5.0	1.55	41.5	11.9
	0.0	10.0	1.44	45.7	13.0
	10.0	0.0	1.45	45.3	11.6
	10.0	5.0	1.36	48.7	15.3
	10.0	10.0	1.23	53.6	18.0
	20.0	0.0	1.24	53.2	16.6
	20.0	5.0	1.13	57.4	18.4
	20.0	10.0	1.02	61.5	20.9
	30.0	0.0	1.04	60.8	19.5
	30.0	5.0	0.96	63.8	21.7
	30.0	10.0	0.87	67.2	24.0
B	0.0	0.0	1.57	40.8	11.8
	0.0	5.0	1.45	45.3	13.1
	0.0	10.0	1.35	49.1	14.2
	10.0	0.0	1.36	48.7	12.8
	10.0	5.0	1.27	52.1	16.5
	10.0	10.0	1.16	56.2	19.2
	20.0	0.0	1.17	55.8	17.8
	20.0	5.0	1.06	60.0	19.6
	20.0	10.0	0.99	62.6	22.1
	30.0	0.0	1.00	62.3	20.7
	30.0	5.0	0.92	65.3	22.9
	30.0	10.0	0.81	69.4	25.2
2020					
A	0.0	0.0	1.69	36.2	11.5
	0.0	5.0	1.53	42.3	12.8
	0.0	10.0	1.42	46.4	13.9
	10.0	0.0	1.43	46.0	12.5
	10.0	5.0	1.34	49.4	16.2
	10.0	10.0	1.21	54.3	18.9
	20.0	0.0	1.22	54.0	17.5
	20.0	5.0	1.11	58.1	19.3
	20.0	10.0	1.01	61.9	21.8
	30.0	0.0	1.13	57.4	20.4
	30.0	5.0	0.94	64.5	22.6
	30.0	10.0	0.85	67.9	24.9
B	0.0	0.0	1.55	41.5	13.6
	0.0	5.0	1.43	46.0	14.4
	0.0	10.0	1.33	49.8	15.5
	10.0	0.0	1.34	49.4	14.1
	10.0	5.0	1.25	52.8	17.8
	10.0	10.0	1.14	57.0	20.5
	20.0	0.0	1.15	56.6	19.1
	20.0	5.0	1.04	60.8	20.9
	20.0	10.0	0.97	63.4	23.3
	30.0	0.0	0.99	62.6	22.0
	30.0	5.0	0.90	66.0	24.2
	30.0	10.0	0.79	70.2	26.5
		LSD (0.05)	0.11	4.2	0.5
Year (Y)			ns	ns	ns
Site (S)			*	*	*
Biochar (B)			*	*	*
Poultry manure (PM)			*	*	*
Y × S			ns	ns	ns
Y × B			ns	ns	ns
Y × PM			ns	ns	ns
B × PM			*	*	*
B × S			*	*	*
PM × S			*	*	*
Y × S × B × PM			ns	ns	ns

Note: *Significant difference at $P \leq 0.05$; ns, not significant at $P \leq 0.05$

Effect of year, site, biochar and poultry manure and their combined application on soil chemical properties

The impact of year, site, biochar and poultry manure, as well as their combined application, on soil chemical properties are presented in Table 5. When examined as individual factors, the year, site, biochar and poultry manure all played a key role in increasing the soil chemical properties. In both years (2019 and 2020), sole biochar or poultry manure application significantly increased soil pH, organic carbon (OC) and total N (TN) (Figure 2, Table 5), as well as available P, exchangeable K, Ca and Mg (Figure 3, Table 5), with concentration increasing with increasing biochar and poultry manure application rates. Increasing the rate of biochar from 0 to 30.0 t ha^{-1}, increased soil pH, OC, TN, P, K, Ca, and Mg. Similarly, increasing the rate of poultry manure from 0 to 10.0 t ha^{-1} increased soil pH, OC, TN, P, K, Ca, and Mg. Among all the treatments, the highest dosage of 30.0 t ha^{-1} biochar + 10.0 t ha^{-1} poultry manure produced the best soil chemical properties. The control had the lowest soil chemical property values.

Year and site had a significant ($P \leq 0.05$) effect on soil pH, OC, TN, P, K, Ca, and Mg concentrations when examined as individual factors (Table 5). Biochar increased soil pH, OC, TN, P, K, Ca, and Mg concentrations significantly ($P \leq 0.05$) when studied as an individual factor. Similarly, applying poultry manure as an individual factor increased soil chemical properties significantly ($P \leq 0.05$). For soil pH, OC, TN, P, K, Ca, and Mg, the interactive effect of Y × S, Y × B, Y × PM, B × S, PM × S, and B × PM was significant. Interactions were significant when all four factors (Y × S × B × PM) were studied together.

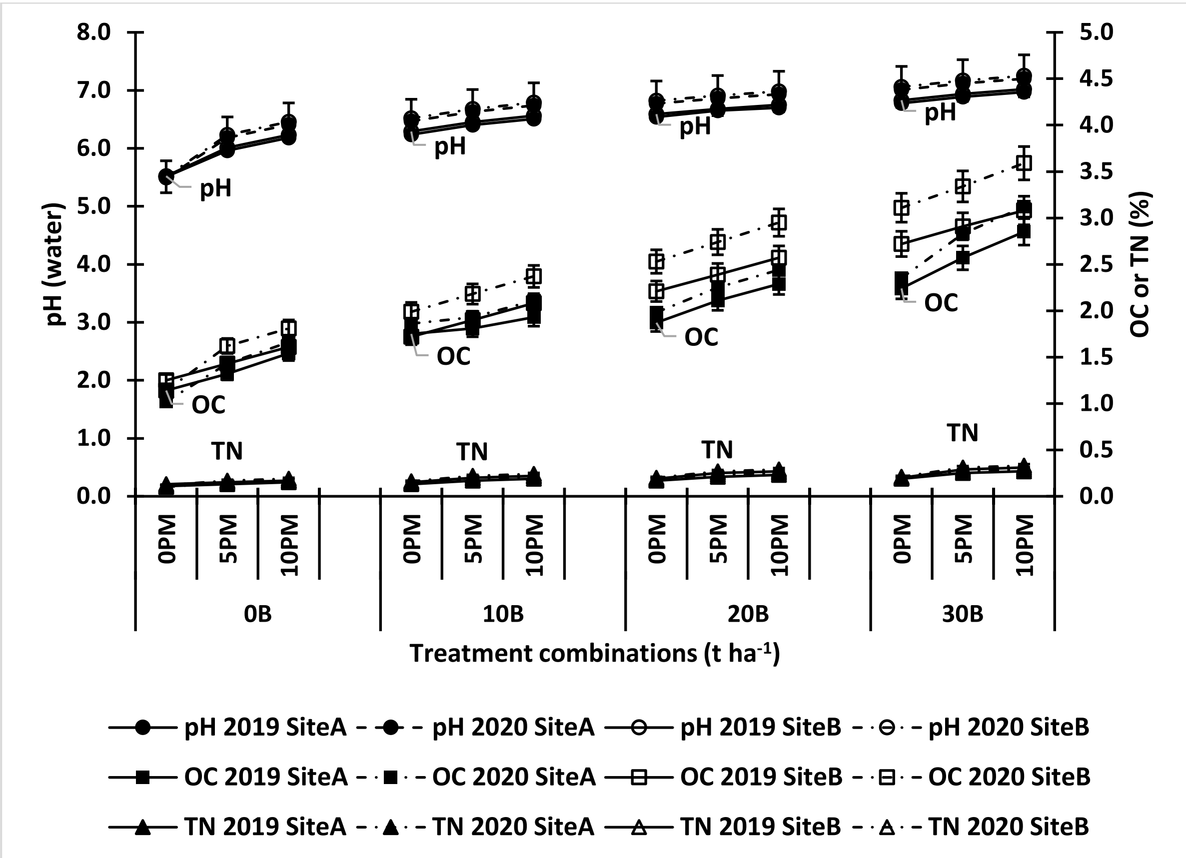

Figure 2. **Effect of site, biochar and poultry manure on soil pH (water), organic carbon (OC) and total nitrogen (TN).**

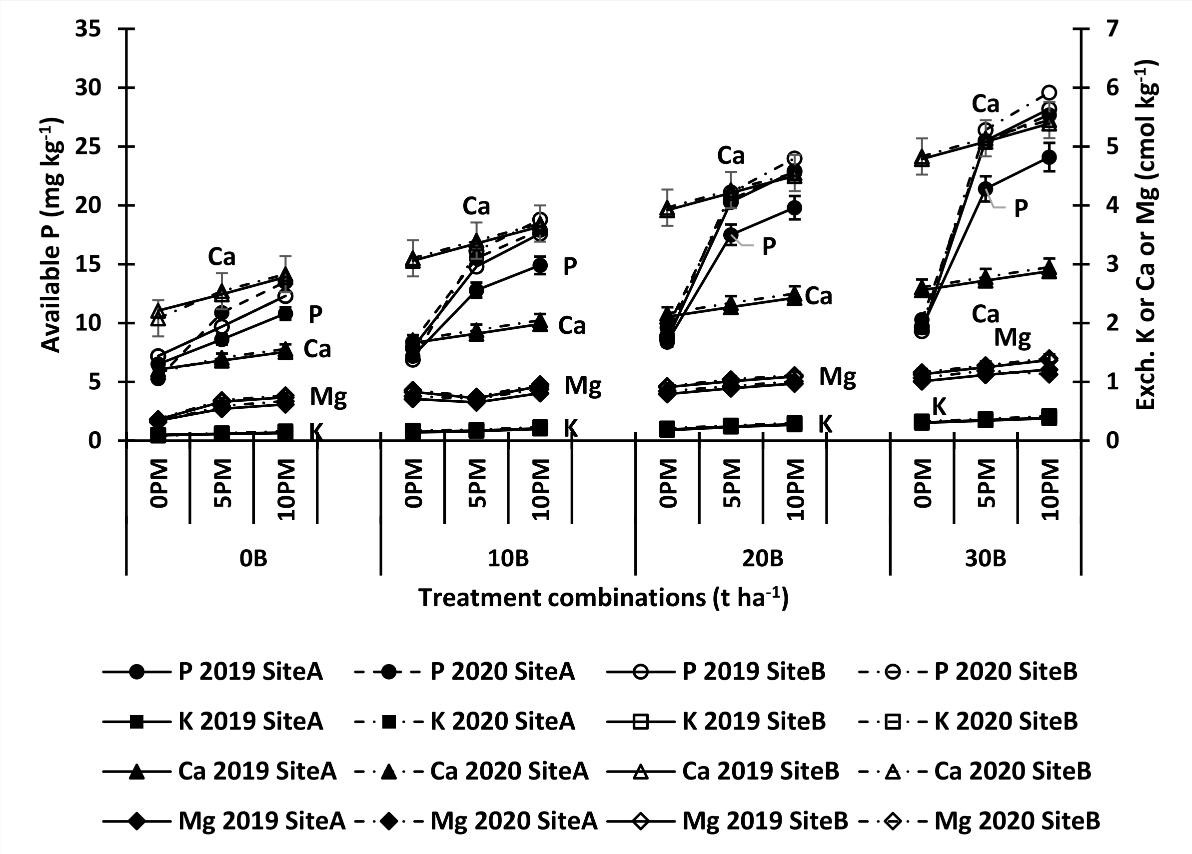

Figure 3. **Effect of site, biochar and poultry manure on soil available phosphorus (P), exchangeable potassium (K), exchangeable calcium (Ca) and exchangeable magnesium (Mg).**

Table 5. Effect of year, site, biochar and poultry manure and their combined application on soil chemical properties (0-15 cm depth).

Year/site	Biochar (t ha^{-1})	Poultry manure (t ha^{-1})	pH (water)	OC (%)	Total N (%)	Available P (mg kg^{-1})	Exchangeable K (cmol kg^{-1})	Exchangeable Ca (cmol kg^{-1})	Exchangeable Mg (cmol kg^{-1})
2019									
A	0.0	0.0	5.51	1.14	0.11	6.5	0.09	1.21	0.34
	0.0	5.0	5.96	1.32	0.13	8.6	0.11	1.36	0.54
	0.0	10.0	6.18	1.54	0.15	10.8	0.13	1.51	0.62
	10.0	0.0	6.24	1.75	0.13	7.2	0.14	1.66	0.71
	10.0	5.0	6.40	1.81	0.17	12.8	0.16	1.82	0.65
	10.0	10.0	6.51	1.93	0.19	14.9	0.20	1.98	0.81
	20.0	0.0	6.54	1.87	0.17	8.4	0.18	2.11	0.79
	20.0	5.0	6.65	2.11	0.21	17.5	0.23	2.27	0.89
	20.0	10.0	6.70	2.29	0.23	19.8	0.27	2.43	0.97
	30.0	0.0	6.78	2.24	0.19	9.6	0.30	2.56	1.01
	30.0	5.0	6.89	2.57	0.25	21.4	0.34	2.72	1.12
	30.0	10.0	6.97	2.85	0.27	24.1	0.38	2.88	1.21
B	0.0	0.0	5.52	1.25	0.13	7.2	0.10	2.21	0.36
	0.0	5.0	6.01	1.43	0.15	9.7	0.12	2.49	0.66
	0.0	10.0	6.23	1.61	0.17	12.3	0.14	2.78	0.74
	10.0	0.0	6.29	1.72	0.15	7.9	0.15	3.06	0.83
	10.0	5.0	6.45	1.90	0.20	14.8	0.17	3.35	0.72
	10.0	10.0	6.56	2.08	0.22	17.6	0.21	3.64	0.93
	20.0	0.0	6.59	2.21	0.19	8.6	0.19	3.92	0.91
	20.0	5.0	6.68	2.39	0.25	20.3	0.24	4.21	1.01
	20.0	10.0	6.75	2.57	0.27	22.9	0.28	4.50	1.09
	30.0	0.0	6.83	2.72	0.20	9.3	0.31	4.79	1.13
	30.0	5.0	6.94	2.91	0.29	25.5	0.35	5.08	1.25
	30.0	10.0	7.02	3.08	0.31	28.2	0.39	5.39	1.37

Year/site	Biochar ($t\ ha^{-1}$)	Poultry manure ($t\ ha^{-1}$)	pH (water)	OC (%)	Total N (%)	Available P ($mg\ kg^{-1}$)	Exchangeable K ($cmol\ kg^{-1}$)	Exchangeable Ca ($cmol\ kg^{-1}$)	Exchangeable Mg ($cmol\ kg^{-1}$)
2020									
A	0.0	0.0	5.49	1.02	0.10	5.3	0.08	1.16	0.32
	0.0	5.0	6.18	1.43	0.15	10.9	0.12	1.41	0.59
	0.0	10.0	6.41	1.66	0.17	13.5	0.14	1.56	0.67
	10.0	0.0	6.47	1.86	0.14	8.4	0.16	1.71	0.76
	10.0	5.0	6.63	1.93	0.19	15.5	0.18	1.88	0.71
	10.0	10.0	6.74	2.11	0.21	17.9	0.22	2.05	0.88
	20.0	0.0	6.77	1.98	0.18	9.6	0.20	2.16	0.84
	20.0	5.0	6.86	2.25	0.23	20.5	0.24	2.34	0.93
	20.0	10.0	6.93	2.44	0.25	22.8	0.28	2.50	1.01
	30.0	0.0	7.01	2.35	0.20	10.3	0.32	2.61	1.07
	30.0	5.0	7.12	2.83	0.27	25.4	0.36	2.78	1.19
	30.0	10.0	7.20	3.12	0.29	27.7	0.41	2.95	1.13
B	0.0	0.0	5.51	1.14	0.12	7.2	0.09	2.08	0.37
	0.0	5.0	6.23	1.62	0.17	9.7	0.13	2.54	0.69
	0.0	10.0	6.46	1.81	0.19	12.3	0.16	2.83	0.77
	10.0	0.0	6.52	1.99	0.16	6.9	0.17	3.10	0.86
	10.0	5.0	6.68	2.18	0.22	16.1	0.19	3.40	0.75
	10.0	10.0	6.79	2.37	0.24	18.8	0.23	3.69	0.96
	20.0	0.0	6.82	2.53	0.20	8.9	0.21	3.96	0.93
	20.0	5.0	6.91	2.74	0.27	21.1	0.26	4.26	1.04
	20.0	10.0	6.98	2.95	0.29	24.0	0.30	4.55	1.11
	30.0	0.0	7.06	3.11	0.21	9.7	0.33	4.83	1.16
	30.0	5.0	7.17	3.34	0.31	26.4	0.37	5.14	1.28
	30.0	10.0	7.25	3.59	0.33	29.6	0.42	5.45	1.40
		LSD (0.05)	0.28	0.06	0.005	0.31	0.004	0.06	0.01
Year (Y)			*	*	*	*	*	*	*
Site (S)			*	*	*	*	*	*	*
Biochar (B)			*	*	*	*	*	*	*
Poultry manure (PM)			*	*	*	*	*	*	*
Y × S			*	*	*	*	*	*	*
Y × B			*	*	*	*	*	*	*
Y × PM			*	*	*	*	*	*	*
B × PM			*	*	*	*	*	*	*
B × S			*	*	*	*	*	*	*
PM × S			*	*	*	*	*	*	*
Y × S x B × PM			*	*	*	*	*	*	*

Note: *Significant difference at $P \leq 0.05$

Effect of year, site, biochar and poultry manure and their combined application on growth and tuber yield of sweet potato

The effect of year, site, biochar and poultry manure, as well as their combined application on the vine length, leaf area and tuber yield of sweet potato are shown in Table 6. When investigated as independent components, the year, biochar, and poultry manure (excluding site) all had a significant effect on sweet potato growth and yield. With the rate of application from 0 to 30.0 t ha^{-1}, biochar considerably ($P \leq 0.05$) increased vine length and leaf area (Figure 4, Table 6) and tuber yield (Figure 5, Table 6) of sweet potato in the first and second years. Similarly, increasing the rate of application from 0 to 10.0 t ha^{-1}, poultry manure considerably ($P \leq 0.05$) enhanced vine length and leaf area (Figure 4, Table 6) and tuber yield (Figure 5, Table 6) of sweet potato. In comparison to all other treatments, the maximum dosage of 30.0 t ha^{-1} biochar + 10.0 t ha^{-1} poultry manure resulted in the longest vine length, leaf area, and sweet potato tuber yield in both years. The control had the shortest vine length, leaf area, and sweet potato tuber yield.

Biochar had a significant impact on sweet potato vine length, leaf area, and tuber yield when investigated as a single factor (Table 6). Poultry manure had an effect on sweet potato vine length, leaf area, and tuber yield as an individual factor. The interaction between biochar and poultry manure (B × PM) was significant for sweet potato vine length, leaf area, and tuber yield. For sweet potato vine length, leaf area, and tuber yield, the interactive effects of Y × B, Y × PM, and B × PM were significant. The Y × S, B × S, and PM × S interactions, as well as the Y × S × B × PM interaction, had no effect on sweet potato vine length, leaf area, or tuber yield.

The coefficients of determination (R^2) for leaf area and tuber yield were 0.853 and 0.863, respectively, when soil physical properties (bulk density, porosity, and moisture content) were regressed as independent variables with leaf area and tuber yield as dependent variables (Table 7). Bulk density, porosity, and moisture content all had a profound influence on sweet potato leaf area and tuber yield, according to multiple regressions. The R^2 for leaf area and tuber yield were 0.975 and 0.973, respectively, when soil chemical properties (pH, OC, TN, P, K, Ca, and Mg) were regressed as independent variables with leaf area and tuber yield as dependent variables. (Table 8).

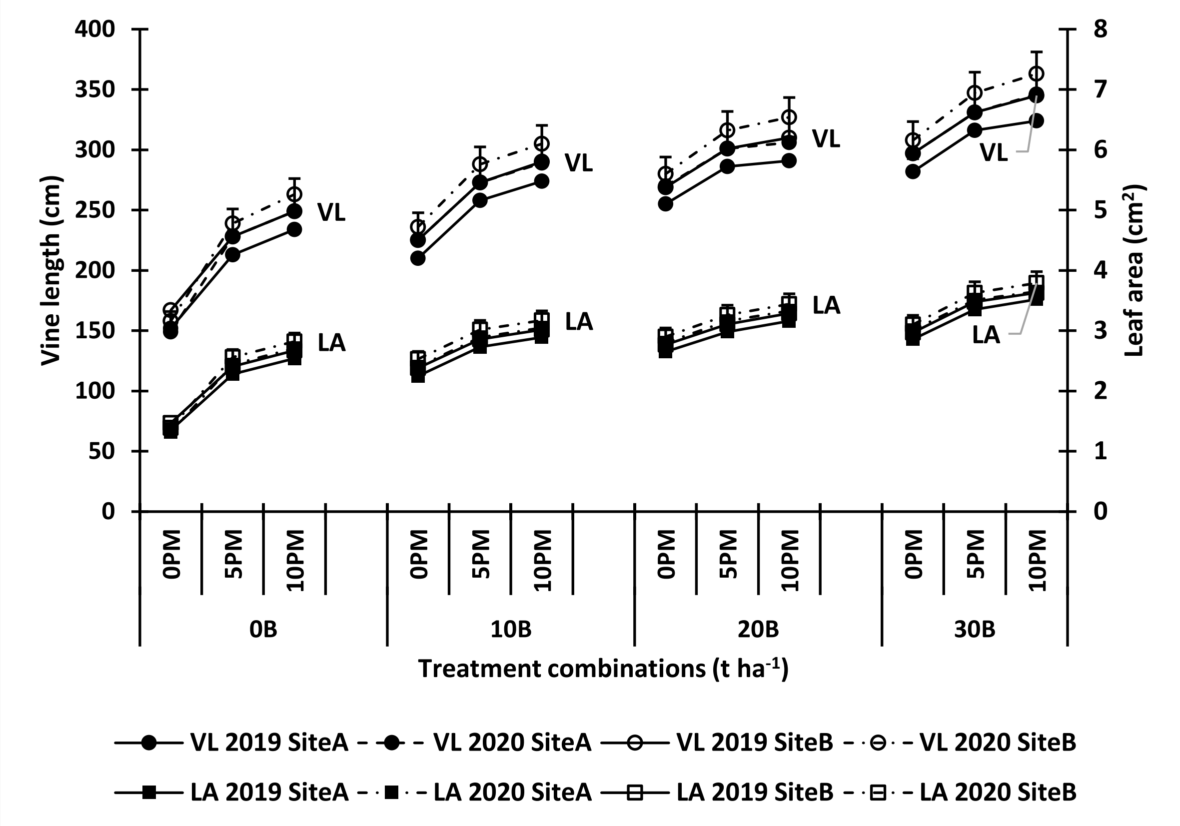

Figure 4. Effect of site, biochar and poultry manure on vine length (VL) and leaf area (LA) of sweet potato.

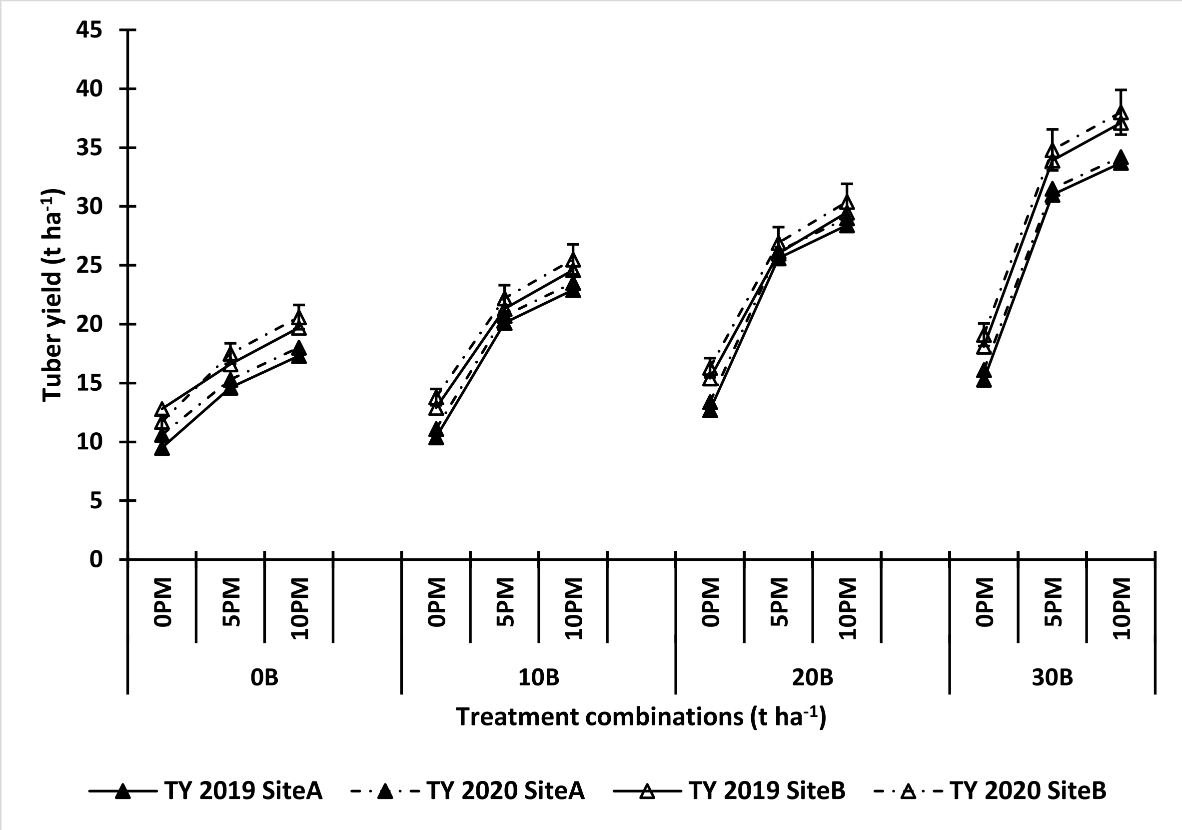

Figure 5. Effect of site, biochar and poultry manure on tuber yield (TY) of sweet potato.

Table 6. Effect of year, site, biochar and poultry manure and their combined application on vine length and leaf area at 90 days after planting and tuber yield of sweet potato at 5 months after planting.

Year/site	Biochar (t ha^{-1})	Poultry manure (t ha^{-1})	Vine length (cm)	Leaf area per plant (cm^2)	Tuber yield (t ha^{-1})
2019					
A	0.0	0.0	152	1.35	9.5
	0.0	5.0	213	2.28	14.6
	0.0	10.0	234	2.54	17.3
	10.0	0.0	210	2.25	10.4
	10.0	5.0	258	2.73	20.1
	10.0	10.0	274	2.89	22.9
	20.0	0.0	255	2.65	12.7
	20.0	5.0	286	2.98	25.6
	20.0	10.0	291	3.16	28.4
	30.0	0.0	282	2.86	15.3
	30.0	5.0	316	3.35	31.0
	30.0	10.0	324	3.52	33.7
B	0.0	0.0	167	1.47	12.8
	0.0	5.0	228	2.41	16.6
	0.0	10.0	249	2.67	19.7
	10.0	0.0	225	2.38	12.9
	10.0	5.0	273	2.86	21.3
	10.0	10.0	290	3.02	24.6
	20.0	0.0	269	2.77	15.4
	20.0	5.0	301	3.11	26.0
	20.0	10.0	310	3.29	29.5
	30.0	0.0	297	2.97	18.1
	30.0	5.0	331	3.48	33.9
	30.0	10.0	345	3.63	37.1

Year/site	Biochar (t ha^{-1})	Poultry manure (t ha^{-1})	Vine length (cm)	Leaf area per plant (cm^2)	Tuber yield (t ha^{-1})
2020					
A	0.0	0.0	149	1.32	10.6
	0.0	5.0	228	2.44	15.3
	0.0	10.0	249	2.71	18.0
	10.0	0.0	225	2.40	11.1
	10.0	5.0	273	2.89	20.7
	10.0	10.0	289	3.05	23.5
	20.0	0.0	270	2.80	13.4
	20.0	5.0	301	3.16	26.2
	20.0	10.0	306	3.33	29.0
	30.0	0.0	297	3.01	16.1
	30.0	5.0	331	3.51	31.5
	30.0	10.0	346	3.65	34.2
B	0.0	0.0	158	1.39	11.7
	0.0	5.0	239	2.56	17.5
	0.0	10.0	263	2.82	20.6
	10.0	0.0	236	2.53	13.8
	10.0	5.0	288	3.02	22.2
	10.0	10.0	305	3.17	25.5
	20.0	0.0	280	2.90	16.3
	20.0	5.0	316	3.26	26.9
	20.0	10.0	327	3.44	30.4
	30.0	0.0	308	3.10	19.1
	30.0	5.0	347	3.63	34.8
	30.0	10.0	363	3.79	38.0
		LSD (0.05)	11	0.06	0.8
Year (Y)			*	*	*
Site (S)			ns	ns	ns
Biochar (B)			*	*	*
Poultry manure (PM)			*	*	*
Y × S			ns	ns	ns
Y × B			*	*	*
Y × PM			*	*	*
B × PM			*	*	*
B × S			ns	ns	ns
PM × S			ns	ns	ns
Y × S × B × PM			ns	ns	ns

Note: *Significant difference at $P \leq 0.05$; ns, not significant at $P \leq 0.05$

Table 7. Multiple regressions of leaf area and tuber yield using soil physical properties.

Leaf area and tuber Yield	R^2	Soil physical properties			*P*-value		
Leaf area	0.853	BD,	PO,	MC,	>0.000,	>0.000,	>0.005
Tuber yield	0.863	BD,	PO,	MC,	>0.005,	>0.006,	>0.003

Note: Significant at $P \leq 0.05$ level; BD: bulk density; PO: porosity; MC: moisture content

Table 8. Multiple regressions of leaf area and tuber yield using soil chemical properties.

Leaf area and tuber yield	R^2	Soil chemical properties	*P*-value
Leaf area	0.975	pH, OC, N, P, K Ca, Mg	>0.000, >0.026, >0.037, >0.044, >0.038, >0.018, >0.027
Tuber yield	0.973	pH, OC, N, P, K, Ca, Mg	>0.005, >0.034, >0.006, >0.000, >0.024, >0.029, >0.035

Note: Significant at $P \leq 0.05$ level; OC: organic carbon; TN: total nitrogen; P: available phosphorous; K: exchangeable potassium; Ca: exchangeable calcium; Mg: exchangeable magnesium.

DISCUSSION

The results revealed that both experimental sites (A and B) had low OC, TN, P, K, Ca, and Mg soil content and were acidic with a high bulk density. The Alfisols in southwest Nigeria have these characteristics (deRidder and van Keulen, 1990; Lal, 1986). The low organic matter of the sites and the sandy nature of the soils were attributed for the high soil bulk densities before the trial began. The low soil fertility condition could also be attributed to years of past cultivation with implements like disc ploughs, disc harrows, and disc ridgers, as well as tractor wheel traffic, which compacts the soil and degrades its qualities.

When compared to the control, the application of sole biochar and poultry manure, or in combination at different doses, considerably improved soil physical characteristics, reducing bulk density and improving moisture content and porosity. Many investigations have indicated that laboratory incubation studies using organic amendments reduce bulk density (Herath et al., 2013; Jien and Wang, 2013; Githinji, 2014; Gamage et al., 2016; Verheijen et al., 2019). Increases in porosity and moisture content, as well as decreases in bulk density, would have mediated the soil biophysical environment for root and microbial respiration (Basso et al., 2013). Agbede et al. (2017) found that poultry manure had a similar effect on improving soil physical properties. The addition of biochar to the sandy soil and sandy loam tested resulted in a considerable reduction in bulk density (Table 4), which is consistent with the biochar analysis's high carbon content (Table 3). Organic matter has been shown to reduce soil bulk density, increase porosity and moisture content (Adekiya et al., 2019), and improve soil structure and aggregate stability (Khademalrasoul et al., 2014). This research corroborates earlier studies on both fine (Chaganti and Crohn, 2015) and coarse textured soils (Lim et al., 2016). The bulk density of most biochars (0.6 Mg m^{-3}) is significantly lower than the bulk density of common agricultural soils (1.2 Mg m^{-3}) (Blanco-Canqui, 2017), and therefore, this could explain the decrease in bulk density. As a result of the dilution or mixing action, biochar application is likely to reduce the density of the bulk soil (Alburquerque et al., 2014; Lehmann et al., 2011). In addition, biochar may affect bulk density indirectly by influencing aggregation. For various soils, such as silt loam, silty clay, sandy loam, and clay, biochar has been proven to promote soil aggregate formation and stability (Liu et al., 2012; Ouyang et al., 2013; Soinne et al., 2014). When compared to the control, biochar application resulted in an increase in moisture content. The findings of Gamage et al. (2016) and Glab et al. (2016) from their short-term and laboratory experiments are supported by this study. This was attributed to more micropores in biochar to physically retain water and/or enhanced aggregation as a result of increased earthworm burrowing, which led in the creation of larger pore spaces. Another cause for the higher moisture content in the plots amended with biochar compared to the control was biochar's higher surface area and porosity compared to other types of soil organic matter, as well as its capacity to improve water retention through improved soil structure and aggregation (Sun and Lu, 2014; Kameyama et al., 2016).

The increase in soil pH, OC, TN, P, K, Ca and Mg concentrations in response to application of biochar and poultry manure was consistent with the analyses recorded for the biochar and poultry manure (Table 3), as well as their nutrients availability. The increase in soil pH observed in biochar or poultry manure alone and their combination at different rates of application could be adduced to increased availability of organic matter and high concentrations of alkali metals and exchangeable basic cations (Ca, Mg, K and Na) present in their ash fractions which act as liming agents in acidic soils. Increases in nutrient concentrations owing to poultry manure addition could be attributed to the nutrients released as a result of the poultry manure decomposition. Poultry manure has been shown to improve soil health characteristics such as soil organic matter and soil fertility (Hoover et al., 2019; Lin et al., 2018), and increase OC, N, P, K, Ca and Mg levels in soil (Agbede and Ojeniyi, 2009; Adekiya et al., 2019). Nutrients were released to the soil when the organic matter components of the poultry manure decomposed, resulting in the findings that N, P, K, Ca, and Mg increased with the rate of poultry manure application from 0 to 10.0 t ha^{-1}.

The increase in soil OC and nutrients with biochar application rates compared to the control was attributed to the traits believed to be derived from adding biochar to the soil, which include increased carbon stability, improved soil structure, decreased soil acidity, addition of nutrients concentrations of the biochar, as well as increased nutrient/water retention and aggregation, improved microbial properties, improved electrical conductivity, improved porosity and increased decomposition of organic materials in soil as reported in earlier studies (Lehmann et al., 2003; Sun and Lu, 2014; Marks et al., 2016; Pandian et al., 2016; Zong et al., 2016). Biochar is known to retain nutrients through capturing nutrient-containing water in its micropores, which is held by capillary forces (Major et al., 2012). The mechanisms that increase the availability of plant nutrients in biochar amended plots are high OC content, high stability, increase in soil pH (in acidic soils), nutrient retention (due to increase in cation exchange capacity and surface area) or directly release of nutrients from the biochar surfaces (Major et al., 2012; Martinsen et al., 2015; Pandit et al., 2018; Minhas et al., 2020). The fact that 30.0 t ha^{-1} biochar in combination with 10.0 t ha^{-1} poultry manure resulted in optimum soil chemical properties could be attributed to increased microbial activities and nutrient mineralization induced by biochar and poultry manure addition, which should have increased nutrient availability.

The large increase in nutritional status and sweet potato yield caused by poultry manure addition was consistent with the initial low fertility of the soils at the experimental sites. Poultry manure has been demonstrated to contain plant nutrients such as N, P and K, as well as secondary and trace elements (Stephenson et al., 1990). The increase in sweet potato performance and nutritional status induced by poultry manure in this study could be attributed to its low C:N ratio (7.72/7.67). The high nutrient contents (Table 3) and a slow decomposition rate of poultry manure in the current study allows nutrient availability and release for the sweet potato crop throughout the life cycle.

The increased sweet potato growth and yield with the rates of biochar application could be attributed to biochar's liming effect in acidic soils, nutrient availability, nutrient use efficiency and modification of physical soil properties (Zhan et al., 2015; Kim et al., 2016; Pandian et al., 2016; Mensah and Frimpong, 2018; Pandit et al., 2018). The sweet potato's better performance might also be related biochar's long-term persistence in the soil, which ensures nutrient availability.

The significant interactions found between biochar and poultry manure on soil physical and chemical properties, growth and sweet potato yield, highlighting the potential of biochar in enhancing poultry manure use efficiency and improving better use of nutrients in the poultry manure. Because of the high C:N ratio of 65.5/64.5, biochar exhibited low nutritional contents and a slow decomposition rate (Table 3). However, using biochar in such mixed treatment applications could have reduced nutrient leaching and improved the soil's nutrient retention capacity, resulting in a higher sweet potato tuber yield (Major et al., 2012). Furthermore, the conditioning and ameliorative actions of biochar may have enhanced the impacts of the poultry manure treatments on sweet potato yield by improving nutrient use efficiency. Some researchers (Lentz et al., 2014; Partey et al., 2014; Zhan et al., 2015; Bass et al., 2016; Naeem et al., 2017; Minhas et al., 2020) have shown that the positive effects of biochar application on plant growth and yield - for example due to retention of nutrients - are strongest when combined with organic manure or inorganic fertilizers in tropical soils. The maximum dosage of biochar (30.0 t ha^{-1}) plus poultry manure (10.0 t ha^{-1}) resulted in the highest soil chemical properties, sweet potato growth and tuber yield. This finding supports the idea that biochar and poultry manure have a positive cumulative effect on soil productivity. In terms of combination, biochar and poultry manure produced synergistic relationships that increased soil OC and nutrients while also improving soil physical and chemical properties, resulting in increased sweet potato growth and yield. The findings showed that combined application of biochar and poultry manure synergistically increased sweet potato growth and yield.

The availability of soil OC, TN, P, K, Ca, and Mg has an effect on sweet potato yield, according to this study. K, N, Ca, Mg, and other trace elements are in high demand in sweet potatoes. Root crops such as sweet potato have been observed to have limited growth and yield due to these nutritional deficiencies and aluminum toxicity (O'Sullivan et al., 1997). At various rates of biochar and poultry manure treatment, the value of soil K, N, Ca and Mg increased significantly ($P \leq 0.05$). Sweet potato production has been shown to be dependent on potassium (Njoku et al., 2001; O'Sullivan et al., 1997). One of the most important minerals for sweet potato growth is K. It affects the plant's capacity to utilize nitrogen efficiently and aids water uptake. Potassium is also necessary for increasing nutrient value and optimizing yield.

Bulk density, porosity, and moisture content all had a substantial impact on sweet potato tuber yield, according to the results of the multiple regression analysis. The multiple regressions showed that pH, OC, TN, P, K, Ca, and Mg all had a significant impact on sweet potato tuber yield. Sweet potato tuber yield increased when bulk density was reduced, porosity and moisture content were increased, and soil chemical properties were improved. As a result, in this study, sweet potato tuber yield is influenced by bulk density, porosity, and moisture content, as well as soil chemical properties. Reduced soil bulk density is known to increase root penetration, and as a result, improve water, nutrient uptake and root formation (Agbede, 2008; Lampurlanes and Cantero-Martinez, 2003), resulting in increased growth and yield. Reduced bulk density and high porosity of biochar and poultry manure amended soils, resulting in reduced mechanical impedance for sweet potato root growth, leading to increased sweet potato tuber length and size. The findings applying 30.0 t ha^{-1} biochar + 10.0 t ha^{-1} poultry manure increased sweet potato yield were consistent with the treatment's better improvement in soil physical and chemical properties.

CONCLUSIONS

This study showed that biochar and poultry manure as soil amendments have the ability to improve the quality of degraded soils. Sand soil and sandy loam soil amended with sole biochar and poultry manure, or their combination at various rates, improved soil physical and chemical properties, growth and sweet potato tuber yield. The capacity of biochar to improve poultry manure use efficiency and enhance better use of nutrients in the poultry manure was underlined by the improvement in sweet potato growth and tuber yields, which was attributable to enhanced soil physical and chemical properties. The highest dosage of 30.0 t ha^{-1} biochar + 10.0 t ha^{-1} poultry manure improved soil properties and sweet potato performance the most, hence this treatment is recommended for soil fertility management and sweet potato production in the research regions (rainforest agroecology of southwest Nigeria). These findings, however, should be confirmed using different soil types, crops, and agroecological zones, as well as different rates and combinations of biochar and poultry manure. For further research, long-term studies concentrating on the persistence of biochar impacts on soils and crops are advised.

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AUTHOR CONTRIBUTIONS

Taiwo Michael Agbede conceived and designed the experiments. Taiwo Michael Agbede and Adefemi Oyewumi performed the experiments. Taiwo Michael Agbede and Adefemi Oyewumi contributed reagents, materials, analysis tools or data. Taiwo Michael Agbede analyzed and interpreted the data. Taiwo Michael Agbede and Adefemi wrote the paper.

CONFLICT OF INTEREST

The authors declare no conflicting interests.

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