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RESEARCH ARTICLE

Effects of biochar and poultry manure on soil properties, growth, quality, and yield of cocoyam (*Xanthosoma sagittifolium* Schott) in degraded tropical sandy soil

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Abstract
Use of biochar (B) and poultry manure (PM) as soil amendments can improve the productivity and sustainability of tropical agriculture. Our fieldwork is the first research on the agronomic use of B and PM for the growth of cocoyam in sandy soil of the humid tropics. In this study, the effects of B, PM and their mixture were investigated on soil properties, mineral and nutrient concentrations, growth, and corm and cormel yields of cocoyam during the 2017 and 2018 cropping seasons. The experiment consisted of 4 × 2 factorial combinations of B (0, 10, 20, and 30 Mg ha^{-1}) and PM (0 and 7.5 Mg ha^{-1}). In both years, the application of B and PM either alone or in combination improved soil physical and chemical properties, plant nutritional status, growth, and corm and cormel yields of cocoyam. The combination of 30 Mg ha^{-1} B and 7.5 Mg ha^{-1} PM (B_{30} + $PM_{7.5}$) gave the highest corm and cormel yields of cocoyam. Pooled over the 2 years, application of B at 30 Mg ha^{-1} and PM at 7.5 Mg ha^{-1} (B_{30} + $PM_{7.5}$) significantly increased corm yield of cocoyam by 47 and 66%, respectively, when compared with sole PM at 7.5 Mg ha^{-1} and B at 30 Mg ha^{-1}. Lowest corm and cormel yields were obtained for the unmanure control. The combination of 30 Mg ha^{-1} B and 7.5 Mg ha^{-1} PM is recommended for soil fertility management and cocoyam production in the rainforest agroecology of SW Nigeria.

Keywords: Biochar; Poultry manure; Soil properties; Cocoyam; Cormel; Tropics; Sandy soil

Introduction

The sustainability of agriculture in tropical sandy soils faces large constraints due to high bulk density, low water-holding and nutrient-retention capacity, and accelerated mineralization of soil organic matter (OM). For these reasons, most sandy soils are unfit to produce high crop yield because they are generally light textured and deficient in nutrient reserves. Sandy soils of the tropics have low OM, nutrient content (N, P, K, Ca, Mg), low cation exchange capacity (CEC), and low soil moisture storage and availability (Uzoma *et al.*, 2011b). Soil fertility can be maintained and improved using either organic manure or inorganic fertilizers.

Soil improvement based on the application of fertilizers is often unaffordable for poor farmers; even the excessive use of chemical fertilizer has not been sustainable because its continuous use causes soil acidity, nutrient imbalance (Agbede *et al.*, 2017), and physical degradation due to decrease in soil OM caused by long-term cultivation, leading to decreased soil aggregate stability, and thereby increasing its erosion potential (Tejada and Gonzalez, 2007). Another disadvantage of chemical fertilizer is that crop response to the applied fertilizer may be limited by low inherent physical, chemical, and biological fertility of the soil (Agegnehu *et al.*, 2016). Therefore, resource-poor farmers are forced to depend on organic manures as a nutrient source.

Although the application of OM (i.e., manure, mulches, and composts) has frequently been shown to increase soil fertility, the benefits are generally short lived in the tropical soils, especially in sandy soils because of the rapid decomposition of soil OM under high temperature and aeration (Glaser *et al.*, 2002; Mekuria and Noble, 2013). Since frequent applications are required, the application of organic amendments become expensive, and thus not popular (Masulili *et al.*, 2010). For this reason, organic amendments have to be applied every year to sustain crop productivity. An alternative to this practice could be the use of more stable compounds such as biochar (B) (Glaser *et al.*, 2002; Uzoma *et al.*, 2011a) instead of the ordinary degradable organic manures.

Biochar, a carbon-rich material obtained from heating organic biomass under limited oxygen conditions appears to be a more stable source of carbon and it remains in the soil for a long time (Lehmann *et al.*, 2006). The beneficial effects of B on soil properties have been reported by many researchers and include physical (Chan *et al.*, 2008), chemical (Yamato *et al.*, 2006), and biological changes in soil (Rondon *et al.*, 2007). Improvements in plant growth and yield following B application has also been reported for a variety of crops, such as radish (Chan *et al.*, 2008), common beans (Rondon *et al.*, 2007), soybean (Tagoe *et al.*, 2008), and maize (Yamato *et al.*, 2006; Sukartono *et al.*, 2011). Although B has recently attracted considerable interest as a sustainable technology to improve soil fertility in the tropics, information on their potential to amend degraded sandy soils under cocoyam cropping system in the rainforest zone of southwest Nigeria does not exist. Most of the B studies were either conducted on clayey soils or sandy soils characterized by a wide range of B mixing rates and plant responses (Glaser *et al.*, 2002; Sohi *et al.*, 2009). Some mixing rates used in early studies, for instance, 135.2 Mg ha^{-1} (Lehmann *et al.*, 2003), 200 Mg ha^{-1} (Rondon *et al.*, 2007), and 100 Mg ha^{-1} (Chan *et al.*, 2007), may not be feasible in regions where feedstock availability is limited such as in sandy dryland areas. Furthermore, little research has been conducted on the effects of B on the physicochemical properties of sandy soil and crop yield. Where such studies were performed, they were pot experiments in a greenhouse and not field experiment.

While B represents a soil conditioner that can change the physical and chemical properties of the soil, it might be limited as a nutrient supplier alone, because of its very low nutrient concentrations and degradation rate (Partey *et al.*, 2014). For improving soil productivity and cocoyam performance, addition of poultry manure (PM) in combination with B may be one of the best options. PM is high in organic materials and contains nutrients essential for crop production. The use of PM as a source of plant nutrients is extremely popular around the globe and it has been used to improve soil fertility and increase crop yield (Abd El-Kader *et al.*, 2010; Agbede and Ojeniyi, 2009).

Dou *et al.* (2012) and Chan *et al.* (2007) reported that B application to soils in combination with either organic or inorganic fertilizer has a remarkable impact on plant growth and yield. The effects of B, compost, their mixture, and nitrogen fertilizer on yield and nitrogen use efficiency of barley grown on a Nitisol in the highlands of Ethiopia were investigated (Agegnehu *et al.*, 2016). Compost or compost + B with N fertilizer increased grain yield up to 60% compared to the yield with the highest N fertilizer alone. In India, Masto *et al.* (2013) tested the synergistic benefits of co-application of fly ash and B on soil quality, plant growth, and yield using maize. Amendment of an acid soil with B and lignite fly ash improved the soil quality and decreased the availability of heavy metals. Besides the improvement in soil quality, B alone and the co-application of B and fly ash increased maize grain by 11 and 28%, respectively. Revell *et al.* (2012) and Naeem *et al.* (2017) suggested B and its combination with other organic residues such as compost or manure for higher crop yields on physically degraded soils. The use of such residues for improving soil quality as well as crop productivity in the forest–savanna transition zone of southwest Nigeria might be ecologically promising.

Cocoyam (*Xanthosoma sagittifolium* (L.) Schott) is an important tuber crop grown in many parts of the world, a major staple food in Nigeria, South Pacific Islands, and some parts of

Table 1. Soil physical and chemical properties of the site prior to experimentation in 2017

Property	Value
Sand (%)	92.4
Silt (%)	2.8
Clay (%)	4.8
Textural class	Sandy soil
Bulk density (Mg m^{-3})	1.58
pH (water)	5.6
Organic carbon (%)	0.74
Total N (%)	0.10
Available P (mg kg^{-1})	2.68
Exchangeable K (cmol kg^{-1})	0.12
Exchangeable Ca (cmol kg^{-1})	3.1
Exchangeable Mg (cmol kg^{-1})	0.98

Asia (Uwah *et al.*, 2011). The corms and cormels are the major economic parts of cocoyam, which is the cheapest and most handy source of carbohydrate in meals recommended for aged people, diabetics, convalescents, and most gastro-intestinal disorder patients (Adekiya *et al.*, 2016). However, cocoyam being a tuber crop is sensitive to poor soil physical conditions (Adekiya *et al.*, 2011) and, therefore, the application of B and PM could be a way of improving the soil physicochemical properties and yield of cocoyam. In Nigeria, few studies had evaluated the effects of B addition to soil in combination with organic fertilizer or inorganic fertilizer on crop yields. Therefore, the objective of this study was to evaluate the effects of B and PM on soil properties, leaf nutrient concentrations, mineral composition, growth, and yield of cocoyam in the forest–savanna transition zone of southwest Nigeria.

Materials and Methods

Site description and treatments

Field experiments were carried out at the Teaching and Research Farm of Rufus Giwa Polytechnic, Owo, Ondo State, Nigeria, in April 2017 and 2018 cropping seasons. Rufus Giwa Polytechnic, Owo (7°12′N and 5°35′E, 348 m above sea level), is located in the forest–savanna transition zone of southwest Nigeria. The soil at Owo is of the Okemesi Series, and Alfisol classified as Oxic Tropuldalf or Luvisol (Soil Survey Staff, 2014) derived from quartzite, gneiss, and schist (Adekiya, 2018). The soil was sandy in texture, slightly acidic, and had high bulk density, low organic carbon (OC), low total N, low exchangeable K, and very low available P, but adequate levels of exchangeable Ca and Mg (Table 1) according to the critical values of 3% OM, 0.2% N, 10 mg kg^{-1} available P, 0.16–0.20 cmol kg^{-1} exchangeable K, 2 cmol kg^{-1} exchangeable Ca, and 0.4 cmol kg^{-1} exchangeable Mg recommended for crop production in ecological zones of Nigeria (Akinrinde and Obigbesan, 2000). Rainfall is bimodal, averaging about 1400 mm per year, with most of it occurring during March–July and mid-August–November. Mean annual air temperature is about 32 °C. The trial was established in a field left fallowed for a year after it had been cropped with yam, maize, cassava, melon, cowpea, and tomatoes, respectively, during the previous 6 years and had not received fertilizer application. Previous soil treatments included tillage practice such as conventional tillage system which involves ploughing, harrowing, and ridging. The predominant weeds at the site were Siam weed (*Chromolaena odorata* L. King and Robinson), Haemorrhage plant (*Aspilia africana* Pers. Adams), and goat weed (*Ageratum conyzoides* L.).

The experiment consisted of 4 × 2 factorial combinations of B (0, 10, 20 and 30 Mg ha^{-1}) and PM (0 and 7.5 Mg ha^{-1}). The B used in the experiment was alkaline, while PM used was slightly acidic (Table 2). B was high in organic C, K, Ca, and Mg, and had a high C:N ratio compared with

Table 2. Chemical composition of biochar and poultry manure used in the experiment

Property	Biochar	Poultry manure
pH (water)	7.62	6.81
Ash (%)	0.028	12.1
Organic C (%)	52.03	21.6
Nitrogen (%)	0.65	2.88
C/N	80.05	7.50
Phosphorous (%)	0.36	1.30
Potassium (%)	1.75	1.67
Calcium (%)	4.51	0.89
Magnesium (%)	7.75	0.54
Copper (%)	0.013	0.35
Manganese (%)	0.068	0.22
Sulphur (%)	0.091	0.31
Zinc (%)	0.008	0.25
Sodium (%)	0.21	0.28

PM, but PM had higher concentrations of N, P, and micronutrients compared with B (Table 2). The eight treatments were factorially arranged in a randomized complete block design with three replications. Each block comprised of eight plots and each plot was 5 × 4 m. Blocks were 3 m apart and plots were 1 m apart.

Biochar and PM preparation and analyses

Biochar used in the experiment was obtained from a local commercial charcoal producer at Owo, Ondo State, Nigeria, who uses hardwood such as *Parkis biglosa, Khaya senegalensis, Prosopis africana* and *Terminalia glaucescens* in traditional kilns to produce charcoal for domestic use. The temperature inside the kiln was monitored with a thermocouple and it was about 580°C for 24 h of carbonizing. The B was ground and sieved through a 2-mm sieve so that its particle size is the same as the sandy soil used in the experiment. The PM was obtained from the poultry farmer in Owo, and decomposed using the passive aeration composting technique as described by Taiwo and Oso (2004). A plastic barrel measuring 2.5 m in diameter and 3 m long with nine holes perforated at intervals of 30 cm apart on the bottom sides was used for composting. PM was moistened with water and placed into the plastic barrel, and its temperature was continuously monitored on weekly basis by inserting a thermometer into the composting plastic barrel until complete decomposition was attained (when temperature was stabilized). The PM and B used for this experiment were analyzed to determine their nutritional compositions after being air-dried and sieved using a 2-mm sieve. The analyses for OC, N, P, K, Ca, and Mg were done in accordance with Tel and Hagarty (1984).

Land preparation, incorporation of B and PM, and planting of cocoyam

The site was manually cleared and weeds were removed. Thereafter, the experimental site was laid out to the required plot size (5 × 4 m). The soil was then disked to 20 cm depth using a traditional hoe. B and PM were weighed and spread uniformly over the soil on the plots according to the required rates (B: 0, 10, 20, and 30 Mg ha^{-1}; PM: 0 and 7.5 Mg ha^{-1}). B and PM were incorporated into the soil (about 10 cm depth) with a traditional hoe in each growing season, during the planting of cocoyam cormels. Cocoyam (*Xanthosoma sagittifolium* cv. Owo local) cormels weighing approximately 150 g were planted on 21 April 2017 and 18 April 2018. One cocoyam cormel was planted per hole at a spacing of 1 × 1 m. Weeding was done manually thrice at 42, 84, and 126 days after planting.

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Determination of soil physical and chemical properties

Before beginning the experiment, soil samples were taken from 0–15 cm depth at 10 points selected randomly from the experimental site using steel coring tubes (4 cm diameter, 15 cm high). The soil samples collected were bulked, air-dried, and sieved using a 2-mm sieve and analyzed for particle size, textural class, organic carbon (OC), N, P, K, Ca, Mg, and pH. Soil samples were also put in an oven set at 100°C for 24 h for the determination of bulk density. Disturbed soil samples were also collected on an individual plot basis at harvest of cocoyam from 0–15 cm depth in 2017 (first crop) and 2018 (second crop) and similarly analyzed for chemical properties. The procedures for the analysis of soil OC, N, P, K, Ca, Mg, and pH are described in detail by Carter and Gregorich (2007) and Agbede *et al.* (2019).

In each year and after 2 months of planting the cocoyam cormels, soil physical properties were evaluated in all plots at 2-month intervals on four occasions and averaged. Five samples (4 cm diameter, 0–15 cm depth) were collected from each plot using a steel coring tube and were used for the evaluation of bulk density, total porosity, and gravimetric moisture content after oven-drying at 100 °C for 24 h (Agbede *et al.*, 2019).

Analysis of cocoyam leaves and cormels

Two- to three-week-old cocoyam leaves were collected at 168 days after planting from five plants per plot and analyzed for N, P, K, Ca, and Mg, following the Association of Official Analytical Chemists (AOAC, 2012). After 9 months of planting, the 10 central plants from each plot were harvested. From all the cocoyam cormels harvested per plot, five of them with uniform sizes were selected randomly. The N, P, K, Ca, Mg, Fe, and Zn contents of cocoyam cormels were determined also in accordance with the Association of Official Analytical Chemists (AOAC, 2012).

Determination of yield parameters

Ten plants were selected per plot for the determination of plant height, number of leaves per plant, and leaf area per plant at 168 days after planting, when the cocoyam plant reached its peak growth (Agbede, 2008). Plant height was measured by meter rule and leaf area by graphical method (Agbede, 2008). Yield attributes measured included the number of tubers, tuber weight (kg plant^{-1}), and tuber yield (Mg ha^{-1}). These were measured at 9 months after planting by harvesting ten cocoyam plants per plot. The total number of corms and cormels produced by each plant was physically counted and recorded as the number of tubers; their weights were determined and recorded, and thereafter converted to tuber yield.

Statistical analysis

Data collected from each experiment were subjected to analysis of variance (ANOVA) using the Genstat statistical package (GENSTAT, 2005) to determine the effects of treatments on soil physical and chemical properties, leaf nutrient concentrations, mineral composition of cocoyam cormel, growth, and corm and cormel yields of cocoyam. The standard error of difference between means (s.e.d.) was used to compare the treatments. Mention of statistical significance refers to $p = 0.05$ unless otherwise stated.

Results

Soil physical and chemical properties

In both years and relative to the control, B and PM treatments significantly reduced bulk density and increased porosity and moisture content (Table 3). Moreover, the bulk density decreased, while the porosity and moisture content increased with the rate of B application. When studied

Table 3. Effect of biochar and poultry manure on soil physical properties (0–15 cm depth) when averaged across four sampling periods (2, 4, 6 and 8 months after planting) in 2017 and 2018

Year	Biochar (Mg ha^{-1})	Poultry manure (Mg ha^{-1})	Bulk density (Mg m^{-3})	Porosity (%)	Moisture content (%)
2017					
	0.0	0.0	1.52	42.64	10.9
	0.0	7.5	1.41	46.79	11.8
	10.0	0.0	1.47	44.53	12.2
	10.0	7.5	1.29	51.32	15.1
	20.0	0.0	1.38	47.92	15.3
	20.0	7.5	1.08	59.25	16.6
	30.0	0.0	1.12	57.74	16.9
	30.0	7.5	0.96	63.77	18.9
2018					
	0.0	0.0	1.56	41.13	11.7
	0.0	7.5	1.29	51.32	14.0
	10.0	0.0	1.35	49.06	14.4
	10.0	7.5	1.15	56.60	17.7
	20.0	0.0	1.18	55.47	16.9
	20.0	7.5	0.94	64.53	19.2
	30.0	0.0	1.00	62.26	18.3
	30.0	7.5	0.82	69.06	21.5
		SE±	0.06	2.10	0.77
Year (Y)	ns	ns	ns	ns	ns
Biochar (B)	*	*	*	*	*
Poultry manure (PM)	*	*	*	*	*
Y × B	ns	ns	ns	ns	ns
Y × PM	ns	ns	ns	ns	ns
B × PM	*	*	*	*	*
Y × B × PM	ns	ns	ns	ns	ns

ns = not significant; * = significant at 5% level of probability.

as individual factors, year (Y) did not influence soil physical properties, whereas the application of B and PM significantly influenced soil physical properties. The application of PM reduced bulk density and increased porosity and moisture content compared with the control. Similarly, the application of B as an individual factor also significantly improved soil physical properties compared with the control. The interaction of B × PM was significant for soil bulk density, porosity, and moisture content. However, the interactive effects of Y × B and Y × PM were not significant. When all the three factors (Y × B × PM) were considered together, the interaction was not significant.

Regardless of the year, B or PM applied alone significantly increased soil pH, organic carbon (OC), N, P, K, Ca, and Mg, and concentrations increased with increasing B application rates (Table 4). The PM alone increased soil chemical properties when applied at 7.5 Mg ha^{-1} compared with the control. The combination of 30 Mg ha^{-1} B + 7.5 Mg ha^{-1} PM (B_{30} + $PM_{7.5}$) had the greatest improvement in soil chemical properties among all the treatments while the control (no application of B or PM) had the least favorable soil chemical properties. When studied as individual factors, Y did not influence soil chemical properties. The interactive effect of B × PM was significant for soil pH, OC, N, P, K, Ca, and Mg. The interactive effect of Y × B and Y × PM was not significant, nor was Y × B × PM interaction significant for soil pH, OC, N, P, K, Ca, and Mg.

Leaf and cormel nutrient concentrations

Compared with the control (no application of B or PM), PM alone applied at 7.5 Mg ha^{-1} significantly increased leaf N, P, K, Ca, and Mg of cocoyam as well as B alone applied at 30 Mg ha^{-1} in

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Table 4. Effect of biochar and poultry manure on soil chemical properties after crop harvest in 2017 and 2018

Year	Biochar (Mg ha^{-1})	Poultry manure (Mg ha^{-1})	pH (water)	OC (%)	N (%)	P (mg kg^{-1})	K (cmol kg^{-1})	Ca (cmol kg^{-1})	Mg (cmol kg^{-1})
2017									
	0.0	0.0	5.64	0.63	0.09	1.95	0.09	1.73	0.37
	0.0	7.5	5.96	1.42	0.15	3.33	0.20	2.86	0.73
	10.0	0.0	6.05	1.12	0.09	1.96	0.22	2.94	0.75
	10.0	7.5	6.58	1.56	0.16	3.45	0.35	4.24	0.99
	20.0	0.0	6.65	1.22	0.11	2.47	0.28	3.20	0.87
	20.0	7.5	6.72	1.69	0.18	4.09	0.38	5.01	1.08
	30.0	0.0	6.80	1.33	0.13	2.70	0.35	4.13	1.02
	30.0	7.5	6.86	1.99	0.20	6.19	0.41	5.41	1.36
2018									
	0.0	0.0	5.62	0.59	0.07	1.87	0.20	1.51	0.33
	0.0	7.5	6.36	1.52	0.17	3.73	0.38	3.06	0.77
	10.0	0.0	6.45	1.18	0.11	2.56	0.42	3.16	0.79
	10.0	7.5	6.98	1.62	0.20	4.15	0.66	4.58	1.05
	20.0	0.0	7.05	1.28	0.13	2.87	0.54	3.64	0.91
	20.0	7.5	7.12	1.75	0.22	4.79	0.70	5.59	1.14
	30.0	0.0	7.20	1.39	0.15	3.10	0.66	4.53	1.04
	30.0	7.5	7.26	2.05	0.24	6.89	0.76	6.01	1.40
		SE±	0.13	0.10	0.01	0.36	0.05	0.33	0.07
Year (Y)	ns	ns	ns	ns	ns	ns	ns	ns	ns
Biochar (B)	*	*	*	*	*	*	*	*	*
Poultry manure (PM)	*	*	*	*	*	*	*	*	*
Y × B	ns	ns	ns	ns	ns	ns	ns	ns	ns
Y × PM	ns	ns	ns	ns	ns	ns	ns	ns	ns
B × PM	*	*	*	*	*	*	*	*	*
Y × B × PM	ns	ns	ns	ns	ns	ns	ns	ns	ns

ns = not significant; * = significant at 5% level of probability.

Table 5. Effect of biochar and poultry manure on leaf nutrient concentrations of cocoyam in 2017 and 2018

Year	Biochar (Mg ha^{-1})	Poultry manure (Mg ha^{-1})	N (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})
2017							
	0.0	0.0	14.1	0.7	15.6	40.3	5.1
	0.0	7.5	22.9	1.4	17.8	56.1	8.7
	10.0	0.0	17.9	0.7	20.2	69.7	9.0
	10.0	7.5	25.1	1.9	21.1	74.8	9.5
	20.0	0.0	20.7	0.9	22.5	76.5	9.7
	20.0	7.5	27.8	2.3	31.2	96.8	10.0
	30.0	0.0	22.7	1.2	24.6	86.1	9.9
	30.0	7.5	38.0	2.7	36.5	105.1	10.1
2018							
	0.0	0.0	13.5	0.5	13.8	36.5	5.5
	0.0	7.5	23.7	1.8	20.8	61.9	9.3
	10.0	0.0	18.7	0.9	24.0	77.7	9.6
	10.0	7.5	26.1	2.3	24.9	82.6	10.1
	20.0	0.0	21.3	1.1	27.1	86.7	10.3
	20.0	7.5	28.8	2.7	36.8	106.8	10.6
	30.0	0.0	23.5	1.4	28.8	95.9	10.5
	30.0	7.5	39.2	3.1	44.5	117.1	10.7
		SE±	1.78	0.20	2.07	5.72	0.41
Year (Y)	ns	ns	ns	ns	ns	ns	ns
Biochar (B)	*	*	*	*	*	*	*
Poultry manure (PM)	*	*	*	*	*	*	*
Y × B	ns	ns	ns	ns	ns	ns	ns
Y × PM	ns	ns	ns	ns	ns	ns	ns
B × PM	*	*	*	*	*	*	*
Y × B × PM	ns	ns	ns	ns	ns	ns	ns

ns = not significant; * = significant at 5% level of probability.

both years (Table 5). The leaf N, P, K, Ca, and Mg of cocoyam increased with rates of B application from 0 to 30 Mg ha^{-1}. However, B applied at 30 Mg ha^{-1} in combination with PM applied at 7.5 Mg ha^{-1} (B_{30} + $PM_{7.5}$) gave the highest leaf N, P, K, Ca, and Mg of cocoyam compared with the other treatments. When studied as individual factors, Y did not influence leaf nutrient concentrations of cocoyam. Sole application of PM and B significantly influenced leaf N, P, K, Ca, and Mg of cocoyam while their interaction was significant for all leaf nutrient concentrations of cocoyam. The interactions of Y × B and Y × PM were not significant for all leaf nutrients of cocoyam, nor was Y × B × PM interaction.

Biochar significantly increased the concentrations of N, P, K, Ca, Mg, Cu, Zn, and Fe in cormels with rates of application from 0 to 30 Mg ha^{-1} (Table 6). Similarly, PM significantly increased nutrient concentrations in cocoyam cormel when applied at 7.5 Mg ha^{-1} compared with the control. In both years, the maximum values of N, P, K, Ca, Mg, Cu, Zn, and Fe were attained when B was applied at 30 Mg ha^{-1} in combination with the application of PM at 7.5 Mg ha^{-1} (B_{30} + $PM_{7.5}$) compared with the other treatments. The control had the lowest values of nutrient concentrations in cocoyam cormel. When studied as individual factors, Y did not affect mineral nutrition in cocoyam cormel, whereas sole application of B and PM significantly influenced cormel mineral status. The interaction of B × PM was significant for most nutrients measured for cocoyam cormel while the effect of Y × B and Y × PM was not significant, nor was Y × B × PM interaction.

Growth, and corm and cormel yields of cocoyam

In both years, PM alone applied at 7.5 Mg ha^{-1} significantly increased plant height, number of leaves, leaf area, and corm and cormel yields of cocoyam compared with the control (no application of

Table 6. Effect of biochar and poultry manure on mineral concentrations of cocoyam cormels in 2017 and 2018

Year	Biochar (Mg ha^{-1})	Poultry manure (Mg ha^{-1})	N (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})	Fe (mg kg^{-1})
2017										
	0.0	0.0	5.5	0.08	4.4	1.3	42.6	1.94	3.10	42.4
	0.0	7.5	12.7	0.21	13.9	2.3	84.6	4.34	6.53	98.6
	10.0	0.0	7.0	0.10	10.4	1.2	57.9	2.28	3.97	57.1
	10.0	7.5	20.5	0.22	16.5	3.4	89.5	4.85	7.56	135.8
	20.0	0.0	8.3	0.12	11.4	1.6	72.8	3.04	4.92	65.1
	20.0	7.5	24.1	0.29	18.4	9.4	98.4	4.92	8.91	189.7
	30.0	0.0	11.5	0.14	13.2	1.9	81.8	3.18	5.18	72.2
	30.0	7.5	32.1	0.37	27.4	12.2	110.6	5.42	13.41	236.4
2018										
	0.0	0.0	4.9	0.06	3.4	0.9	39.8	1.78	2.86	37.4
	0.0	7.5	13.5	0.24	15.5	2.9	90.4	4.62	7.03	104.8
	10.0	0.0	7.6	0.11	11.6	1.6	62.5	2.48	4.39	61.9
	10.0	7.5	21.5	0.25	18.3	4.0	9.59	5.27	8.14	148.4
	20.0	0.0	8.9	0.14	12.6	2.0	78.4	3.46	5.34	70.5
	20.0	7.5	23.3	0.32	20.2	9.8	106.6	5.58	9.75	219.9
	30.0	0.0	12.3	0.16	14.4	2.1	87.6	3.92	5.94	86.4
	30.0	7.5	33.3	0.41	29.6	12.6	118.8	6.28	14.45	286.0
		SE±	2.30	0.03	1.73	1.03	7.20	0.35	0.84	19.0
Year (Y)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Biochar (B)	*	*	*	*	*	*	*	*	*	*
Poultry manure (PM)	*	*	*	*	*	*	*	*	*	*
Y × B	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Y × PM	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
B × PM	*	*	*	*	*	*	*	*	*	*
Y × B × PM	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

ns = not significant; * = significant at 5% level of probability.

Table 7. Effect of biochar and poultry manure on growth parameters, corm and cormel yields of cocoyam in 2017 and 2018

Year	Biochar ($Mg\ ha^{-1}$)	Poultry manure ($Mg\ ha^{-1}$)	Plant height (cm)	Number of leaves per plant	Leaf area per plant (m^2)	Corm yield ($Mg\ ha^{-1}$)	Cormel yield ($Mg\ ha^{-1}$)
2017							
	0.0	0.0	62.1	5.27	0.92	3.3	4.8
	0.0	7.5	92.4	6.42	1.55	5.1	6.4
	10.0	0.0	72.1	5.68	1.06	3.5	4.8
	10.0	7.5	107.7	6.74	1.78	5.7	7.0
	20.0	0.0	81.0	5.93	1.27	4.0	5.3
	20.0	7.5	119.1	6.82	2.00	6.4	7.7
	30.0	0.0	88.7	6.25	1.50	4.5	5.8
	30.0	7.5	136.4	7.04	2.25	7.6	8.9
2018							
	0.0	0.0	55.3	4.69	0.86	2.9	4.2
	0.0	7.5	99.6	7.04	1.61	5.5	7.0
	10.0	0.0	78.7	6.30	1.12	3.9	5.4
	10.0	7.5	114.9	7.36	1.84	6.1	7.6
	20.0	0.0	87.2	6.55	1.33	4.4	5.9
	20.0	7.5	125.9	7.42	2.06	6.8	8.3
	30.0	0.0	95.9	6.87	1.56	4.9	6.4
	30.0	7.5	144.0	7.66	2.31	8.0	9.5
		SE±	6.41	0.20	0.11	0.38	0.39
Year (Y)	ns	ns	ns	ns	ns	ns	ns
Biochar (B)	*	*	*	*	*	*	*
Poultry manure (PM)	*	*	*	*	*	*	*
Y × B	ns	ns	ns	ns	ns	ns	ns
Y × PM	ns	ns	ns	ns	ns	ns	ns
B × PM	*	*	*	*	*	*	*
Y × B × PM	ns	ns	ns	ns	ns	ns	ns

ns = not significant; * = significant at 5% level of probability.

B or PM), as shown in Table 7. Application of B alone significantly increased plant height, number of leaves, leaf area, and corm and cormel yields of cocoyam in both years. The effect of Y was not significant on growth and yield of cocoyam, while the interaction of B × PM was significant for growth parameters and corm and cormel yields of cocoyam. Application of B at 30 $Mg\ ha^{-1}$ and PM at 7.5 $Mg\ ha^{-1}$ ($B_{30} + PM_{7.5}$) significantly increased the growth parameters and corm and cormel yields of cocoyam compared with all other treatments. Therefore, using the mean of the two cropping seasons, the application of B at 30 $Mg\ ha^{-1}$ and PM at 7.5 $Mg\ ha^{-1}$ ($B_{30} + PM_{7.5}$) significantly increased the corm yield of cocoyam by 152% when compared with the control treatment (no application of B or PM).

Correlation between soil properties and mineral composition of cocoyam cormels, growth, and yield of cocoyam

There was a significant correlation between soil bulk density, porosity, moisture content, OC, N, P, K, Ca, and Mg and mineral N, P, K, Ca, Mg, Cu, Zn, and Fe composition of cocoyam cormel. However, there was no significant correlation between soil pH and mineral composition of cocoyam cormels (Supplementary Material Table S1). High negative correlations were recorded between bulk density and growth and yield of cocoyam, while high positive correlations were found between porosity, moisture content, and soil chemical properties and growth and yield of cocoyam in pooled data of 2017 and 2018 (Supplementary Material Table S2). However, there was no significant correlation between soil pH and corm and cormel yields of cocoyam.

Discussion

Results showed that the site of experiment was low in OC, N, P, and K, and slightly acidic with high bulk density (Table 1). These conditions are the characteristics of Alfisols of southwest Nigeria (de Ridder and van Keulen, 1990; Lal, 1986). The high bulk density before the commencement of the experiment was attributed to the low OM of the site (Obi and Nnabude, 1995) and sandy nature of the soil. The low soil fertility status could also be adduced to the continuous previous cultivation using implements such as disc plough, disc harrow and disc ridger, and wheel traffic of tractor passes over years, which compacts the soil and degrades the soil properties.

The application of B and PM alone, or in combination with each other, significantly improved soil physical properties compared with the control, and decreasing bulk density and increasing moisture content and porosity (Table 3). Laboratory incubation experiments based on organic amendments have been shown to reduce bulk density in many studies due to the enhancement of soil OM by the B and PM, which act as binding agents to stabilize soil structure thereby reducing bulk density and increasing porosity and moisture content (Gamage *et al.*, 2016; Githinji, 2014; Herath *et al.*, 2013; Uzoma *et al.*, 2011a. The decrease in bulk density had been observed in line with increased soil porosity and soil moisture, which mediates the biophysical environment for root and microbial respiration (Basso *et al.*, 2013). A similar effect of PM in terms of improving soil physical properties has been reported by Agbede *et al.* (2017), with the addition of B significantly decreasing the bulk density of the sandy soil studied (Table 3). This is consistent with previous studies on both fine- (Chaganti and Crohn, 2015) and coarse-textured soils (Lim *et al.*, 2016). At least two mechanisms could be responsible for the reduction in bulk density after B application. First, B has lower bulk density (<0.6 g cm^{-3}) than field soil (~ 1.2 g cm^{-3}). Thus, B application probably reduces the density of the bulk soil through the mixing or dilution effect (Alburquerque *et al.*, 2014; Lehmann *et al.*, 2011). Second, B can reduce bulk density by interacting with soil particles and improving aggregation and porosity (Blanco-Canqui, 2017). In addition, B can alter the packing of soil particles, and create additional external soil porosity (Lim *et al.*, 2016).

Overall, B and PM application reduced bulk density, suggesting the potential to improve soil structural development and stability. There was an increase in moisture content as a result of B application compared with the control (Table 3). This study corroborates the findings of Glab *et al.* (2016) and Zhang *et al.* (2016) from their short-term laboratory studies. Increases in soil moisture are attributed to more micropores in B to physically retain water and/or improved aggregation that resulted in more pore spaces. Another reason for increased moisture content in the B-applied plots compared with the control was adduced to B's relatively higher surface area and higher porosity compared to other types of soil OM, and its ability to improve water retention through the improvement of soil structure and soil aggregation (Asai *et al.*, 2009; Brockhoff *et al.*, 2010).

The result that B and PM increased soil pH, OC, P, K, Ca, and Mg concentrations is consistent with the chemical composition of the B and PM used (Table 2). The mechanisms responsible for increasing soil pH with PM application may include ion exchange reactions between terminal OH^- of Al^{3+} or Fe^{2+} hydroxyl oxides and organic anions produced from the decomposition of PM such as malate, citrate, and tartrate (Dikinya and Mufwanzala, 2010). The ability of organic manure to increase soil pH could also be attributed to the presence of basic cations contained in the PM, which are released upon microbial decarboxylation. As the OM components of the PM decomposed, nutrients were released into the soil, and hence the increasing rate of 7.5 Mg ha^{-1} increased N, P, K, Ca, and Mg (Table 4).

According to Berek (2014), important properties of B are the high surface area and porosity, low bulk density, high nutrient content, high stability, high cation exchange capacity (CEC), neutral to high pH, and high carbon content. These properties make it suitable as an amendment for tropical sandy and clay soil in sub-Saharan Africa (Gwenzi *et al.*, 2015). The increase in pH as a

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result of B application is due to its high liming potential (pH 7.62) and Ca content. The increase in soil nutrients in plots amended with B compared with the control (Table 4) was attributed to the addition of nutrients contained in B, and through improved nutrient retention, modified soil microbial dynamics, and increased decomposition of organic material in soil as reported in previous studies (Lehmann and Joseph, 2009; Lehmann and Rondon, 2006; Lehmann *et al.*, 2003; Sohi *et al.*, 2009). According to Major *et al.* (2009), B is known to retain nutrients by capturing of nutrient-containing water in its micropores, which is held by capillary forces. B particles are assumed to act like clay and thus hold large amounts of immobile water even at increased matric potentials. Consequently, nutrients dissolved in this immobile water would be kept near the soil surface and would be available for plants (Major *et al.*, 2009). In addition, due to the adsorption of cations and anions by B, leaching of applied nutrients is reduced (Major *et al.*, 2009).

Nutrient concentrations in the leaves of cocoyam plants in the control plots (Table 5) were below the critical levels of 3.2% N, 0.5% P, 2.3% K, 0.9% Ca, and 1.3% Mg, as recommended by Kabeerathumma *et al.* (1987). As a consequence, leaves of cocoyam plants exhibited symptoms of deficiencies in N (yellow color), P (purple color), and K (burnt leaf margin). The application of B and PM increased the leaf N, P, K, Ca, and Mg concentrations of cocoyam plants compared with the control, which could be attributed to the improvement of soil chemical properties with these amendments (Table 4). There was increased nutrient availability in the soil as a result of the application of B and PM leading to increased uptake by cocoyam plants. The increase in leaf nutrient concentrations of cocoyam with rates of B suggests an increase in soil chemical properties as the rates of B increase. According to Lehmann and Rondon (2006), high B application rates in a tropical environment led to increased uptake of P, K, Ca, Zn, and Cu by plants. Steinbeiss *et al.* (2009) observed an increase in plant uptake of P, K, and Ca after B application. Accordingly, B amendment on different soils has led to increased availability and uptake of nutrients by plants (Hass *et al.*, 2012; Uzoma *et al.*, 2011b). Agbede (2010) also found that the application of PM to soil increased leaf N, P, K, Ca, and Mg concentrations of sweet potato plants.

The significant influence of B and PM on the mineral composition of cocoyam cormel indicated that B and PM contain some nutrients which are released into the soil upon mineralization. The findings that mineral composition of cocoyam cormel increases with rates of B is consistent with the soil chemical properties of the biochar rates (Brockhoff *et al.*, 2010; Chaganti and Crohn, 2015). The findings that PM improved nutrient availability in soil which leads to significant improvement in nutrient status and yield of cocoyam are consistent with the initial low fertility of the soil at the experimental site. Stephenson *et al.* (1990) and Kingery *et al.* (1994) reported that plant nutrients found in PM include N, P, and K as well as secondary and trace elements. Enhancement of cocoyam performance and nutrient status by PM in this study was attributable to the fact that PM had a low C:N ratio (7.5). The high nutrient concentrations and the low C:N ratio of the PM should have increased decomposition and nutrient release for a long-duration crop like cocoyam. The main reasons for increased crop productivity following biochar application can be attributed to the following: direct alteration of soil chemistry through biochar's inherent characteristics including liming effect in acidic soils, direct nutrient addition through B, overall higher nutrient availability, and nutrient use efficiency; allocation of chemically active surfaces that influence the dynamics of soil nutrients; and modification of physical soil properties that lead to increased root growth and/or water and nutrient retention and plant availability (Hossain *et al.*, 2010; Jeffery *et al.*, 2011; Lehmann *et al.*, 2003; Sohi *et al.*, 2009; Sukartono *et al.*, 2011). The good performance of cocoyam due to B application could also be due to the nature of B applied and the long growing period of the cocoyam crop (9-month field experiment for each year 2017, 2018). In their earlier studies, Asai *et al.* (2009) reported that the strong resistance of B to microbial decomposition and hence its persistence in the soil ensure the benefits of is application.

Significant interactions were found between B and PM on soil physical and chemical properties, leaf and cormel nutrient concentrations, growth, and corm and cormel yields of cocoyam (Tables 3–7), which supported reports of the B's ability to improve the efficiency of utilization

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of nutrients in the PM. B itself had low nutrient concentrations and decomposition rate because of the high C:N ratio (Table 2). However, the inclusion of B in mixed treatments could have potentially reduced nutrient leaching and increased the nutrient holding capacity of the soil, increasing cocoyam yield. Furthermore, the conditioning effect of the B may have increased the effects of the PM on cocoyam yield through improved nutrient use efficiency. The positive effects of B application on plant growth – for example, due to retention of nutrients – are strongest when combined with organic or inorganic fertilizers, especially on tropical soils (Alburquerque *et al.*, 2013; Glaser *et al.*, 2002; Hossain *et al.*, 2010; Ogawa *et al.*, 2006; Schulz and Glaser, 2012; Van Zwieten *et al.*, 2010). Peng *et al.* (2011) found an increase in maize biomass by 64% (without NPK fertilizer) and an increase of maize biomass by 146% (with NPK fertilizer) for an Ultisol following B application (2.4 Mg ha^{-1}). Our findings attest to the positive cumulative effect of B and PM on soil productivity. B and PM had synergistic relations in terms of combination to further enhance soil OC and nutrients and improve soil physical properties.

The correlations between soil properties (except soil pH) and mineral nutrition in cocoyam cormels were significant (Supplementary Material Table S1) as well as between soil properties and growth and yield of cocoyam (Supplementary Material Table S2). The non-significant correlation between soil pH and mineral nutrition in cocoyam cormels, and between soil pH and corm and cormel yields of cocoyam may be due to the initial soil pH of 5.6 before the start of the experiment, as it falls within the optimum soil pH of 5.5–6.5 recommended for cocoyam production (Anikwe *et al.*, 2015; Onwueme, 1999). This implies that pH was not a limiting factor for cocoyam performance. The significant correlations of bulk density, porosity, and moisture content *vs.* growth, yield, and chemical properties could be adduced to the residual effects of the B and PM in the second year of application. Such effects would be increased soil OC and OM decomposition, which led to enhancement of soil porosity and reduction in bulk density. Reduction in soil bulk density is known to increase root penetration and, therefore, enhance water and nutrient uptake and root formation (Agbede, 2008; Lampurlanes and Cantero-Martinez, 2003), which will consequently increase growth and yield. The correlations showed that bulk density, porosity, moisture content, OC, N, P, K, Ca, and Mg significantly influenced the mineral composition and yield of cocoyam. In general, cocoyam has high demand for K, Ca, Mg, Fe, P, N, and other trace elements, and the deficiencies of these nutrients, as well as aluminum toxicity, have been reported to limit growth and yield of root crops (Anikwe *et al.*, 2015). Finally, reduced bulk density and high porosity of B and PM soils would have reduced mechanical impedance to cocoyam root growth and increased the length and size of the corm and cormels.

Conclusions

This is the first report on the agronomic use of B and PM for growing cocoyam in a sandy soil of the humid tropics. Sandy soil amended with sole B and PM and their combination improved soil physical and chemical properties, plant nutritional status, growth, and corm and cormel yields of cocoyam. The improvement in mineral composition, growth, and corm and cormel yields of cocoyam was attributed to the reduced bulk density, increased porosity, and moisture content, and increases in soil OC, N, P, K, Ca, and Mg contents. There were significant interactions of B × PM on soil bulk density, porosity, and moisture content; soil pH, OC, N, P, K, Ca, and Mg; leaf N, P, K, Ca, and Mg; mineral concentrations, growth, and corm and cormel yields of cocoyam, which highlighted the improvement of nutrient utilization from PM by B. The combination of 30 Mg ha^{-1} B and 7.5 Mg ha^{-1} PM gave the best soil properties, growth, yields, and nutrient quality of cocoyam and is, therefore, recommended for soil fertility management and cocoyam production in the study area (rainforest agroecology of southwest Nigeria). These findings should be validated using other sites (soils and agroecologies) and in addition to variable rates and combinations of B or PM.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/S0014479720000137

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