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Integrated application of banana peduncle-derived biochar and fertilizer affect soil physicochemical properties and plant nutrient uptake

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ABSTRACT

Spreading banana peduncle residues in banana plantations to enhance soil physicochemical properties is common practice and has also been identified as vector of mealybug re-infestation. This greenhouse study was conducted to assess the effects of banana peduncle-derived biochars produced at pyrolysis temperatures of 300°C (BC300) and 500°C (BC500), and their combination with inorganic fertilizer on soil nutrient status, plant growth and nutrient uptake in banana plantlets grown in soil-filled polythene bags. Six treatments; control–no input, 30 g BC300, 30 g BC500, 30 g inorganic fertilizer, 15 g BC300 + 15 g inorganic fertilizer, and 15 g BC500 + 15 g inorganic fertilizer were applied. BC300 had significantly higher yield, volatile matter, nitrogen and moisture content, whereas pH, fixed C, Ca, K and ash contents were lower as compared to BC500. Post-planting soil parameters (pH, organic C, available P, exchangeable K, Mg, and ECEC) increased significantly for the biochar treatments (BC300 and BC500) as compared to control and pre-planting soil. Integrated biochar and inorganic fertilizer significantly increased organic carbon and pH as compared to inorganic fertilizer alone. Significant negative correlations demonstrated the effects of sole biochar on soil C/N ratio and pH, which might have reduced nutrient (N and K) uptake and accumulation in banana leaves, while pH also affected leaf Mg. Principal Component Analysis (PCA) also revealed greater leaf nutrient uptake and accumulation in relation to inorganic fertilizer input alone or in combination with biochar, as compared to biochar alone. The combination of biochar with reduced-dose of fertilizer enhanced the potency of the inorganic fertilizer with BC500 as the most effective.

Keywords: Banana peduncle biochar, fertilizer, plant nutrition, pyrolysis

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1 Introduction

Bananas and plantains are important food crops in the tropic and subtropical regions, and are essential in maintaining food and nutrition security in Sub-Saharan Africa (SSA) with over 70 million people deriving more than 25% of their daily carbohydrate intake. However, for each ton of banana harvested, about four tons of lignocellulosic wastes are produced, including three tons stem, 480 kg leaves, 160 kg peduncles, 100 kg rotten fruits, and 440 kg peels (Fernandes et al., 2013). Some of these banana residues are mostly spread over the fields and allowed to decompose to improve soil organic matter. Banana peduncles are an important source of fibres, ash and other nutrients and their decomposition could release essential mineral elements for the nutrition and growth of banana plants and other crops (Oliveira et al., 2007).

Mealybug which is a serious pest is mostly concentrated on bunches (Okolle et al., 2018a) and disposing banana peduncles in fields could increase mealybug infestation of farms (Okolle et al., 2018b). Banana peduncle-derived biochar could therefore be a sustainable option for improving soil organic matter and nutrient contents of banana farms. Biochar is a high carbon material produced by pyrolysis of organic materials at low temperatures below 700 °C under limited oxygen conditions. It can be produced from diverse biomass materials and has the potential to improve soil-plant relations (Lehmann and Joseph, 2015) and represents a promising management tool to mitigate soil degradation and anthropogenic climate change effects (Sikder and Joardar, 2019).

The effectiveness of biochar on plant productivity are that biochar improves the specific surface area, cation exchange capacity, bulk density, pH, water, and nutrients within the soil matrix (Thies and Rillig, 2012; Glaser et al., 2002; Trupiano et al., 2017). It may also alter the soil microbial diversity, abundance, and functions, which may affect soil quality and plant growth (Steiner et al., 2008; Warnock et al., 2010). Besides the benefits of biochar, some negative effects have been attributed to type of feedstock and pyrolysis process, biochar application rate, plant species, and soil characteristics (Spokas et al., 2012; Lentz and Ippolito, 2012). This highlights the need to identify appropriate feedstock (Karim et al., 2017, 2018), pyrolysis rates and methods of production (Antal and Grønli, 2003; Singh et al., 2010), and nutrient enrichment strategies in relation to different crop types (Rafael et al., 2019).

Banana peduncle contains considerable amount of cellulose, lignin and hemicellulose, which makes it a good candidate material for biochar production (Preethi and Balakrishna Murthy, 2013). However, the use of banana peduncle-derived biochar to enhance soil quality and plant growth has not been investigated. Hence, this study was intended to evaluate the effect of biochars derived from banana peduncles alone or integrated with inorganic fertilizer on soil physicochemical properties, plant growth and nutrient uptake in banana plantlets. It was hypothesized that banana peduncle biochar produced by pyrolysis at 500°C will be more effective when combined with reduced dose of inorganic fertilizer on plant nutrition than at 300°C.

2 Materials and Methods

2.1 Study site

The study was conducted at Institute of Agricultural Research for Development (IRAD) Ekona, South West Region, Cameroon, situated at 4°16′44′′ N and 9°17′50′′ E. Mean annual temperatures range between 23.7 and 24.4 °C, with minimum in August and maximum in February-March. The area has humid tropical climatic conditions with two distinct seasons and rich volcanic soils. The long rainy season ranges from mid-March to mid-November and short dry season from mid-November to mid-March. Mean annual rainfall varies between 2085 mm near Ekona on the leeward side, to 9086 mm at Debundscha on the windward side of Mount Cameroon (Fraser and Hall, 1998; Manga et al., 2014).

2.2 Soil sampling and analysis

Soil samples were randomly collected at 0 – 20 cm depth from fields at IRAD Ekona and homogenized by manually sieving through 5 mm mesh to remove stones and plant debris, while the portion of soil used for analysis was air-dried and sieved through 2 mm screen. The pre-planting soil belongs to the Ekona series and soils in this area are formed on older mudflows and have a well-developed argillic horizon (Nanganoa et al., 2019). The soil was silty clay with 45.73% clay, 43.84% silt, and 10.43% sand. Soil pH was determined in the ratio of 1:2.5 soil–water suspensions using a digital pH meter. Available phosphorus was determined by Bray II method (Van Reeuwijk, 1992), organic carbon by the Walkley and Black wet digestion method (Kalra and Maynard, 1991) and total nitrogen by the Kjeldahl digestion method (Bremner and Mulvaney, 1982). Soil exchangeable bases were determined after extraction with 1 N ammonium acetate (NH_4OAc) solution at pH 7. Calcium and magnesium were analysed with atomic absorption spectrometer (AAS), while sodium and potassium were analysed by flame photometer (Rowell, 2014). Exchangeable acidity was determined by 1 N KCl extraction method, and titrated with 0.01 N NaOH using phenolphthalein indicators (Van Reeuwijk, 1992). Effective cation exchange capacity (ECEC) was determined by sum of exchangeable cations and acidity, while particle size distribution was determined by the pipette method and textural class assigned according to the USDA textural triangle (Van Reeuwijk, 1992).

2.3 Production and characterization of biochar

Banana peduncles of Cavendish subgroup of the AAA Group (*Musa acuminata*) were collected from the packinghouse of Cameroon Development Cooperation (CDC) at Mussaka, South West Region, Cameroon. Peduncles were randomly collected and transported to the laboratory at IRAD Ekona where they were washed with distilled water, chopped into smaller pieces using a knife, air-dried and used as feedstock to prepare biochar by pyrolysis. Banana peduncles were placed in lid-covered crucibles and pyrolysed in a muffle furnace at 300 °C for two hours (BC300) and 500 °C for one hour (BC500), followed by cooling to room temperature inside the furnace. Percentage biochar yield was calculated using the following equation as suggested by Karim et al. (2015).

$$Y_B = \frac{M_a}{M_b} \times 100 \tag{1}$$

Where, Y_B = biochar yield (%), and M_a and M_b are sample masses after and before pyrolysis, respectively.

For volatile matter, 5 g oven-dried (105 °C) samples were heated (300 °C) in a muffle furnace for two minutes followed by 500 °C for three minutes, and 950 °C for six min. Volatile matter was calculated as the proportion of oven-dry weight of biochar. Ash content was determined by heating (750 °C) 0.5 g oven-dried (105 °C) samples in an uncovered crucible for six hours in a muffle furnace, and allowed to cool in a desiccator before weighing. Ash content was calculated as proportion of residue (ash) weight to the oven-dry weight of samples. Moisture content, ash content and volatile matter were determined from fine-ground oven-dried samples of biochar using the following equations:

$$MC = \frac{A - B}{A} \times 100 \tag{2}$$

$$AC = \frac{D}{B} \times 100 \tag{3}$$

$$VM = \frac{B - C}{B} \times 100 \tag{4}$$

Where MC, VM and AC are moisture, volatile matter, ash, and fixed carbon contents expressed in percentages (%); A and B are mass of sample before and after drying at 105 °C, respectively; C = mass of sample after calcination at 950 °C, and D = mass of residue (ash).

Fixed carbon (FC) was calculated using the following equation as suggested by Zhao et al. (2017).

$$FC = 100 - (AC + VM) \tag{5}$$

Total nitrogen (N) of the biochars was determined by Kjeldahl digestion method (Rowell, 2014), while phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) were extracted by dry ashing – dilute nitric acid (HNO_3) method (Jones, 2001), and read like other soil samples above. Three randomly collected sub samples of biochar were analysed with standard error (SE) of approximately 0.01.

2.4 Treatments and experimental design

Banana plantlets were produced through macropropagation at the greenhouse of IRAD Ekona with corms placed into a growth chamber and buried in sawdust substrates, watered and covered with plastic paper (Ntamwira et al., 2017). Homogeneous shoots were removed after 16 weeks with a sanitized knife and transplanted into polythene bags (25 × 13 cm) containing 2 kg soil. One banana plantlet was transplanted per bag with 10 bags per treatment and three replications giving a total of 180 plants, laid out in completely randomized design. Six treatments were applied to the soil, *viz.*, T1 = control–no input, T2 = 30 g BC300, T3 = 30 g BC500, T4 = 30 g inorganic fertilizer (local recommendation), T5 = 15 g BC300 + 15 g inorganic fertilizer, and T6 = 15 g BC500 + 15 g inorganic fertilizer. Inorganic fertilizer (12% N, 14% P_2O_5, 19% K_2SO_4, 3.5% MgO and 0.15% B) was purchased from the local market (Sam-Sam, Cameroon). 0.36 L tap water was added to each treatment soil at the beginning of the trial to achieve field capacity, and adequate soil moisture was maintained regularly, while weed emergence was monitored regularly and weeded manually.

2.5 Data collection and analysis

Post-planting soil and banana growth parameters (plant height, number of leaf, leaf area and pseudostem girth) were recorded at 12 weeks after planting (WAP). Plant height was measured from the surface of the soil to the last V-forked leaves of the plant and recorded in cm per plant. The number of leaves were visually observed and recorded per plant, while the leaf area was measured by multiplying the length by the widest breadth of each leaf and by 0.8 and recorded as cm^2 $leaf^{-1}$ (Obiefuna and Ndubizu, 1979). Pseudostem girth was measured at 1 cm above the soil surface using a thread tied round the stem of each plant and diameter covered by the thread was measured on a calibrated ruler and recoded in cm $plant^{-1}$. The oldest plant leaves were harvested from each treatment replicate, oven-dried at 80 °C and their nutrient (N, P, K, Ca and Mg) contents analysed after extraction by dry ashing – dilute HNO_3 method (Jones, 2001). Post-planting experimental soils were collected from each treatment replicate and thoroughly mixed to form a composite sample. The

Table 1. Characteristics of banana peduncle biochars produced at two pyrolysis rates of 300 °C (BC300) and 500 °C (BC500)

Biochar characteristics	Value		Sig. level
	BC300	BC500	
pH	8.81b	10.23a	***
Yield (%)	78a	46b	***
Moisture content (%)	12.64a	7.45b	***
Ash content (%)	30b	44a	***
Volatile matter (%)	42.92a	20.35b	***
Fixed carbon (%)	27.08b	35.65a	***
Nitrogen (%)	2.48a	2.09b	***
Phosphorus (%)	0.27a	0.26a	ns
Potassium (%)	31.09b	38.33a	***
Calcium (%)	0.20b	0.23a	*
Magnesium (%)	0.11a	0.12a	ns

Data means within rows with different letters are significantly different at P = 0.05. * and *** designate the values are significantly different at $p \leq 0.05$ and $\leq <0.001$, respectively; ns = not significant

soil was air-dried and sieved through 2 mm mesh size for analysis of soil organic carbon, total N, available P, pH, ECEC, and exchangeable bases (K, Ca, Mg and Na), following the procedures described above for the pre-experimental soil.

2.6 Statistical analyses

Data were analysed using statistical software package STATISTICA 13.2 for Windows (Statsoft, 2016). One-way analysis of variance (ANOVA) was performed to determine treatment effects on soil (organic C, total N, C/N, P, K, Ca, Mg, Na, Al, ECEC and pH-H2O) and plant (growth, and leaf nutrients) parameters. Separation of the means of the soil and plant parameters was performed by Tukey's post-hoc (P = 0.05) test. In addition, Pearsons Product–Moment Correlation (P = 0.05) was employed to test the significance of correlations between soil parameters and leaf nutrients (N, P, K, Ca, and Mg). Furthermore, the data was log transformed and visualized by Principal Component Analysis (PCA) performed using CANOCO 5 (Ter Braak and Smilauer, 2002).

3 Results

3.1 Biochar characteristics

The different pyrolysis temperatures produced two distinct banana peduncle biochars that differed significantly ($p<0.05$), with idiosyncratic responses in terms of quantity and quality (Table 1). Quantitatively, pyrolysis of banana peduncle yielded more BC300 (78%) than BC500 (46 %) ($p<0.001$). BC300 had more volatile matter and nitrogen as compared to BC500 ($p<0.001$), whereas BC500 had more ash content, fixed carbon, potassium ($p<0.001$) and calcium when compared to BC300 ($p<0.05$). Strongly alkaline pH values were recorded for BC300 (8.81) and BC500 (10.23).

3.2 Effect of treatments on soil properties

Significant treatments effects were observed on soil properties with the high alkaline and organic nature of both biochars reflected in the soil pH, organic carbon, and C/N ratio, which increased ($p<0.05$) significantly for solely biochar-amended soil compared to fertilizer alone (Table 3). Soil available phosphorous increased significantly for fertilizer and biochar-amended soils as compared to the combination of biochar and fertilizer amended soils (Table 3). Sole BC300 or fertilizer recorded the highest nitrogen content, followed by BC500 + fertilizer ($p<0.05$, Table 3). The soil potassium content differed significantly between treatments with the highest in sole BC300 or fertilizer, followed by sole BC500, BC300 + fertilizer, and BC500 + fertilizer ($p<0.05$, Table 3). Sole fertilizer and its combination with biochar recorded the highest exchangeable acidity, while both sole biochar treatments had similar exchangeable acidity as the control ($p<0.05$, Table 3) and pre-planting soil (Table 2). The highest magnesium and calcium contents were recorded in treatment combinations of biochar and fertilizer when compared to the control ($p<0.05$, Table 3) and pre-planting soil (Table 2). Sole fertilizer recorded the highest sodium content, followed by sole BC300, sole BC500 and biochar + fertilizer treatments in relation to control ($p<0.05$, Table 3) and pre-planting soil (Table 2). The highest ECEC content was recorded in sole BC300 or fertilizer and their combination, followed by sole BC500 in relation to control ($p<0.05$, Table 3) and pre-planting soil (Table 2).

Table 2. Physicochemical properties of pre-planting soil

Soil parameters	Value
pH (soil: water = 1: 2.5)	5.93 ± 0.02
Organic carbon (%)	2.39 ± 0.02
Total nitrogen (%)	0.21 ± 0.02
C/N ratio	11.0 ± 0.20
Available P (mg kg^{-1})	47.0 ± 2.0
Na (cmol kg^{-1})	0.11 ± 0.02
K (cmo kg^{-1})	0.49 ± 0.03
Mg (cmol kg^{-1})	3.76 ± 0.01
Ca (cmol kg^{-1})	6.76 ± 0.04
Exch. acidity (cmol kg^{-1})	0.08 ± 0.01
ECEC (cmol kg^{-1})	11.2 ± 0.10

3.3 Plant growth and nutrient uptake

The effect of biochar and fertilizer amendments was reflected in the plant growth (Table 4) and leaf nutrient (Fig. 1) content, with significant ($p<0.05$) differences between treatments. Plant height ranged from 31.65–73.75 cm and differed significantly across treatments, with the highest in sole fertilizer and fertilizer + BC500, followed by fertilizer + BC300, sole BC300 and sole BC500 in relation to the control ($p<0.05$). The number of leaves ranged from 8.03–9.62 plant^{-1} and differed significantly across treatments, with the highest in sole fertilizer and its combination with biochar as compared to sole biochar and control ($p<0.05$). The leaf area ranged from 132.48–179.29 cm^2 and differed significantly across treatments, with the highest in sole fertilizer and its combination with biochar as compared to sole biochar and control ($p<0.05$, Table 4). Pseudostem girth ranged from 4.70–7.41 cm and differed significantly across treatments, with the highest in sole fertilizer and its combination with biochar as compared to sole biochar and control ($p<0.05$, Table 4).

The nitrogen content in banana leaves ranged from 1.52–6.76%, with the highest in sole fertilizer, followed by fertilizer + BC500, fertilizer + BC300, sole BC300 or BC500 as compared to the control ($p<0.05$, Fig. 1). Leaf phosphorus ranged from 0.12–0.29%, with the highest in sole fertilizer and BC500 + fertilizer ($p<0.05$). Magnesium ranged from 0.06–0.09%, with the highest in sole fertilizer as compared to other treatments ($p<0.05$). Treatments had no significant effect on leaf potassium (ranging from 2.46% in control to 3.3 % in fertilizer alone) and calcium contents (ranging from 0.25% in control to 0.31% in BC500 + fertilizer) (data not presented). Meanwhile, treatment induced changes in soil parameters were significantly correlated ($p<0.05$) with the leaf nutrient contents (Table 5). C/N ratio correlated negatively with leaf N and K. Soil K correlated positively with leaf N, while soil Ca and Mg correlated positively with leaf N, Ca and Mg. Soil Na correlated positively with leaf N and P, while soil exchangeable acidity correlated positively with leaf N, K and Mg. The soil ECEC correlated positively with leaf N, Ca and Mg, while soil pH correlated negatively with leaf N, K and Mg. Meanwhile, treatments accounted for 89.94% variation in leaf nutrients as PCA revealed the role of fertilizers in plant nutrition with strong clustering of leaf nutrients along PC 1 (horizontal) (0.8027) and PC 2 (vertical) (0.1126) in relation to fertilizer, while PC 3 (0.0497) and PC 4 (0.0303) demonstrated significant leaf nutrient separation in relation to biochar amendments (Fig. 2).

4 Discussion

4.1 Effect on of treatments soil properties

Pre-planting soil (Table 2) organic carbon was low, nitrogen and calcium were medium, potassium and magnesium were high, and phosphorus was very high (Landon, 2014). The soil C/N ratio of 11 falls within the generally accepted C/N ratio range of 8–12 considered as favourable for relatively fast N-mineralization from organic materials (Makoi, 2014).

Decreased biochar yield with increased pyrolysis temperature from 300°C to 500°C, corresponds with reports that biochar yield varies according to type of feedstock, pyrolysis temperature and heating rate (Zhao et al., 2017). Decreased biochar yield is likely due to decomposition of most lignocellulosic materials at higher temperature of 500°C (Rehrah et al., 2014; Zhao et al., 2017). High ash content in BC500 than BC300 likely resulted from concentration of combusted residues of minerals and organic matter at higher pyrolysis temperature (Cao and Harris, 2010). The high alkaline status of both biochars, and the increased pH at higher pyrolysis temperatures is probably due to high ash content as positive correlations have been reported between pH values and ash content (Karim et al., 2015; Zhao et al., 2017). This can be attributed to the release of basic cations such as Ca^{2+} and Mg^{2+} from the organic matrix in feedstock during high temperature pyrolysis (Rehrah et al., 2014; Novak et al., 2009). The different elemental composition of BC300 and BC500 might have resulted from increased biomass combustion and organic volatilization at high temperature that decreased N but increased K, Ca and Mg contents in BC500 (Cao and Harris, 2010).

The overall effect of biochar and their combination with fertilizer on soil properties is commensurate with the findings of Rafael et al. (2019). Significant increases in soil pH due to biochar addition; irrespective of biochar type are in line with other reports (Ch'ng et al., 2014; Manickam et al., 2015; Alling et al., 2014; Simarani et al., 2018). Increased soil pH is probably due to high pH of biochar inputs that ensued from the presence of organic ions, inorganic carbon-

Table 3. The effect of treatments on post-planting soil physicochemical properties at 12 weeks after planting

Soil parameters	Post-planting treatment soils						Sig.
	T1	T2	T3	T4	T5	T6	
pH	5.79 ± 0.06c	7.64 ± 0.04a	7.26 ± 0.05b	4.72 ± 0.03e	5.05 ± 0.03d	4.75 ± 0.05e	****
Organic C (%)	2.21 ± 0.14c	4.38 ± 0.03a	2.77 ± 0.06b	2.25 ± 0.02c	2.86 ± 0.25b	2.92 ± 0.17b	****
Total N (%)	0.20 ± 0.03c	0.30 ± 0.03ab	0.18 ± 0.03c	0.35 ± 0.03a	0.23 ± 0.04bc	0.29 ± 0.01ab	****
C/N ratio	11.5 ± 2.3abc	14.91 ± 1.84ab	15.65 ± 2.57a	6.53 ± 0.57c	12.44 ± 2.36ab	10.19 ± 0.8bc	***
Av. P (mg kg^{-1})	7.38 ± 1.31d	59.65 ± 3.60ab	49.32 ± 5.93b	64.60 ± 5.03a	33.66 ± 4.98c	28.94 ± 4.34c	****
Na (cmol kg^{-1})	0.08 ± 0.02d	0.67 ± 0.11b	0.50 ± 0.14bc	1.06 ± 0.14a	0.39 ± 0.06bcd	0.35 ± 0.16cd	****
K (cmol kg^{-1})	0.28 ± 0.01e	8.99 ± 0.26a	6.50 ± 0.38b	9.57 ± 0.13a	5.59 ± 0.40c	4.73 ± 0.29d	****
Mg (cmol kg^{-1})	3.37 ± 0.09b	4.67 ± 0.74ab	4.63 ± 0.47ab	4.61 ± 0.84ab	5.43 ± 0.13a	5.26 ± 0.31a	**
Ca (cmol kg^{-1})	4.76 ± 0.20b	5.99 ± 1.32ab	5.67 ± 0.58ab	5.77 ± 0.58ab	7.33 ± 0.68a	7.07 ± 0.84a	*
Ex.Ac. (cmol kg^{-1})	0.14 ± 0.06b	0.06 ± 0.0b	0.11 ± 0.01b	0.87 ± 0.30a	0.52 ± 0.23ab	0.69 ± 0.16a	***
ECEC (cmol kg^{-1})	8.86 ± 0.25c	20.39 ± 2.17ab	17.42 ± 0.72b	21.87 ± 0.91a	19.25 ± 1.35ab	18.10 ± 1.48b	***

pH in terms of soil: water = 1: 2.5; † Data means within rows with different letters are significantly different at P = 0.05. *, ** and *** designate the values are significantly different at $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$, respectively, ns = not significant; ‡ T1 = control–no input, T2 = 30 g BC300, T3 = 30 g BC500, T4 = 30 g inorganic fertilizer, T5 = 15 g BC300 + 15 g inorganic fertilizer, and T6 = 15 g BC500 + 15 g inorganic fertilizer

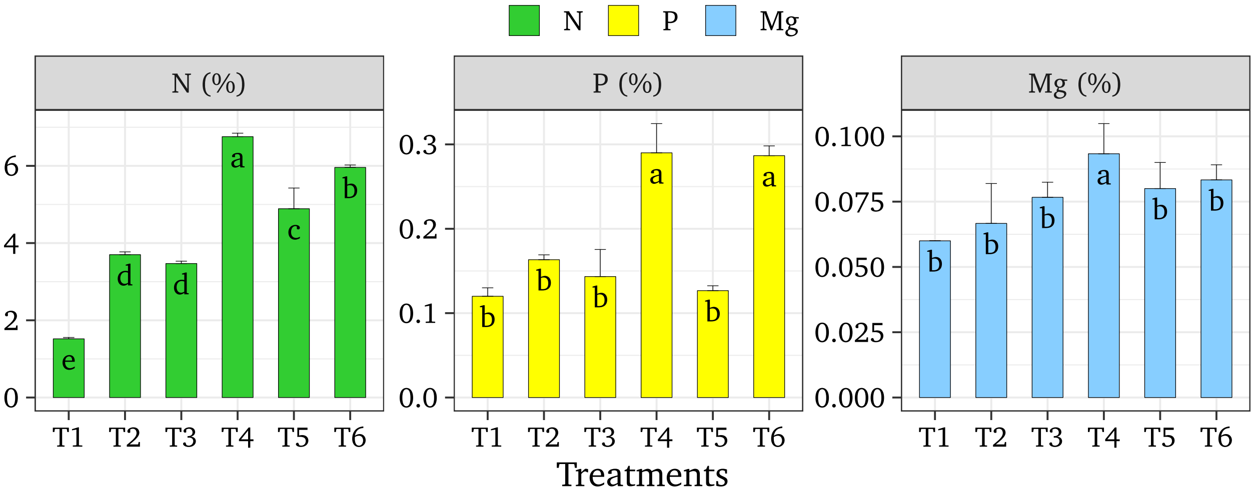

Figure 1. Effect of treatments on banana leaf nutrient content (%DW) at 12 weeks after planting. Data means for specific nutrients with different letters across treatments are significantly different $p \leq 0.05$. T1 = control–no input, T2 = 30 g BC300, T3 = 30 g BC500, T4 = 30 g inorganic fertilizer, T5 = 15 g BC300 + 15 g inorganic fertilizer, and T6 = 15 g BC500 + 15 g inorganic fertilizer

Table 4. The effect of treatments on plant height, number of leaves, leaf area, and pseudostem girth at 12 weeks after planting

Treatments	Plant height (cm)	Number of leaves	Leaf area (cm^2)	Pseudostem girth (cm)
T1	31.65 ± 1.50e	8.03 ± 0.06c	132.48 ± 8.05b	4.70 ± 0.05d
T2	54.37 ± 2.88c	8.40 ± 0.26bc	145.58 ± 3.04b	5.07 ± 0.05cd
T3	46.63 ± 4.51d	8.57 ± 0.12b	145.22 ± 4.84b	5.58 ± 0.40c
T4	73.75 ± 1.41a	9.29 ± 0.32a	176.89 ± 6.75a	7.41 ± 0.15a
T5	63.30 ± 2.51b	9.14 ± 0.15a	168.07 ± 2.25a	6.87 ± 0.12b
T6	72.99 ± 1.40a	9.62 ± 0.29a	179.29 ± 1.61a	7.15 ± 0.16ab

T1 = control–no input, T2 = 30 g BC300, T3 = 30 g BC500, T4 = 30 g inorganic fertilizer, T5 = 15 g BC300 + 15 g inorganic fertilizer, and T6 = 15 g BC500 + 15 g inorganic fertilizer

Table 5. Pearsons Product–Moment Correlation (*r*) values between soil parameters (organic C, total N, C/N, P, K, Ca, Mg, Na, Al, ECEC, pH-H_2O, and pH-KCl) and leaf nutrients (N, P, K, Ca, and Mg)

Soil parameters	Leaf nutrient contents				
	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium
Organic carbon	ns	ns	ns	ns	ns
Nitrogen	0.77	0.71	ns	ns	ns
C/N	-0.62	ns	-0.5	ns	ns
Phosphorus	ns	ns	ns	ns	ns
Potassium	0.48	ns	ns	ns	ns
Calcium	0.56	ns	ns	0.68	0.55
Magnesium	0.51	ns	ns	0.71	0.53
Sodium	0.56	0.54	ns	ns	ns
Aluminium	0.73	ns	0.76	ns	0.52
ECEC	0.72	ns	ns	0.65	0.53
pH (water)	-0.74	ns	-0.65	ns	-0.62

r values are significant at $p \leq 0.05$, ns = not significant

ates, K, Ca, Mg, and Na in biochars, which resulted in lower exchangeable soil acidity (Abbasi and Anwar, 2015; Qadeer et al., 2014). The increased P in biochar-amended soils is consistent with reports that P availability is highly affected by soil pH (Dinkecha, 2017). This is because biochar acted as a modifier of soil pH ameliorating the P complexing metals such as Al^{3+} or Ca^{2+}, provided a direct source of P, and might have also promoted microbial activity and P mineralization (Lehmann et al., 2011). The liming effect of biochar could be considered favourable for the study area with tropical acid soils that often require liming of the arable fields. Fertilizer application also enriched soil available phosphorus and the values of inorganic fertilized samples were higher compared to the control and biochar treatments. It has been reported that changes in the composition of soil solution due to fertilizer addition can affect the dynamics of phosphorus availability (Kahura et al., 2018). High ECEC in biochar amended soils is likely due to inherent K, Ca, Mg, and Na coupled with biochar's potential to raise soil CEC because of high surface area and porous nature that increases surface sorption and base saturation (Mensah and Frimpong, 2018). Meanwhile, increased soil organic carbon for biochar-amended soils demonstrates the potential of biochar to enhance carbon accumulation and sequestration in soils (Trupiano et al., 2017).

4.2 Plant growth and nutrient uptake

This study demonstrated the agronomic benefits of banana peduncle biochars for plant nutrition and growth, with significant increase in leaf N content (Nigussie et al., 2012; Chan et al., 2008; Zwieten et al., 2009). The effect of sole biochar on some of the plant growth parameters such as leaf area in relation to the control was not significant. However, significant results were obtained when biochar was applied in combination with fertilizer and is consistent with Asai et al. (2009) who concluded that the efficacy of biochar is highly dependent on the soil fertility and fertilizer management practice. Accordingly, banana growth in BC500 + fertilizer was similar to sole fertilizer, which highlights the importance of fertilizer inputs and demonstrates the role of biochar in optimising nutrient use efficiency and reducing fertilizer inputs (Abbasi and Anwar, 2015). The increased plant growth parameters in BC500 + fertilizer treatment could be attributed to the ability of biochar to increase nutrient retention and availability through adsorption or desorption processes on biochar surfaces and precipitation or dissolution of biochar minerals (Bornø et al., 2018, 2019). Lower growth parameters for BC300 + fertilizer than sole fertilizer and BC500 + fertilizer is likely because of variations in soil solution chemistry due to differences in the structural and chemical nature of biochar as influenced by pyrolysis conditions (Gundale and DeLuca, 2006). Deenik et al. (2011) showed that low-volatile matter corncob charcoal with fertilization significantly increased maize growth in the first planting cycle as compared to maize growth in high-volatile matter corncob charcoal supplemented with fertilizer treatment. Deenik et al. (2010) also demonstrated that the negative effect of the high-volatile matter charcoal on the fertilizer is caused by bioavailable carbon in the charcoal, which increased soil microbial activity accompanied by a decline in soil NH_4^+–N in soil due to N immobilization. This is corroborated by the significant high leaf N concentration in BC500 + fertilizer and fertilizer alone as compared to BC300 + fertilizer. Also, the low pH associated with BC300 compared to BC500 may also have decreased P availability and uptake in BC300 + fertilizer treatment as demonstrated by the low P content of leaves.

Similar high leaf N content for plants amended with sole fertilizer and its combination with biochar

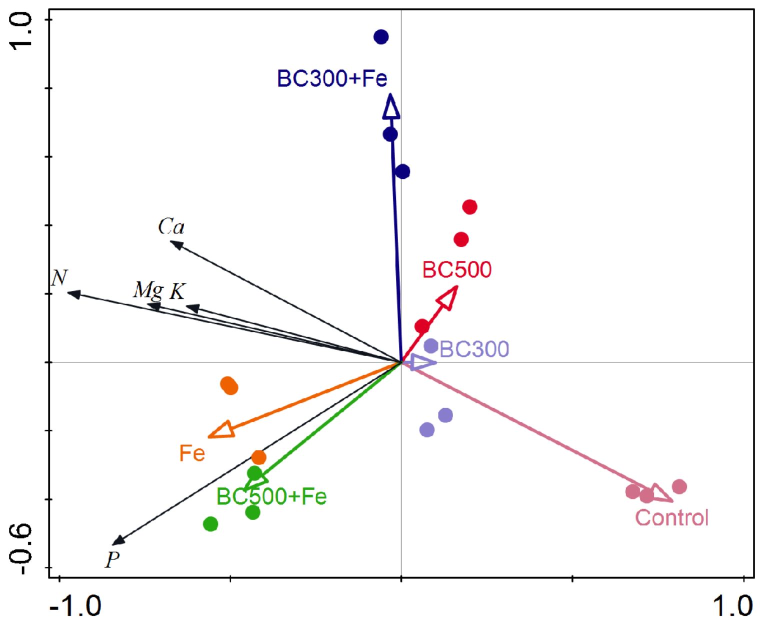

Figure 2. Principal Component Analysis (PCA) of leaf nutrients (N, P, K, Ca and Mg) of banana plantlets after 12 weeks growth in soils treated as control–no input, low pyrolysis biochar (BC300), high pyrolysis biochar (BC500), inorganic fertilizer (Fe), BC300 + Fe, and BC500 + Fe

or biochar alone as compared to the control highlights the role of biochar in optimising nitrogen use efficiency of fertilizer inputs. Biochar likely enhanced nutrient availability for plants by modulating soil pH, improving nutrient retention via cation exchange capacity and enhanced soil moisture, nitrogen, carbon and phosphorus (Liang et al., 2006; Zwieten et al., 2009; Trupiano et al., 2017). In addition, biochar induced increase in CEC might have contributed in retaining NH_4^+ that probably improved N uptake (Vaccari et al., 2015; Trupiano et al., 2017). The none significant effect of sole biochar on P and Mg uptake could be attributed to adequate soil supply of essential nutrients by the rich pre-planting soil properties (Table 2), which is consistent with the reports that biochar did not enhance plant P uptake and yield in high Olsen P soils (Shen et al., 2016; Kahura et al., 2018). In sum, the significant negative correlations demonstrated the effects of sole biochar on soil C/N ratio and pH, which might have reduced nutrient (N and K) uptake and accumulation in banana leaves, while pH also affected leaf Mg content. Overall, the favourable plant nutrient uptake and accumulation in relation to fertilizer input and/or its combination with biochar validates the hypothesis of this study.

5 Conclusions

The study demonstrated the potentials of banana peduncle-derived biochar as a sustainable alternative to improve soil quality and nutrient uptake by banana plantlets when compared to traditional practices of spreading banana peduncles to decompose in farms which have been identified as vector of mealybug re-infestation. The soil chemical properties such as pH, organic carbon, total nitrogen, available phosphorus, and effective cation exchange capacity were enhanced by biochar amendments as compared to the control. Application of biochar alone at the studied dose, affected soil C/N ratio and pH on the uptake and accumulation of N and K in banana leaves, while pH also affected Mg. Combining banana peduncle biochar with reduced-dose of inorganic fertilizer enhanced plant nutrient uptake that decrease the use of fertilizer, thereby, highlighting the importance of banana peduncle biochar as sustainable farm-level adaptation within the nexus of integrated soil fertility management.

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Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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