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Synergistic effects of biochar and poultry manure on soil and cucumber (*Cucumis sativus*) performance: A case study from the southeastern Nigeria

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Abstract

This study explores the suitability of different biomass feedstocks for biochar production and their effects on soil health and crop yield. Two planting seasons were conducted, involving cucumber as the test crop and eleven treatments combining biochar and poultry manure. Soil analysis revealed initial soil conditions with high sand content and low pH. Poultry manure and biochar exhibited pH, organic carbon, and nutrient level variations. Significant differences in cucumber growth and yield were observed, with the longest vine length in plots treated with palm kernel husk biochar and poultry manure. Residual effects in the second planting season displayed similar trends. Soil pH, organic carbon, and total nitrogen remained consistent between seasons, while available phosphorus increased significantly in plots amended with goat manure biochar and poultry manure. Calcium, magnesium, potassium, and sodium contents also varied. Fruit length, weight, and yield were significantly improved by biochar treatments, with the combination of palm kernel husk biochar and poultry manure yielding the highest fruit weight. Correlation and structural equation analyses ($p < 0.05$) highlighted the relationships between plant characteristics, soil properties, and fruit indices, emphasizing the importance of nitrogen and phosphorus in supporting fruit development. The study suggests that biochar application enhances soil nutrients, crop growth, and fruit yields while reducing reliance on chemical fertilizers. It recommends considering biochar for land reclamation and as an alternative to traditional fertilizers, supported by appropriate regulations.

1. Introduction

Biochar plays a significant role in soil nutrient and environmental management by sequestering carbon and improving soil properties (Lehmann and Joseph, 2009). The suitability of different biomass feedstock for biochar production depends on various chemical, physical, and environmental factors. For instance, olive husks, which have high lignin content, produce high biochar yields due to the stability of lignin during thermal degradation (Demirbas, 2004). On the other hand, Woody feedstock typically contains low ash proportions (< 1% by weight). Biomass with high mineral content, such as grass, grain husks, and straw residues, tends to produce ash-rich biochar (Demirbas, 2004).

Studies have shown that biochar produced from different feedstock, environmental conditions, and production temperature values influence chemical properties and soil water retention (Brown et al., 2006; Katy et al., 2015). Katy et al. (2015) found that poultry droppings increased pH (8.0) and other nutrient levels in Arkansas loamy soil. Similarly, woodchip biochar application raised the pH (8.9) and altered the nutrient concentrations, indicating varying effects on soil properties.

Applying biochar to soil is gaining relevance in sustainable food production due to its ability to trap carbon, reduce compaction, improve soil physical conditions, and enhance nutrient uptake (Lehmann and Rondon, 2006). In highly weathered tropical soils with acidic nature, crop productivity is often constrained by nutrient loss through leaching and surface run-off, which decreases basic cation concentration and increases soil acidity (Shamshuddin and Daud, 2011). Regular fertilizer application in such soils is not always successful due to nutrient loss caused

Supplementary materials avalable at:
https://www.soilsa.com/SuppFile/183903/8713/74086dc271fe7d03798be3f02f62a7fa/

by high weathering, leading to reduced economic efficiency and environmental concerns (Ch'ng et al., 2014). Therefore, organic amendments are necessary to retain applied fertilizers in tropical soils for longer periods.

Previous research indicates that adding charcoal to soil enhances the yields of various crops, such as mung, soybean, pea, and maize (Rondon et al., 2007; Ingold et al., 2015). Biochar application in Colombian savanna soil significantly increased maize yield (Major et al., 2010). In low-fertility Ferralsol, biochar addition improved nitrogen fixation by bean plants, leading to increased biomass production and bean yield (Rondon et al., 2007). Compost and charcoal treatments also showed higher nitrogen recovery compared to mineral fertilization on similar soil types (Steiner et al., 2008). Biochar application improved upland rice yields in low-P availability sites in northern Laos and enhanced fertilizer response. In the Mediterranean basin, large-volume biochar applications increased durum wheat biomass and yield by up to 30% over two seasons (Asai et al., 2009; Vaccari et al., 2011). Cucumber (*Cucumis sativus*), a widely grown vegetable in Nigeria, has a high water content and contains essential macronutrients and micronutrients (Abulude et al., 2007). Many cucumber varieties have varying shapes, skin colour, and carotene content. The variation in the performance of cucumber varieties has been widely documented by many scholars (Ajisefinanni, 2004; Eifediyi and Remison, 2010; Bisht et al., 2011; Ene et al., 2016; Kathayat et al., 2018), which could result from environmental factors or genetic composition. Cucumber requires deep, well-drained, structurally stable, fertile soil with high pore volume. High porosity and stability are essential for managing high and frequent water supply and stress due to agricultural practices. This can be achieved by incorporating large amounts of organic matter and adopting proper tillage measures. However, the low soil fertility resulting from land degradation poses a significant problem for their sustainable production in Sub-Saharan Africa (Rockstrom et al., 2009). Access to mineral fertilizers is a challenge for many farmers in Nigeria and Sub-Saharan Africa (Ayito et al., 2018). Consequently, applying biochar as a soil amendment to enhance soil fertility and crop productivity has become crucial.

The present study hypothesized that biochar might have direct and residual effects on soil health and the yield of crops. Biochar derived from various feedstock types may affect soil properties in highly weathered soils, such as pH, organic carbon content, and nutrient levels.

Furthermore, the response of cucumber to the different feedstock of biochar combined with poultry manure has not been investigated that much, and the chemical composition of some easily accessible feedstock materials has not been well studied. Therefore, this research aims to explore the effectiveness and chemical composition of charred materials, such as plantain peels, cassava peels, neem seeds, goat manure, and palm kernel shells, and their synergistic effect with poultry manure, as soil amendments for cucumber growth and soil improvement.

2. Materials and methods

2.1. Research location description and input materials

The research was conducted in southeastern Nigeria under the Cross River State community in Ekpene Tete in Akpabuyo Local Government Area. Akpabuyo lies within latitudes 4°45' and 5°10' N and longitudes 8°25' E and 8°40' E of the Greenwich meridian (Fig. 1).

The area is characterized by a humid tropical environment (Tropical-A) defined by two separate seasons (i.e., rainy season and dry season) according to the Koppen climatic classification (Koppen, 1936). Within a year, the region experiences a wet season from March to October and a dry period from November to February. Initial rain happens from March to July; late rain begins in August and ends in October. Between the end of the

Fig. 1. Map of Akpabuyo Local Government Area of Cross River State showing the experimental site of the study.

initial rains and the start of the late rains, the region experiences what is called “August break”. The rainfall amounts ranged from 1900 mm to 2650 mm yearly.

Similarly, the minimum and maximum annual temperatures ranged between 19–24°C and 28–34°C, respectively. Relative humidity ranged from 39–81% and 52–87% for minimum and maximum humidity. According to the USDA soil taxonomic classification system, the soil of the experimental site was classified as Ultisols (Soil Survey Staff, 2014). In the FAO World Reference Base for Soil Resources (WRB), most Ultisols are known as Acrisols and Alisols1. These soils generally have inherent low fertility conditions (Esu, 2005).

2.2 Biochar Preparation

The University of Calabar in Nigeria developed a controlled slow pyrolysis system using a local metallic drum, processing various feedstocks (palm kernel shells, cassava peels, plantain peels, neem seeds, and goat manure) at 350–400 ± 25°C for 5–6 h to produce biochar with a biomass of 3–6 kg/h. See a sample of the biochar produced (Supplementary materials, Plate 1A & Plate 1B).

2.2.1. Treatments combinations

According to Table 1, the sole use of biochar from different feedstock and the biochar synergized with poultry manure was incorporated into a specified seedbed and allowed for seven days before sowing. The treatments were incorporated into a well-prepared seedbed and allowed fourteen (14) days before planting (See Supplementary materials, Plate 1C to Plate 1G). Two cucumber seeds were sown per hole at a planting distance of 60 cm by 60 cm on a well-prepared seedbed. The plants were thinned to one seedling per stand two weeks after sowing (WAS), giving a total plant density of 15 plants per plot and 27778 plants per hectare. The experiment was conducted in two planting seasons of cucumber (2018 and 2019) (See Supplementary materials, Plate 1H to Plate 1I).

Table 1.
Treatments and quantity applied per hectare and plot size of 5.4 m^2

Treatment	Rate of Application per hectare
T0 (control)	0
T1 (PPB)	20 t/ha
T2 (PPB + PM)	10 t/ha + 10 t/ha
T3 (CPB)	20 t/ha
T4 (CPB + PM)	10 t/ha +10 t/ha
T5 (NSB)	20 t/ha
T6 (NSB + PM)	10 t/ha+ 10 t/ha
T7 (GMB)	20 t/ha
T8 (GMB + PM)	10 t/ha + 10 t/ha
T9 (PKHB)	20 t/ha
T10 (PKHB + PM)	10 t/ha + 10 t/ha

NB: PM: Poultry Manure; NSB: Neem seed biochar; CPB: Cassava peels biochar; GMB: Goat manure biochar; PPB: Plantain peels biochar; PKHB: Palm kernel husk biochar

2.3. Soil and plant data collection

Composite soil samples were taken before and after each planting season in 2018 and 2019 using a soil auger. These samples were air-dried, ground, and sieved with a 2 mm sieve for subsequent analysis.

Three plants from each experimental plot were tagged to measure growth and yield parameters, including vine length, leaf count, and leaf area at 4, 6, and 8 weeks after planting. The measurements were conducted according to the method outlined by Blanco et al. (2003). Fruit length was measured in centimetres and assessed from stem to tip at each collection interval for three marked plants. Fruit diameter, recorded in millimetres, was determined at harvest using a vernier calliper, with the mean value representing the diameter per plant. Fruit yield per hectare (t/ha) was calculated by dividing the total harvest weight by the land size.

In contrast, the weight per plant was determined using an electronic scale and converted to kg/ha based on various plant populations.

2.4. Soil, plant, and fruit laboratory analysis

Particle size analysis was conducted using the Bouyoucos Hydrometer methodusing sodium hexametaphosphate to determine sand, silt, and clay percentages. The soil texture was selected based on the plotted values on the soil textural triangle (Udo et al., 2009). Soil pH was determined by shaking 10 g of air-dried, 2 mm sieved soil with 25 ml of ultra-pure water and recording the pH using a pH electrode in the soil suspension for 30 seconds. Organic carbon (OC) and total nitrogen (TN) content were analyzed using a Flash Smart Elemental AnalyzerSoil exchangeable bases (Ca, K, Mg, and Na), total phosphorus (P) and sulphur (S) were determined treated with Aqua regia reagent (a mixture of HCl and HNO3 in the ratio of 3:1), the mixture was used to extract the soil pseudo-total concentration of elements according to Tejnecky et al. (2015) and Cools and De Vos (2016). The pseudo-total elements were measured via Inductively Coupled Plasma Mass Spectroscopy (ICP-MS). The soil analysis was performed in duplicates and later averaged, with a blank sample intermittently measured via ICP-MS.

Nutrient composition in plants and fruits was analyzed using samples from three tagged plants per plot. The samples were oven-dried at 70°C for 24 hours to determine dry matter weight (Yildirim et al. 2008), followed by milling and acid digestion (e.g., aqua regia) of plant samples and fruits passing through a 1.00 mm screen. Each sample category, N, P, K, Mg, Ca, and S, was determined using the ICP-MS.

The platform and equipment for conducting all the analyses in this study were provided by the Department of Soil Science and Soil Protection, Czech University of Life Sciences in Prague (CZU), the University of Reading, United Kingdom, and the School of Chemistry and Physics, University of KwaZulu-Natal, Durban, South Africa.

2.6. Statistical analysis

A simple correlation matrix was performed to find the magnitude and nature of the association between soil pH and yield parameters. A significant correlation was established at $p < 0.05$, 0.01 and 0.001. The SEM was carried out in R using the „*sem package*" developed by John Fox (Fox et al. 2012).

In addition, we employed a structural equation modelling (SEM) approach to investigate the relationships among 13 latent constructs and their corresponding observed variables. The model included factors such as FL, FW, FD, Wplot, VL4, VL6, VL8, NL4, NL6, NL8, LA4, LA6, and LA8, with predictors including OC, N, P, Ca, K, pH, Na, Mg, and environmental factors. The SEM model was estimated using maximum likelihood estimation (ML) with the NLMINB optimization method. Fit indices such as the Comparative Fit Index (CFI) and Root Mean Square Error of Approximation (RMSEA) were used to assess the goodness of fit.

The performance of the different biochar on the soil, plant, and yield of cucumber was evaluated, and means were compared using the Tukey HSD test at a 5% probability level. The statistical analysis was implemented in R software (version 4.0.0).

3. Results and discussion

3.1. Summary statistics of soil properties before cucumber planting

The laboratory analysis results of the soil samples before applying biochar treatments are presented in Table 2. The analysis showed that the soil had a sand fraction of 780 gkg^{-1}, silt content of 140 gkg^{-1}, and clay content of 80 gkg^{-1}. The high sand content poses challenges in nutrient retention and contributes to poor drainage. This finding aligns with the classification of the study area as Ultisol with low silt content, as reported by Akpan-Idiok et al. (2012), indicating that the soil is predominantly sandy loam. The soil pH was slightly acidic, measuring 5.08, which is consistent with the findings of Chude et al. (2004), who reported pH values ranging from 5.0 to 6.0 for soils in southeastern Nigeria. However, this pH level falls below the recommended range of 6.5–7.5 for optimal fruit and vegetable cultivation, as suggested by Liu and Hanlon (2012). Acidic soil conditions can have detrimental effects on plant growth and yield due to increased concentrations of aluminium (Al), iron (Fe), and manganese (Mn) while also reducing the availability of calcium (Ca), magnesium (Mg), and phosphorus (P). The organic carbon (OC) content was determined to be 8.4 gkg^{-1}, which is considered low according to the classification rating provided by Adaikwu et al. (2012). Furthermore, the exchangeable calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na) values were found to be low, indicating poor acid sand soil commonly found in tropical humid rainforest zones, as reported by Aihou et al. (1998) and Akpan-Idiok et al. (2012).

Table 2.
Properties of the experimental soil before planting

Parameter	Estimates
Sand (g/kg)	780
Silt (g/kg)	140
Clay (g/kg)	80
Texture	Sandy Loam
pH (H_2O)	5.08
OC (g/kg)	8.40
Ca (cmol/kg)	1.01
Mg (cmol/kg)	0.30
Na (cmol/kg)	0.07
K (cmol/kg)	0.38

3.2. Nutrient composition of the poultry droppings and different biochar amendments

The nutrient composition of poultry manure (PM) and biochar, as presented in Table 3, revealed that PM had a nearly neutral pH of 6.8. In contrast, the pH of the biochar materials, measured in water, ranged from neutral to very strongly alkaline in the following order: GMB > NSB > CPB > PM > PPB > PKHB. The organic carbon (OC) content followed the order of PKHB >

Table 3.
Chemical composition of Poultry manure and Biochar materials used for the experiment

Parameters	Biochar					
	PM	NSB	CPB	GMB	PPB	PKHB
pH (H_2O)	6.8	10.8	9.9	10.9	10.7	6.9
OC (g/kg)	247	481	385	207	311	527
N (mg/kg)	286	282	97	160	109	72
P (mg/kg)	1800	856.1	974.4	1610.2	497.3	198.7
Ca (cmol/kg)	0.4	44.6	12.3	59.7	9.6	5.6
Mg (cmol/kg)	102	42.8	20.4	71.8	47.2	5.9
Na (cmol/kg)	57.6	4.3	1.7	20.5	5.3	1.0

NB: PM: Poultry Manure; NSB: Neem seed biochar; CPB: Cassava peels biochar; GMB: Goat manure biochar; PPB: Plantain peels biochar; PKHB: Palm kernel husk biochar; OC: organic carbon

NSB > CPB > PPB > PM > GMB, with PKHB having the highest OC content. The OC content of PM in this study aligns with the findings of Iren et al. (2014). Phosphorus content was highest in PM (1800 mg/kg^{-1}), followed by GMB (1610.1 mg/kg^{-1}), and lowest in PKHB (198.7 mg/kg^{-1}). The high phosphorus content in animal manure biochar is consistent with previous studies indicating that animal manure sources typically contain significant levels of available phosphorus (Vassilev et al., 2013; Glaser and Lehr, 2019). The chemical composition of PM and biochar materials varied. The PM had the highest total nitrogen (N) value (286 mgkg^{-1}), followed by NSB (282 mgkg^{-1}), and the lowest value was observed in PKHB (72 mgkg^{-1}). GMB had the highest calcium (Ca) content, while PM had the lowest. The calcium value obtained from PKHB was higher than that reported by Simarani et al. (2018). Poultry manure exhibited higher magnesium (Mg) and sodium (Na) contents, with 102 mmolkg^{-1} values and 57.6 mmolkg^{-1}, respectively. At the same time, PKHB had the lowest values of 5.9 mmolkg^{-1} for magnesium and 1.0 mmolkg^{-1} for sodium.

3.3. Direct and residual effects of sole biochar from different feedstock and synergized with poultry manure on soil properties in the 2018/2019 planting seasons

Table 4 shows the direct and residual effects of sole biochar from different feedstock fortified with poultry manure on soil properties in the first 2018 (direct effect) and the second 2019 planting seasons (residual effect). In the first planting (direct effect), the pH values obtained from soils treated with the various amendments were statistically at par ($p > 0.05$). During the second planting (residual effect), pH in soil amended with goat manure biochar (6.04) and plantain peels biochar (5.91) were statistically at par ($p > 0.05$) but significantly ($p \le 0.05$) higher than the control plot (5.27) and those treated with neem seed biochar, palm kernel husk biochar and cassava peels biochar and its combination with poultry manure. Uzoma et al. (2011), Van Zwieten et al. (2010), and Iren et al. (2021) also observed an increase in soil pH after the application of biochar.

Table 4.
Direct and residual effects of sole biochar from different feedstock and synergized with poultry manure on soil properties in the 2018/2019 planting seasons

Treatments	pH	OC (g/kg)	TN (g/kg)	Tot. P (mg/kg)	Ca (mg/kg)	K (mg/kg)	Mg (mg/kg)	Na (mg/kg)
First Planting (direct effect) in 2018								
Control	5.1a	18.2a	1.8a	3109a	334a	41.8c	60.4d	14.8a
PPB	5.0a	17.4a	1.3a	2428a	365a	325.0a	88.7bcd	14.2a
PPB + PM	4.8a	16.3a	1.4a	3008a	501a	104.6bc	90.7bcd	15.3a
CPB	4.5a	23.9a	1.4a	2612a	426a	80.9bc	81.5bcd	16.7a
CPB + PM	4.9a	20.2a	1.3a	2561a	484a	64.4bc	101.0abc	14.8a
NSB	5.6a	17.8a	1.4a	2839a	550a	134.1b	91.0bcd	18.5a
NSB + PM	5.1a	21.6a	1.8a	2712a	454a	102.2bc	89.5bcd	19.7a
GMB	4.9a	17.4a	1.4a	3229a	550a	83.1bc	123.9a	16.3a
GMB + PM	4.8a	18.7a	1.7a	3423a	624a	106.1bc	112.4ab	17.0a
PKHB	4.5a	20.2a	1.4a	2798a	415a	59.6bc	77.8cd	16.0a
PKHB +PM	4.3a	17.1a	1.4a	2659a	497a	45.8c	75.6cd	16.7a
Second Planting (residual effect) in 2019								
Control	5.1de	15.2a	1.6a	140.3cd	334de	41.8c	60.4d	7.3a
PPB	5.9ab	17.1a	1.3a	129.8d	365de	352.0a	88.7bcd	5.2a
PPB + PM	5.5cde	17.3a	1.4a	163.4ab	501bcde	104.6bc	90.7bcd	7.0a
CPB	5.2e	23.9a	1.5a	156.7bc	426cde	80.9bc	81.5bcd	12.2a
CPB + PM	5.5cde	20.2a	1.4a	172.2ab	590abc	64.4bc	101.0ab	5.9a
NSB	5.6bcde	17.8a	1.4a	161.3abc	426cde	134.1bc	91.0bcd	7.9a
NSB + PM	5.6bcd	20.5a	1.8a	154.0bc	544abcd	103.2bc	89.5bcd	12.1a
GMB	6.0a	17.4a	1.4a	169.4ab	700a	83.1bc	123.9a	11.8a
GMB + PM	5.7bc	18.7a	1.8a	181.5a	624ab	106.1bc	112.4ab	8.8a
PKHB	5.5cde	20.2a	1.4a	165.5ab	415cde	59.6bc	77.8cd	7.4a
PKHB +PM	5.6bcde	19.1a	1.4a	160.3abc	497bcde	45.8c	75.6cd	5.4a

NB: The values that do not share the same letters are significantly different at $p \le 0.05$ level of significance

This study's increase in pH due to biochar application coincided with the linear decrease in exchangeable Al concentration with biochar rate. Soil organic carbon and total nitrogen contents obtained from the various amendments were statistically similar in both planting seasons (i.e., first and second planting in 2018 and 2019). Available phosphorus was statistically similar in the first planting but showed a significant difference ($p \leq 0.05$) in the second planting (residual planting). The highest available phosphorus was obtained in plots amended with GMB + PM (181.5 $mgkg^{-1}$) and was significantly higher than the control plot. Besides, the non-significant difference obtained in the first planting may be attributed to the low quantity of biochar used (less than 10 $mgha^{-1}$), as Glaser et al. (2019) suggested. Calcium was not significantly ($p < 0.05$) different in the first planting of 2018 (direct effect), but significant differences were recorded in the second planting of 2019 (residual effect). Exchangeable Ca in control plots was significantly ($p \leq 0.05$) different from those treated with biochar and its combination. Further results showed that Ca contents obtained in soils treated with goat manure biochar, neem seed biochar combined with poultry manure, and goat manure biochar mixed with poultry manure were statistically similar ($p > 0.05$) but significantly different from other treatments. Similarly, in both planting seasons, 2018 and 2019, K contents in plantain peel biochar were significantly ($p \leq 0.05$) different from the control plot and those treated with neem seed biochar, palm kernel husk biochar, and cassava peel biochar and its combinations with poultry manure. Magnesium contents in cassava peel biochar, goat manure biochar, goat manure biochar, plus poultry manure treated soils were statistically at par ($p > 0.05$) but significantly ($p \leq 0.05$) different from other treatments. Similarly, Na in soil amended with biochar only and biochar combined with poultry manure were rated high and statistically at par ($p > 0.05$).

3.4. Direct and residual effects of biochar on growth and yield components of cucumber in the 2018/2019 planting seasons

3.4.1. Vine length

Table 5 presents the vine length of cucumber plants in the 2018 first planting (direct effect) and second planting (residual planting). At 4 weeks after planting (WAP), all the treatments showed significant differences ($p < 0.05$) compared to the control, except for PKHB, which was not different. The longest vine length was observed in plots treated with PKHB + PM (76.9 cm), while the shortest was in control (26.8 cm). Plots amended with PPB, PPB + PM, CPB, CPB + PM, NSB, NSB + PM, GMB, GMB + PM, and PKHB + PM were not significantly different ($p < 0.05$). Similarly, at 6 WAP, there was a significant difference ($p < 0.05$) in vine length between the treatments and the control. The longest vine length was obtained in plots treated with PKHB + PM (151.8 cm), followed closely by NSB + PM (144.0 cm). Conversely, the lowest vine length was observed in plots treated with PKHB (81.6 cm), followed by the control (89.1 cm). Furthermore, at 8 WAP, the treatments showed a significant difference ($p < 0.05$) in vine length compared to the control. The combination of PKHB + PM and GMB + PM produced the longest vines, measuring 144.4 cm and 143.3 cm, respectively. On the other hand, the shortest cucumber vine length was observed in plots treated with PKHB only (84.4 cm), followed by the control (103.4 cm). This study's findings are consistent with the report by Mbah et al. (2017), who observed a significant increase in cucumber vine length when soils were treated with a 5 t/ha rate of hardwood biochar. However, there were some differences between the studies. In contrast, Schultz et al. (2014) found a negative effect of biochar-treated soils on oat plant growth and yield. However, their research was conducted in a greenhouse, and further field research is needed to confirm or refute their findings. Therefore, this study provides evidence to the contrary.

Table 5.
Influence of sole biochar from different feedstock and fortified with poultry manure on cucumber vine length (cm) for 2018/2019 planting seasons

Treatment	Vine length (cm)					
	First Planting 2018 (direct effect)			Second Planting 2019 (residual effect)		
	4WAP	6WAP	8WAP	4WAP	6WAP	8WAP
Control	26.8c	89.1c	103.4bc	11.9c	40.0b	68.2c
PPB	57.5ab	138.5ab	142.3a	46.6a	110.3a	125.3ab
PPB + PM	63.2a	135.1ab	150.0a	48.4a	112.0a	135.9ab
CPB	52.3ab	111.3abc	125.6ab	33.0ab	97.9a	111.9ab
CPB + PM	74.7a	140.1ab	128.3ab	35.0ab	112.5a	127.4ab
NSB	50.9ab	124.7abc	130.0ab	36.0ab	96.9a	118.7ab
NSB + PM	65.3a	144.0a	136.6a	39.1ab	112.5a	130.5ab
GMB	60.2ab	139.5ab	142.2a	38.9ab	109.3a	244.1a
GMB + PM	65.3a	131.5abc	143.3a	38.2ab	112.6a	132.7ab
PKHB	27.0c	81.6bc	84.4c	22.6ab	99.2a	121.1ab
PKHB +PM	76.9a	151.8a	144.4a	37.8ab	102.5a	130.5ab

NB: The values that do not share the same letters are significantly different at $p \leq 0.05$ level of significance

The results of the residual effect (2019 second planting) revealed that none of the treatment materials significantly differed in increasing cucumber vine length at all growth stages (4, 6, and 8 WAP). Still, they were significantly different ($p < 0.05$) from the control. The residual effect results were somewhat consistent with the direct effect, as all the treatments performed better than the control. In the residual phase, PPB + PM had the longest vine with a mean of 48.4 cm at 4 WAP, but at 6 WAP, the longest vine was from GMB + PM (112.6 cm), and at 8 WAP, GMB produced the longest vine (244.1 cm). Therefore, the research suggests that biochar is recalcitrant in soils and does not immediately enter the carbon cycle, thereby exhibiting carbon sequestration properties. This finding is supported by Gundale and DeLuca (2007).

3.4.2. Number of leaves

The effect of treatments on the number of cucumber leaves is presented in Table 6. In the 2018 direct planting phase, at 4 WAP, plots treated with PKHB + PM, GMB + PM, NSB + PM, CPB + PM, and PPB + PM showed significant differences ($p < 0.05$) compared to the control but were not different from plots amended with GMB, NSB, CPB, and PPB. Similarly, GMB, NSB, CPB, and PPB were not significantly different from the control. The highest number of cucumber leaves was observed in plots amended with PKHB + PM (23.64), followed by CPB + PM (22.56), while the lowest number of cucumber leaves was observed in control (8.89). At 6 WAP, the number of leaves per cucumber plant in plots amended with PKHB + PM, GMB + PM, NSB + PM, CPB + PM, PPB + PM, and PPB was higher than the control, while the number of leaves in plots amended with PKHB, GMB, NSB, and CPB was not significantly different from the control. The highest number of leaves at 6 WAP was obtained in plots amended with PKHB + PM (60.9), while the lowest was obtained in plots amended with PKHB (22.3). At 8 WAP, none of the treated plots significantly increased the number of leaves per cucumber plant compared to the control. The highest number of cucumber leaves at 8 WAP was observed in plots treated with GMB, while the lowest value was observed in plots treated with PKHB.

The studies conducted by Mbah et al. (2017) in Abakaliki, southeastern Nigeria, and Upadhyay and Neupane (2020) in Khumaltar, Nepal, support the results of this study. Their research reported a significant increase in cucumber leaves, lettuce, and potatoes when amended with biochar. However, the lowest mean value observed in plots amended with PKHB could not be justified during this study. It could be associated with the slightly acidic nature of the biochar or the application method. Solaiman et al. (2020) reported in their research that the application of sole poultry biochar did not enhance the growth and yield of cucumber but resulted in a substantial decrease in output after one month of application.

In the residual phase (2019 second planting), the highest number of cucumber leaves was observed in plots treated with PPB (15.23), while the lowest was in control (5.53) at 4 WAP. Plots treated with PPB showed significant differences ($p < 0.05$) compared to the control, PPB + PM, and PKHB, but were not significantly different ($p < 0.05$) from plots treated with CPB + PM, NSB, NSB + PM, GMB, GMB + PM, and PKHB + PM. At 6 WAP, plots amended with NSB + PM produced the highest number of leaves (21.7), while the lowest number of cucumber leaves was observed in control (10.1). Therefore, the treatments were not significantly different from each other but showed a statistical difference from the control. Similarly, at 8 WAP, the highest number of leaves was observed in plots amended with GMB (22.0), while the lowest was observed in the control (14.4). Overall, the treatments consistently showed a significant increase ($p < 0.05$) in the number of cucumber leaves during the residual phase compared to the control. This suggests that the applied nutrients remained in the soil.

Table 6.
Influence of sole biochar from different feedstock and synergized with poultry manure on the number of leaves of cucumber in the 2018/2019 planting seasons

Treatments	Number of leaves					
	2018-First Planting (direct effect)			2019-Second Planting (residual effect)		
	4WAP	6WAP	8WAP	4WAP	6WAP	8WAP
Control	8.9d	26.2cd	20.0ab	5.5d	10.1b	14.4bc
PPB	15.9abcd	49.8ab	25.4a	15.2a	19.9a	19.3ab
PPB + PM	18.3abc	52.0abc	26.4a	12.1c	20.9a	19.8a
CPB	12.7bcd	31.8bcd	23.1ab	14.0abc	18.5a	17.5ab
CPB + PM	22.6a	50.2ab	24.6a	13.3abc	20.5a	20.1a
NSB	14.9abcd	47.0abcd	25.7a	13.9abc	18.9a	21.0a
NSB + PM	19.4ab	59.2a	25.9a	14.0abc	21.7a	19.6a
GMB	15.7abcd	47.4abcd	26.8a	13.1abc	20.7a	22.0a
GMB + PM	19.6ab	57.2ab	25.7a	14.2abc	21.1a	20.4a
PKHB	9.9cd	22.3d	17.1b	12.4bc	17.9a	21.1a
PKHB +PM	23.6a	60.9a	25.9a	14.8ab	19.0a	21.3a

NB: The values that do not share the same letters are significantly different at $\alpha \leq 0.05$ level of significance

Table 7.
Effects of sole biochar from different feedstock and fortified with poultry manure on the leaf area (cm^2) of cucumber in the 2018/2019 planting season

Treatments	Leaf Area (cm^2)					
	First Planting (direct effect)			Second Planting (residual effect)		
	4WAP	6WAP	8WAP	4WAP	6WAP	8WAP
Control	94.6ab	100.9a	102c	67.1b	85.2b	102b
PPB	112.9ab	159.2a	110a	110.0ab	110.7a	109a
PPB + PM	124.1a	152.0a	110ab	111.6a	109.3a	110a
CPB	109.0ab	109.4a	110abc	105.4ab	105.6ab	106ab
CPB + PM	137.8ab	146.6a	112a	109.9ab	107.7ab	108ab
NSB	111.3ab	110.1a	110a	108.3ab	106.6a	107ab
NSB + PM	123.6ab	113.4a	110a	107.6ab	108.4a	107ab
GMB	134.4ab	135.5a	111a	106.4a	108.9a	110a
GMB + PM	146.4ab	127.6a	110a	109.6ab	109.9a	109a
PKHB	88.9b	99.4a	102bc	105.5ab	105.0ab	107ab
PKHB +PM	158.8a	124.5a	110abc	110.4a	109.8a	110a

NB: The values that do not share the same letters are significantly different at $p \leq 0.05$ level of significance

3.4.3. Leaf area

The results of the effect of sole biochar from different feedstock, synergized with poultry manure, on the leaf area of cucumber are presented in Table 7. Specifically, during the 2018 first planting, there were no significant differences ($p < 0.05$) between the control and treatments at 4 and 6 WAP. However, the widest leaf area was observed in plots amended with PKHB + PM (158.8 cm^2) and PPB (159.2 cm^2) at 4 and 6 WAP, respectively, while the narrowest leaf area was observed in plots amended with PKHB in the first planting. Similarly, at 8 WAP, all the treatments showed significant differences from the control. The widest leaf area was obtained in plots amended with the combination of CPB + PM. Meanwhile, during the 2019 second planting, the residual effect of treatments on the leaf area was significant. Plots treated with PPB + PM, GMB, and PKHB + PM produced the widest leaf area and showed statistical differences from the control at 4, 6, and 8 WAP. This result is consistent with the findings of Upadhyay et al. (2014), who reported a significant difference in leaf area at 5 WAP. Overall, the results indicate that any biochar rate was beneficial compared to the control in the first (direct) and second (residual) planting.

3.5. Yield components of cucumber

The selected yield indices considered in the cucumber study include fruit length, diameter, weight, and weight/plot, as presented in Figs 2a and 2b. In the first (direct) planting, treatments showed no significant difference in fruit length from each other. However, plots amended with GMB + PM (18.94 cm), which recorded the longest fruit, were significantly different from the control (9.75 cm) and plots amended with PKHB (8.07 cm). For fruit diameter, the treatments applied showed no significant difference when compared with the control. However, the highest fruit diameter was obtained in plots amended with PKHB + PM (3.69 cm), while the lowest was obtained in plots amended with PKHB (1.65 cm), the treatment with sole application of palm kernel husk biochar. The weight of cucumber was significantly increased ($p < 0.05$) in plots treated with the combination of goat manure biochar and poultry manure (GMB + PM) and PKHB + PM when compared with the control. Still, it was not significantly different from other treatments (PPB, PPB + PM, CPB, CPB + PM, NSB, NSB + PM and GMB). The highest fruit weight was obtained in plots treated with PKHB + PM, followed by GMB + PM, while the lowest was from the control. Similarly, fruit weight per plot produced in plots amended with PKHB + PM and GMB + PM were statistically different ($p < 0.05$) from the control. The results show that combining biochar with poultry manure gave better yield indices in cucumber production in the highly weathered soils of southeastern Nigeria. Similarly, Iren et al. (2018) reported significant increases in the fresh shoot weight of *Amaranthus cruentus* in Calabar. Southeastern Nigeria as a result of using wood biochar solely at 20 t/ha and in various combinations with urea fertilizer. In neighbouring Ghana, Yeboah et al. (2016) found a significant increase in maize yield with application rates of 5 t/ha of corn cob, rice straw, and cocoa pod husk biochar on an Ultisol (FAO WRB: acrisols). On the other hand, Major et al. (2010) found no significant increase in yield during the first growing season in Amazonian oxisols (FAO WRB: Ferralsol) when biochar was applied.

During the 2019 second planting (residual effect), for fruit length and fruit diameter, all the treatments were significantly different ($p < 0.05$) from the control. Still, they were not different from each other (see Figs 3a and 3b). The highest fruit length and diameter were obtained in plots amended with PKHB + PM and GMB + PM. Fruit weight per plot in the residual effect was significantly different in plots amended with GMB + PM, GMB,

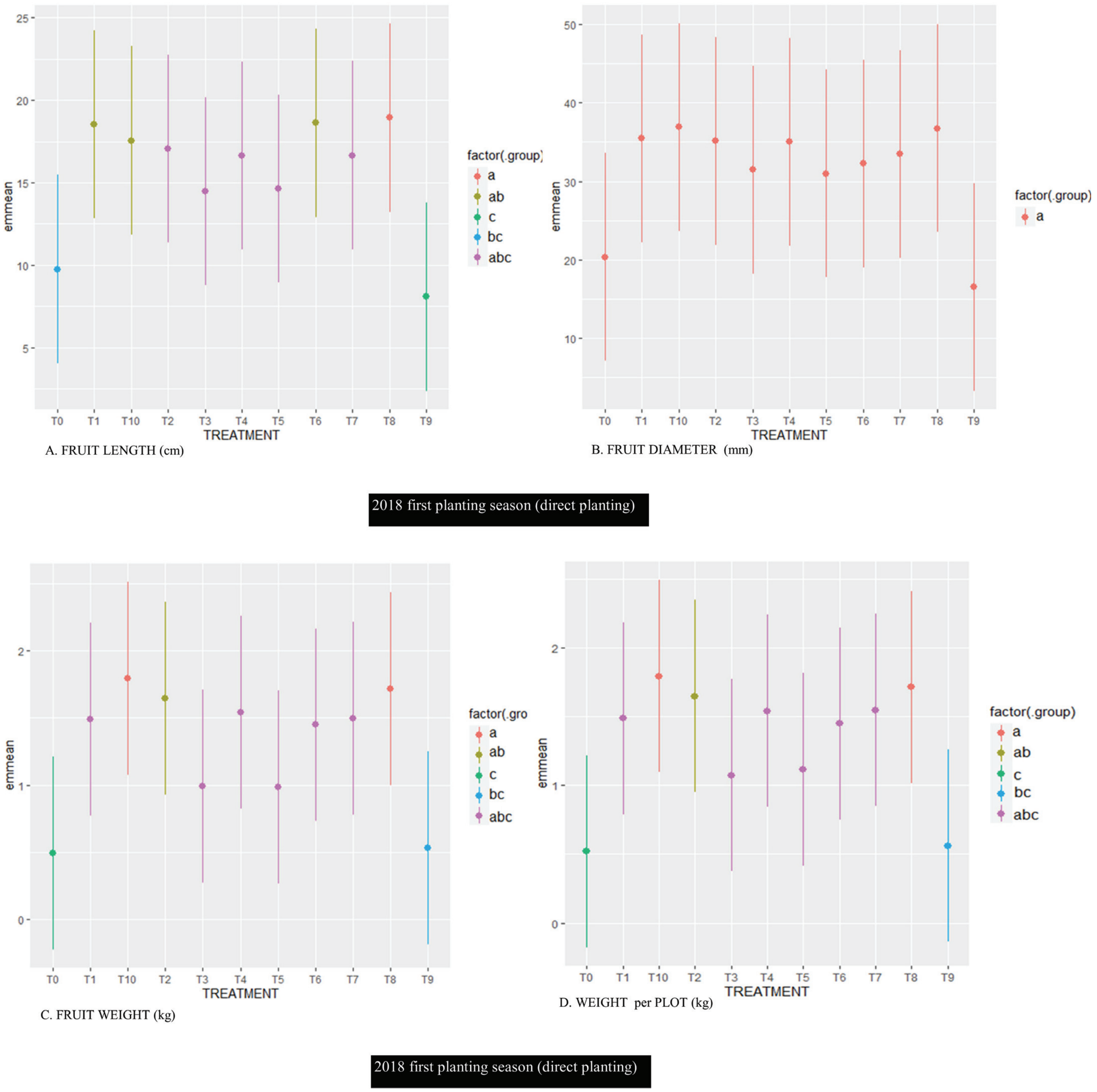

Fig. 2. (a) The impact of sole and poultry manure synergized with biochar from different feedstock on the yield components of cucumber in the 2018 planting season. (b) The impact of sole and poultry manure synergized with biochar from different feedstock on the yield components of cucumber in the 2018 planting season.

PPB, PPB + PM, CPB, CPB + PM, NSB, NSB + PM, and PKHB + PM when compared with the control. The highest cucumber fruit weight per plot was obtained in plots treated with PPB + PM, while the lowest was obtained in the control. In cucumber fruit weight per plot, the result showed that the highest weight was obtained with the combination of plantain peels biochar and poultry manure (1.19 t/ha) and showed a significant difference ($p < 0.05$) between the control (0.31 t/ha), the plot with the lowest fruit weight per plot.

The result of the residual planting revealed the sustainability of cucumber production using biochar mixed with poultry manure. The results obtained here are promising as they support the integrated soil nutrient management technology reported by Vanlanwe et al. (2002), Tahir et al. (2011), and Tejada and Gonzalez (2009). Besides that, the result supports that the biochar is recalcitrant (i.e., stays longer in the soil), as reported by other authors (de la Rosa et al., 2018; Dong et al., 2017; Hammes and Schmidt, 2009).

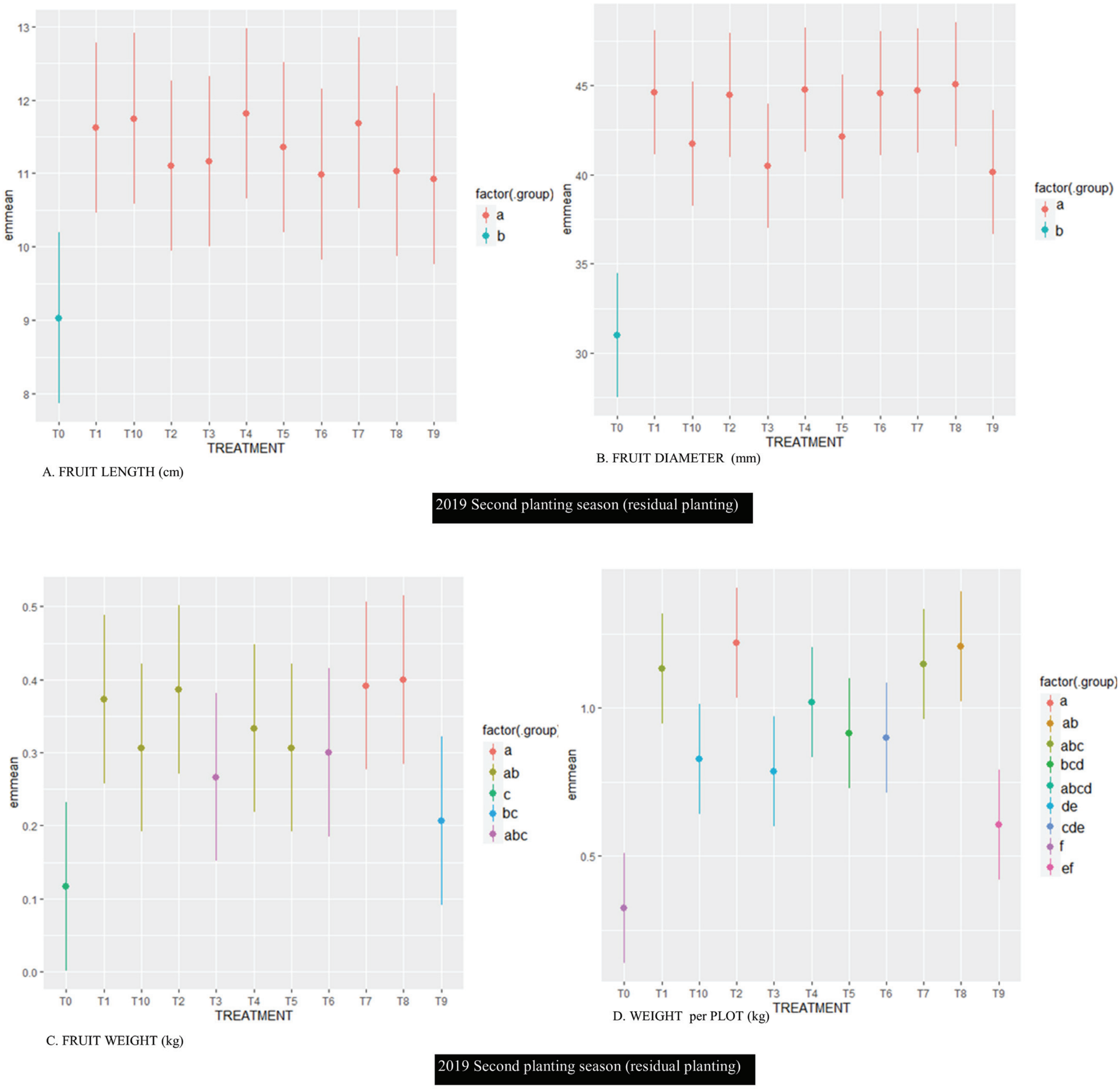

Fig. 3. (a) The impact of sole and poultry manure synergized with biochar from different feedstock on the yield components of cucumber in the 2019 planting season (residual planting). (b) The impact of sole and poultry manure synergized with biochar from different feedstock on the yield components of cucumber in the 2019 planting season (residual planting).

3.6. The impact of sole biochar from different feedstock and synergized with poultry manure on nutrient uptake of cucumber plant in the 2018/2019 planting seasons

The results of the 2018 and 2019 planting seasons (first and second planting) for nutrient uptake by the cucumber plant (Table 8) showed that N and Ca uptake were not significantly affected ($p > 0.05$) as a result of the amendments used. However, all other nutrient elements (K, P, S) showed significant differences ($p < 0.05$) in the first planting of 2018. Further results revealed that K uptake by cucumber plants in plots amended with plantain peel biochar, plantain peel biochar plus poultry manure, neem seed biochar, and goat manure biochar were statistically similar ($p > 0.05$) but significantly different from other biochar-amended soils and the control in the first planting (direct effect) in 2018. The residual effects of the amendments from the first planting season might have still been

Table 8.
Cucumber plant nutrient uptake as influenced by sole biochar from different feedstock and fortified with poultry manure in the 2018/2019 planting season

Treatments	N	P	K mg/kg	Mg	Ca	S
2018 First planting (direct effect)						
Control	17.0a	5991bc	21136cd	4386a	31291a	2423d
PPB	20.3a	6025bc	69731a	4967a	19904a	4097cd
PPB + PM	19.1a	7437abc	51546ab	6474a	31004a	5579bc
CPB	17.8a	7402abc	44542b	6180a	35330a	7926a
CPB + PM	17.1a	5817c	35489bcd	4981a	29774a	4210cd
NSB	20.5a	5975bc	51025ab	6759a	24948a	5856abc
NSB + PM	18.8a	7549ab	43081b	6834a	31098a	6714ab
GMB	23.9a	7689a	53379ab	6646a	30852a	5363bc
GMB + PM	18.1a	6539abc	46017b	5158a	28239a	4931bc
PKHB	18.5a	6066bc	19919d	6595a	30772a	2367d
PKHB +PM	19.6a	7043abc	40590bc	5690a	30430a	4453bcd
2019 Second planting (residual effect)						
Control	13.5a	6326a	50357a	4374a	31885a	4270a
PPB	22.8a	6849a	47316a	4856a	35777a	4361a
PPB + PM	17.4a	7747a	45467a	6174a	28747a	4942a
CPB	15.3a	7101a	44018a	5146a	21308a	5140a
CPB + PM	19.7a	7030a	49952a	6583a	31103a	6426a
NSB	22.9a	6354a	45802a	6637a	29908a	5438a
NSB + PM	15.4a	6805a	38365a	5678a	33834a	4681a
GMB	19.7a	6959a	26557a	4955a	33660a	3569a
GMB + PM	16.6a	8121a	46979a	4937a	28120a	4470a
PKHB	19.2a	7067a	38823a	7290a	23534a	6125a
PKHB +PM	20.0a	6819a	42821a	7907a	32860a	4506a

NB: The values that do not share the same letters are significantly different at $p \leq 0.05$ level of significance

present in the soil during the second planting. This could have led to a sustained supply of nutrients to the cucumber plants, resulting in no significant differences in nutrient uptake between treatments and the control.

3.7. The impact of sole biochar from different feedstock and synergized with poultry manure on nutrient uptake of cucumber fruit in the 2018/2019 planting seasons.

The uptake of N, P, K, Mg, Ca, and S by cucumber fruit in the first planting (direct effect) 2018 was influenced by the amendments used, as depicted in Table 9. Significant differences were observed in the nutrient uptake of cucumber fruit, except for N, Mg, Ca, and S. All other fruit nutrients and macronutrients assessed were significantly absorbed ($p < 0.05$) due to the various amendments employed. Furthermore, the results revealed that K contents in plots amended with plantain peels biochar, plantain peels biochar mixed with poultry manure, neem seed biochar, and goat manure biochar were statistically similar ($p > 0.05$) but significantly different from other biochar-amended soils and the control. On the other hand, in the 2019 second planting (residual planting), no significant differences ($p < 0.05$) were observed in the selected nutrients of cucumber fruit. The soil's inherent fertility and nutrient composition may have played an important role in providing adequate nutrient levels for the cucumber plants during the second planting.

3.8. Correlation between fruit indices, growth parameters and soil properties

Fig. 4 illustrates the correlation analysis between fruit indices, growth parameters and soil properties at different significance levels: *** $p < 0.1\%$ ** $p < 1\%$ and *$p < 5\%$. The correlation matrix revealed significant relationships among the variables. VL4 showed a positive and significant correlation with VL6 ($r = 0.72$, $p < 0.001$), and VL6 exhibited a positive and significant correlation with VL8 ($r = 0.34$, $p < 0.01$) and Ca ($r = 0.38$, $p < 0.01$). Similarly, VL8 showed a positive and significant correlation with Ca ($r = 0.45$, $p < 0.01$). For the number of leaves at

Table 9.
Cucumber fruit nutrient uptake as influenced by sole biochar from different feedstock and fortified with poultry manure in the 2018/2019 planting season

Treatments	N	P	K mg/kg	Mg	Ca	S
2018 First planting (direct Planting)						
Control	18.5a	2996bc	10568cd	5678a	15645a	1754a
PPB	19.2a	3012bc	34866a	4955a	9952a	1760a
PPB + PM	18.0a	3718abc	25773ab	6462a	15502a	2161a
CPB	16.7a	3701abc	22271b	6168a	17665a	1919a
CPB + PM	15.9a	2908c	17745bcd	4969a	14887a	1634a
NSB	19.4a	2987bc	25512ab	6747a	12474a	1971a
NSB + PM	17.7a	3774ab	21540b	6822a	15549a	1994a
GMB	22.8a	3845a	26690ab	6634a	15426a	2124a
GMB + PM	17.0a	3270abc	23009b	5146a	14120a	1769a
PKHB	17.4a	3033bc	9960d	6583a	15386a	2092a
PKHB +PM	15.9a	3522abc	20295bc	4374a	15215a	1498a
2019 Second planting (residual Planting)						
Control	20.2a	8589a	52810a	7907a	4486a	2150a
PPB	16.3a	8573a	53455a	4856a	4484a	1587a
PPB + PM	22.8a	7459a	43954a	6174a	4588a	2135a
CPB	17.0a	7991a	47875a	5146a	5215a	1769a
CPB + PM	17.4a	7594a	52435a	6583a	4454a	2092a
NSB	15.9a	7724a	53074a	4374a	3511a	1498a
NSB + PM	18.5a	8856a	45454a	5678a	3972a	1754a
GMB	19.2a	7874a	45835a	4955a	3706a	1760a
GMB + PM	15.0a	8391a	48616a	4937a	4290a	1758a
PKHB	19.2a	8121a	48622a	7290a	4491a	1915a
PKHB +PM	20.1a	7594a	51974a	6637a	5868a	2259a

NB: The values that do not share the same letters are significantly different at $p \leq 0.05$ level of significance

different weeks after planting (WAP), the correlation matrix revealed strong positive and significant correlations between the number of leaves at 4, 6, and 8 WAP. For example, NL4 showed a significant correlation with NL6 ($r = 0.79$, $p < 0.001$) and NL8 ($r = 0.58$, $p < 0.001$). Similarly, NL6 showed a positive and significant correlation with NL8 ($r = 0.58$, $p < 0.001$). These findings suggest that an increase in the number of leaves at 4 WAP results in a corresponding increase in 6 WAP and 8 WAP. NL6 also showed a positive and significant correlation with Ca ($r = 0.44$, $p < 0.001$), while NL8 showed a significant and positive correlation with Ca ($r = 0.30$, $p < 0.05$). Leaf area (LA) 4, 6, and 8 weeks after planting showed significant correlations. LA4 and LA6 were highly correlated ($r = 0.98$, $p < 0.001$), indicating a strong association. LA4 showed a positive and significant correlation with LA8 ($r = 0.38$, $p < 0.01$), while LA6 showed a positive and significant correlation with LA8 ($r = 0.45$, $p < 0.01$). Similarly, LA8 showed a positive and significant correlation with Ca ($r = 0.40$, $p < 0.01$). The correlation matrix revealed significant relationships between fruit indices (FL, FW, FD, and Wplot) and soil properties. FL showed a negative and significant correlation with FW ($r = -0.54$, $p < 0.001$), K ($r = -0.36$, $p < 0.01$), and Mg ($r = -0.40$, $p < 0.01$). FL exhibited a positive and significant correlation with FD ($r = 0.81$, $p < 0.001$), Wplot ($r = 0.87$, $p < 0.001$), P ($r = 0.60$, $p < 0.001$), and N ($r = 0.54$, $p < 0.001$), indicating a close association. FW showed a negative and significant correlation with Wplot ($r = -0.35$, $p < 0.05$), FD ($r = -0.91$, $p < 0.001$), P ($r = -0.95$, $p < 0.001$), and N ($r = -0.90$, $p < 0.001$). Similarly, FW showed a positive and significant correlation with OC ($r = 0.51$, $p < 0.001$), K ($r = 0.61$, $p < 0.001$), Mg ($r = 0.62$, $p < 0.001$), and pH ($r = 0.74$, $p < 0.001$). FD showed a positive association with Wplot ($r = 0.64$, $p < 0.001$), P ($r = 0.92$, $p < 0.001$), and N ($r = 0.54$, $p < 0.001$). Conversely, FD exhibited a negative and significant correlation with OC ($r = -0.44$, $p < 0.01$), K ($r = -0.57$, $p < 0.001$), Mg ($r = -0.59$, $p < 0.001$), and pH ($r = -0.60$, $p < 0.001$), indicating a strong negative association. Wplot showed a positive and significant correlation with P ($r = 0.45$, $p < 0.01$), N ($r = 0.44$, $p < 0.01$), and Ca ($r = 0.32$, $p < 0.05$), suggesting that an increase in fruit weight plot corresponds to an increase in P, N, and Ca

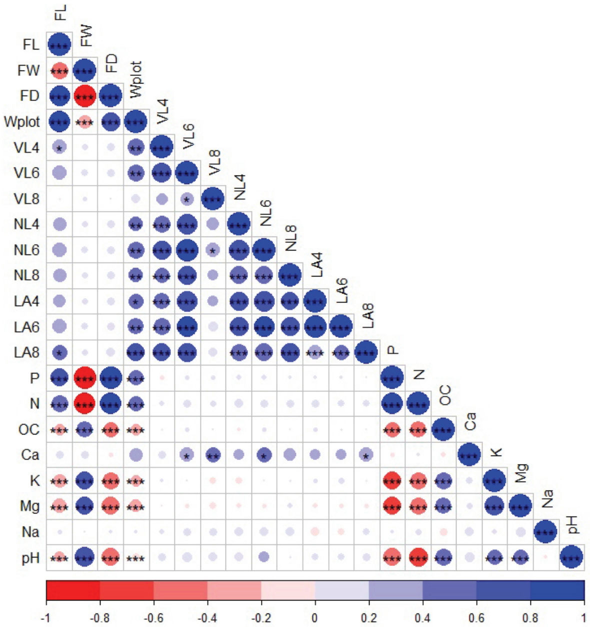

Fig. 4. Overall correlation matrix between fruits indices, growth parameters and soil properties (***p < 0.1% **p < 1% and *p < 5%)

contents. Additionally, P and N demonstrated a strong positive correlation ($r = 0.87$, $p < 0.001$), indicating their close association. There was a moderate negative correlation between P and OC ($r = –0.43$, $p < 0.01$), P and K ($r = –0.61$, $p < 0.001$), as well as between P and Mg ($r = –0.61$, $p < 0.001$). N also exhibited moderate negative correlations with K ($r = –0.57$, $p < 0.001$) and Mg ($r = –0.57$, $p < 0.001$). OC showed a negative but significant correlation with P ($r = –0.43$, $p < 0.01$) and N ($r = –0.50$, $p < 0.001$) (For more details see Table 1A-S, 1B-S & 1C-S).

The correlation matrix reveals significant relationships among various variables, indicating the interplay between plant characteristics and soil properties. The number of leaves (NL) at different weeks after planting (WAP) showed strong positive correlations, suggesting a consistent increase in leaf numbers. Leaf area (LA) also exhibited significant associations, with LA4 and LA6 showing a high correlation and LA4 and LA6 positively correlating with LA8. These findings align with literature highlighting the importance of leaf development and expansion in plant growth and productivity (Ayito et al., 2018; Iren et al., 2016; and Iren et al. (2021). Moreover, fruit indices (FL, FW, FD, and Wplot) demonstrated significant correlations with soil properties, emphasizing the influence of soil conditions on fruit characteristics. Fruit weight (FW) showed negative correlations with FL, K, and Mg but positive associations with FD, Wplot, P, N, OC, and pH. These results support existing research indicating the impact of soil nutrient availability on fruit development and quality. Additionally, the study observed associations between soil properties, such as P, N, and OC, providing insights into the nutrient dynamics and interactions within the soil-plant system. These findings contribute to the existing literature by enhancing our understanding of the relationships between plant characteristics, soil properties, and fruit indices, thereby aiding in developing effective agricultural management strategies (For more details see Table 1D-S).

3.9. Structural equation model

In Fig. 5, we implemented our structural equation model in the regression model. For the two years, the out-of-regression analyses reveal important insights into the relationships between various variables, such as fruit indices, growth parameters, and soil properties. Thirteen regression models were employed to estimate the effects of predictor variables on different dependent variables. The analysis using lavaan version 0.6.15 concluded after 4399 iterations, indicating successful convergence. The model was estimated using the ML estimator with the NLMINB optimization method. The model included 119 parameters and was examined based on 66 observations. The user model was evaluated against the baseline model, revealing a significant improvement. The Comparative Fit Index (CFI) yielded a value of 0.959, indicating a good fit, while the Tucker-Lewis Index (TLI) showed a value of 0.902. The loglikelihood of the user model was –2192.873, and the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) were 4623.746 and 4884.314, respectively. The Root Mean Square Error of Approximation (RMSEA) was 0.119, with a 90% confidence interval ranging from 0.089 to 0.147. The p-value for the hypothesis test of RMSEA <= 0.050 was 0.000, indicating a significant discrepancy from the desired fit. However, the p-value for the RMSEA >= 0.080 hypothesis test was 0.983, suggesting a good fit. The Standardized Root Mean Square Residual (SRMR) was found to be 0.099, indicating a reasonable fit of the model.

The results indicate the magnitude and significance of these effects. For instance, in the FL regression, the predictor variable N exhibited a significant positive effect (estimate = 2.568, $p < 0.001$), while the OC variable showed a non-significant negative effect (estimate = – \0.141, $p = 0.650$). Similarly, in the FW regression, the P and N variables had significant negative effects (estimate = – \0.009, $p < 0.001$; estimate = –11.379, $p < 0.001$, respectively). The FD regression revealed significant

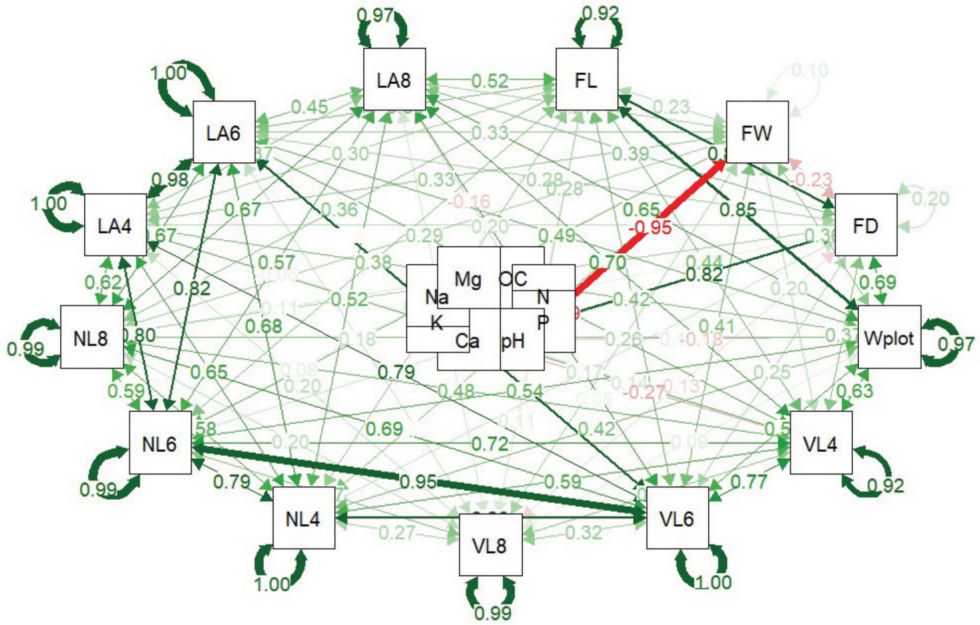

Fig. 5. Structural equation model (SEM) showing the inter-relationship between soil properties, growth parameters yield parameters of cucumber (p ≤ 0.05)

positive effects for the P (estimate = 0.006, $p < 0.001$) and N (estimate = 9.474, $p < 0.001$) variables. These findings highlight N and P's importance in supporting FL, FW, and FD of cucumber (For more details see Table 2A-S).

4. Conclusion

The application of biochar, either alone or in combination with other amendments, demonstrated positive effects on soil nutrients, cucumber growth, and fruit yields. Although the increase in cucumber yield was not highly visible, it was still significant. Importantly, biochar enhanced plant nutrient uptake efficiency, suggesting the potential to reduce reliance on chemical fertilizers. Our fieldwork in tropical soils supported the promising benefits of biochar, but longer-term studies are necessary to observe its long-term effects and adapt soil environments accordingly. Adding biochar led to increased soil carbon content, especially when derived from palm kernel husk via slow pyrolysis, indicating its potential as a stable carbon pool. However, further evidence is needed in Nigeria to demonstrate biochar's ability to improve crop yields.

In conclusion, the treatments employed in this study, such as palm kernel husk biochar combined with poultry manure, goat biochar mixed with poultry manure, and sole or mixed plantain peel biochar, effectively sequestered carbon and nitrogen, improved fertilizer efficiency, enhanced productivity, and contributed to global food security. Additionally, biochar technology offers various ecosystem services, including reduced soil erosion and contamination of water sources, increased species diversity, and improved ecosystem health. Consequently, biochar can be utilized for land reclamation purposes and should be considered an alternative to chemical fertilizers in soil nutrient management programs, supported by future regulations. Furthermore, increasing the quantity of biochar applied to degraded soils is recommended, as 20 tons/ha may not yield good residual effects for subsequent planting seasons. Exploring alternative methods of biochar application beyond surface spreading should also be considered.

5. Recommendations

Based on our results, we recommend combining biochar with poultry manure to improve soil properties and enhance crop growth. Our study showed that biochar amendments can improve soil quality where environmental conditions prevail. However, it is important to note that adverse climatic factors (i.e., high precipitation and high humidity) may impact the biochar fortification outcome with other organic manure on soil and crop yield. Therefore, an erosion-prone site should be properly managed and good drainage implemented before applying this amendment. Nevertheless, biochar could be a viable alternative to chemical fertilizers in soil nutrient management programs, particularly in regions with dominated sandy soil. Also, we noted that the quantity of biochar applied to the soil should be increased for better residual effects in subsequent planting seasons. Additionally, alternative methods of biochar application beyond surface spreading could be explored for potentially improved outcomes.

Availability of data and materials

Data will be made available upon reasonable request from the corresponding author.

Competing interests

The authors declare that they have no known competing personal relationships or financial interests that could have appeared to influence the work reported in this paper.

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References

Abulude, F.O., Akinjagunla, Y.S., Abe, T., Awanlemhen, B.E., Afolabi, O., 2007. Proximate composition, selected mineral, physical characteristics and in vitro multienzyme digestibility of cucumber (Cucumis sativus) fruit from Nigeria. American Journal of Food Technology 2, 196–201. https://10.3923/ajft.2007.196.201

Adaikwu, A.O., Obi, M.E., Ali, A., 2012. Assessment of degradation status of soil in selected areas of Benue state Southern Guinea Savanna of Nigeria. Nigerian Journal of Soil Science 22(1), 168–177.

Aihou, K., Sanginga, N., Vanlauwe, B., Lyasse, O., Diels, J., Merckx, R., 1998. Alley cropping in the moist savanna of West-Africa: I. Restoration and maintenance of soil fertility on'terre de barre 'soils in Bénin Republic. Agroforestry Systems 42, 213–227. https://doi.org/10.1023/A:1006114116095

Ajisefinanni, A., 2004. Performance of two cucumber varieties in response to manure rates and types at Samaru. Undergraduate project Agronomy Department Ahmadu Bello University Zaria, Nigeria.

Akpan-Idiok, A.U., Udo, I.A., Braide, E.I., 2012. The use of human urine as an organic fertilizer in the production of okra (Abelmoschus esculentus) in South Eastern Nigeria. Resources, Conservation and Recycling 62, 14–20. https://doi.org/10.1016/j.resconrec.2012.02.003

Asai, H., Samson, B.K., Stephan, H.M., Songyikhangsuthor, K., Homma, K., Kiyono, Y., Inoue, Y., Shiraiwa, T., Horie, T., 2009. Biochar amendment techniques for upland rice production in Northern Laos: 1. Soil physical properties, leaf SPAD and grain yield. Field crops research 111(1–2), 81–84. https://doi.org/10.1016/j.fcr.2008.10.008

Ayito, E.O., Iren, O.B., John, K., 2018. Effects of neem-based organic fertilizer, npk and their combinations on soil properties and growth of Okra (Abelmoschus esculentus) in a Degraded Ultisol of Calabar, Nigeria. International Journal of Plant & Soil Science 24(5), 1–10. https://doi.org/10.9734/IJPSS/2018/43027

Bhawana Bisht, B.B., Singh, M.P., Srivastava, B.K., Singh, P.K., 2012. Performance of cucumber varieties in a naturally ventilated polyhouse. Indian Journal of Horticulture 68(4), 575–577.

Blanco, F.F., Folegatti, M.V., 2003. A new method for estimating the leaf area index of cucumber and tomato plants. Horticultura Brasileira 21, 666–669. https://doi.org/10.1590/S0102-05362003000400019

Brown, R.A., Kercher, A.K., Nguyen, T.H., Nagle, D.C. and Ball, W.P., 2006. Production and characterization of synthetic wood chars for use as surrogates for natural sorbents. Organic Geochemistry 37(3), 321–333. https://doi.org/10.1016/j.orggeochem.2005.10.008

Ch'ng, H.Y., Ahmed, O.H., Majid, N.M.A., 2014. Biochar and compost influence the phosphorus availability, nutrients uptake, and growth of maize (Zea mays L.) in tropical acid soil. Pakistan Journal of Agricultural Sciences 51(4). https:// 10.4081/ija.2019.1107

Chude, V.O., Malgwi, W.B., Amapu, I.Y., Ano, O.A., 2004. Manual on soil fertility assessment. Federal Fertilizer Department (FFD) in collaboration with Food and Agricultural Organization (FAO) and National Special Programme for Food Security. Abuja-Nigeria, 47.

de la Rosa, J.M., Rosado, M., Paneque Carmona, M., Miller, A.Z., Knicker, H., 2018. Effects of aging under field conditions on biochar structure and composition: Implications for biochar stability in soils. Science of the Total Environment 613, 969–976. https://doi.org/10.1016/j.scitotenv.2017.09.124

Demirbas, A., 2004. Effects of temperature and particle size on biochar yield from pyrolysis of agricultural residues. Journal of analytical and applied pyrolysis, 72(2), 243–248. https://doi.org/10.1016/j.jaap.2004.07.003

Dong, X., Li, G., Lin, Q., Zhao, X., 2017. Quantity and quality changes of biochar aged for 5 years in soil under field conditions. Catena 159, 136–143. https://doi.org/10.1016/j.catena.2017.08.008

Eifediyi, E.K., Remison, S.U., 2010. The effects of inorganic fertilizer on the yield of two varieties of cucumber (Cucumis sativus L.). Report and Opinion 2(11), 1–5.

Ene, C.O., Ogbonna, P.E., Agbo, C.U., Chukwudi, U.P., 2016. Studies of phenotypic and genotypic variation in sixteen cucumber genotypes. Chilean Journal of Agricultural Research 76(3), 307–313. http://dx.doi.org/10.4067/S0718-58392016000300007

Esu, I.E., 2005. Characterization, Classification and Management Problems of the major soil orders in Nigeria. 26th Inaugural lecture held at University of Calabar, Calabar. ISBN 978-007-148-2, 1–66.

Glaser, B., Lehr, V.I., 2019. Biochar effects on phosphorus availability in agricultural soils: A meta-analysis. Scientific Reports 9(1), 9338. https://doi.org/10.1038/s41598-019-45693-z

Gundale, M.J., DeLuca, T.H., 2007. Charcoal effects on soil solution chemistry and growth of Koeleria macrantha in the ponderosa pine/Douglas-fir ecosystem. Biology and Fertility of Soils 43, 303–311. https://doi.org/10.1007/s00374-006-0106-5

Hammes, K., Schmidt, M.W., 2012. Changes of biochar in soil. In Biochar for environmental management (201–214). Routledge.

Ingold, M., Al-Kindi, A., Jordan, G., Dietz, H., Schlecht, E., Buerkert, A., 2015. Effects of activated charcoal and quebracho tannins added to feed or as soil conditioner on manure quality in organic agriculture. Organic Agriculture 5, 245–261. https://doi.org/10.1007/s13165-015-0104-8

Iren, O.B., Ijah, C.J., Asawalam, D.O., Osodeke, V.E., 2016. Comparative effect of pig manure, urea fertilizer and their combinations on the performance of Amaranthus cruentus in a Rainforest Ultisol, Nigeria. Integrity Research Journal-Journal of Agricultural Science and Practice 1, 52–57. https://doi.org/10.31248/JASP2016.014

Iren, O.B., Uwah, I.D., Umanah, M.I., 2018. Response of Amaranthus cruentus to biochar combined with urea fertilizer in Calabar, Nigeria. Journal of Agriculture, Forestry & Environment 3(1), 192-203.

Iren, O.B., Ediene, V.F., 2021. Soil pH and Microbial Properties as Affected by Integrated Use of Biochar, Poultry Manure and Urea. Pakistan Journal of Biological Sciences 24, 90–98. 10.3923/pjbs.2021.90.98

Kathayat, K., Rawat, M., Kandpal, G., Pandey, G., Chauhan, P., Tiwari, R., 2018. Genetic Variability In Cucumber (*Cucumis sativus L.*) Plant Archives 18(2), 1223–1228.

Katy, E.B., Kristofor, R.B., Savin, M.C., David, E.L., 2015. Biochar source and application rate effects on soil water retention determined using wetting curves. Open Journal of Soil Science 5(1), 1–10. https://10.4236/ojss.2015.51001

Koppen, W., 1936. Das geographische system der klimat. Handbuch der klimatologie, 46.

Kyveryga, P.M., Blackmer, A.M., Ellsworth, J.W., Isla, R., 2004. Soil pH effects on nitrification of fall-applied anhydrous ammonia. Soil Science

Society of America Journal 68(2), 545–551. https://doi.org/10.2136/sssaj2004.5450

Lehmann, J., Joseph, S., 2009. Biochar for environmental management 1st Edition. Science and Technology, Earthscan, London, 331.

Lehmann, J., Rondon, M., 2006. Bio-char soil management on highly weathered soils in the humid tropics. Biological approaches to sustainable soil systems 113(517), e530.

Liu, G., Hanlon, E., 2012. Soil pH Range for Optimum Commercial Vegetable Production: HS1207/HS1207, 10/2012. EDIS, 2012(11). https://doi.org/10.32473/edis-hs1207-2012

Major, J., Lehmann, J., Rondon, M., Goodale, C., 2010. Fate of soil-applied black carbon: downward migration, leaching and soil respiration. Global Change Biology 16(4),1366–1379. https://doi.org/10.1111/j.1365-2486.2009.02044.x

Mbah, C.N., Njoku, C., Okolo, C.C., Attoe, E.E., Osakwe, U.C., 2017. Amelioration of a degraded Ultisol with hardwood biochar: Effects on soil physico-chemical properties and yield of cucumber (Cucumis sativus L). African Journal of Agricultural Research 12(21),.1781–1792. https:// http://dx.doi.org/10.5897/AJAR2016.11654

Nwofia, G.E., Ogbonna, N.D., Agbo, C.U., Mbah, E.U., 2015. Growth and yield of some vegetable cowpea genotypes as influenced by planting season. International Journal of Agriculture and Forestry 5(3), 205–210. https:// 0.5923/j.ijaf.20150503.05

Rockström, J., Kaumbutho, P., Mwalley, J., Nzabi, A.W., Temesgen, M., Mawenya, L., Barron, J., Mutua, J., Damgaard-Larsen, S., 2009. Conservation farming strategies in East and Southern Africa: Yields and rain water productivity from on-farm action research. Soil and tillage research 103(1), 23–32. https://doi.org/10.1016/j.still.2008.09.013

Rondon, M.A., Lehmann, J., Ramírez, J., Hurtado, M., 2007. Biological nitrogen fixation by common beans (Phaseolus vulgaris L.) increases with bio-char additions. Biology and Fertility of Soils 43, 699–708. https://doi.org/10.1007/s00374-006-0152-z

Schulz, H., Dunst, G., Glaser, B., 2014. No effect level of co-composted biochar on plant growth and soil properties in a greenhouse experiment. Agronomy 4(1), 34–51. https://doi.org/10.3390/agronomy4010034

Shamshuddin, J., Daud, N.W., 2011. Classification and management of highly weathered soils in Malaysia for production of plantation crops Rijeka, Croatia: InTech 1, 75–86. https:// 10.5772/29490

Simarani, K., Azlan Halmi, M.F., Abdullah, R., 2018. Short-term effects of biochar amendment on soil microbial community in humid tropics. Archives of Agronomy and Soil Science 64(13), 1847–1860. https://doi.org/10.1080/03650340.2018.1464149

Soil Survey Staff, 2014. Soil survey field and laboratory methods manual. soil survey investigations Report, 51, Version 2.0. R. Burt and Soil Survey Staff (ed.). U.S. Department of Agriculture, Natural Resources Conservation Service.

Solaiman, Z.M., Shafi, M.I., Beamont, E., Anawar, H.M., 2020. Poultry litter biochar increases mycorrhizal colonisation, soil fertility and cucumber yield in a fertigation system on sandy soil. Agriculture 10(10), 480. https://doi.org/10.3390/agriculture10100480

Steiner, C., Glaser, B., Geraldes Teixeira, W., Lehmann, J., Blum, W.E., Zech, W., 2008. Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal. Journal of Plant Nutrition and Soil Science 171(6), 893–899. https://doi.org/10.1002/jpln.200625199

Tahir, M., Ayub, M., Javeed, H.M.R., Naeem, M., Rehman, H., Waseem, M., Ali, M., 2011. Effect of different organic matter on growth and yield of wheat (Triticum aestivum L). Pakistan Journal of Life and Social Sciences 9, 63–66.

Tejada, M., González, J.L., 2009. Application of two vermicomposts on a rice crop: effects on soil biological properties and rice quality and yield. Agronomy Journal, 101(2), 336–344. https://doi.org/10.2134/agronj2008.0211

Udo, E.J., Ibia, T.O., Ogunwale, J.A., Ano, A.O., Esu, I.E. (2009). Manual of soil, plant and water analyses. Lagos: Sibon Books, Publishers Ltd., Nigeria., 183.

Upadhyay, K.P., George, D., Swift, R.S., Galea, V., 2014. The influence of biochar on growth of lettuce and potato. Journal of Integrative Agriculture 13(3), pp. 541–546. https://doi.org/10.1016/S2095-3119(13)60710-8

Uzoma, K.C., Inoue, M., Andry, H., Fujimaki, H., Zahoor, A., Nishihara, E., 2011. Effect of cow manure biochar on maize productivity under sandy soil condition. Soil Use and Management 27(2), 205–212. https://doi.org/10.1111/j.1475-2743.2011.00340.x

Vaccari, F.P., Baronti, S., Lugato, E., Genesio, L., Castaldi, S., Fornasier, F., Miglietta, F., 2011. Biochar as a strategy to sequester carbon and increase yield in durum wheat. European Journal of Agronomy 34(4), 231–238. https://doi.org/10.1016/j.eja.2011.01.006

Van Zwieten, L., Kimber, S., Morris, S., Chan, K.Y., Downie, A., Rust, J., Joseph, S., Cowie, A., 2010. Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. Plant and Soil, 327, 235–246. https://doi.org/10.1007/s11104-009-0050-x

Vanlauwe, B., Diels, J., Sanginga, N., Merckx, R. eds., 2002. Integrated plant nutrient management in sub-Saharan Africa. Wallingford, CT: CABI.

Vassilev, S.V., Baxter, D., Andersen, L.K., Vassileva, C.G., 2013. An overview of the composition and application of biomass ash. Part 1. Phase–mineral and chemical composition and classification. Fuel 105, 40–76. https://doi.org/10.1016/j.fuel.2012.09.041

Yeboah, E., Asamoah, G., Kofi, B., Abunyewa, A.A., 2016. Effect of biochar type and rate of application on maize yield indices and water use efficiency on an Ultisol in Ghana. Energy Procedia, 93, 14–18. https://doi.org/10.1016/j.egypro.2016.07.143

Yildirim, E., Turan, M., Guvenc, I., 2008. Effect of foliar salicylic acid applications on growth, chlorophyll, and mineral content of cucumber grown under salt stress. Journal of Plant Nutrition 31(3), 593–612. https://doi.org/10.1080/01904160801895118