Agro-Science Journal of Tropical Agriculture, Food, Environment and Extension
Volume 21 Number 2 (April 2022) pp. 53 - 65

ISSN 1119-7455

IMPACT OF BAMBARA SEED RESIDUE BIOCHAR AND NPK ON SOIL FERTILITY, AGGREGATE CARBON AND NITROGEN CONCENTRATIONS AND YIELD OF CUCUMBER

***1, 2Okebalama C.B., 1Asogwa K.C., 1Uzoh I.M. and 2Marschner B.**

[1]Department of Soil Science, Faculty of Agriculture, University of Nigeria Nsukka, Nigeria
[2]Department of Soil Science/Soil Ecology, Ruhr-Universität Bochum, Germany

*Corresponding author's email: chinyere.okebalama@unn.edu.ng; Tel: +234803-538-7310

ABSTRACT

The mechanisms of biochar effects on soil and crop yield are still elusive. Assessing the influence of biochar on total carbon (TC) and total nitrogen (TN) concentrations in hierarchical soil aggregates could provide an explanation. In a randomized complete block design were control, bambara seed residue biochar (BSB), NPK and NPK + BSB treatments superimposed on a two-year bambara seed residue amended Ultisols, in a four-year continuous cucumber cultivation. The effects of the treatments on optimizing cucumber yield and soil sustainability parameters, particularly the aggregate- (4.75-2.00, 1.00-2.00, 0.25-1.00 and < 0.25 mm) associated TC and TN concentrations were studied. The BSB and NPK + BSB treatments significantly ($p \leq 0.05$) increased the concentrations of TC by 113.79 and 104.60%; TN by 100 and 87.50%; and available P by 172% and 415%, respectively. Furthermore, both treatments significantly reduced exchangeable Al^{3+} but increased Mg^{2+} and soil moisture content 4-6 weeks after planting. Exchangeable K^{+} was significantly increased by BSB. The BSB and NPK + BSB significantly improved TC and TN in all aggregate fractions with minimal effect in the 0.25-1.00 mm fraction. However, the overall percentile TC and TN increase by these treatments was more in the macro- (4.75-0.25 mm) than in the micro (< 0.25 mm) aggregates. Application of BSB and NPK + BSB significantly improved cucumber fruit weight by 12- and 24-fold, respectively, compared to NPK treatment. The study demonstrated that BSB enhanced soil fertility, while NPK + BSB further improved cucumber productivity. In addition, these treatments have the potential to substantially sequester carbon and nitrogen more in macro- than micro- aggregates.

Key words: Ultisol, vegetable crop, nutrient retention, continuous cultivation, soil aggregates

INTRODUCTION

In the tropics, subsistence farming using traditional cultivation methods dominates even though it lacks the potential to increase food demands for the teeming population (Muhammad, 2014). In a region faced with poverty amidst global pandemic and global climate change, intensification of food production within the domain of household/ national food security via soil fertility sustenance is inevitable in averting hunger and malnutrition. Hence, research on effect of any management system affecting soil fertility and crop productivity in degraded and highly weathered tropical soils is paramount. In recent times, many organic materials from plant/crop residues, tree/wood biomass, animal manure and municipal waste/sewage sludge are synthesized into biochar and used for different purposes. Biochar is a dark carbon- (C) rich material synthesized from organic waste feedstock via pyrolysis, gasification and hydrothermal carbonization and utilized for various environmental purposes (Cha *et al.*, 2016). Owing to its high C content and cation exchange capacity, large specific surface area and stable structure, different biochar types can be used for C sequestration, soil remediation, organic solid waste composting, decontamination of water pollutants, and as electrode modifier, and catalyst and activator amongst others (Wang and Wang, 2019).

Efforts in demystifying the impacts of various biochar types for agronomic improvement under different agroecosystems have received increasing research attention (Dume *et al.*, 2015; Clark *et al.*, 2019; Kätterer *et al.*, 2019; Peng *et al.*, 2021). In horticultural based cropping systems, influence of cereal-based derived biochar such as rice husk, corn cob, maize straw and wheat straw have received substantial research compared to legume-based biochar such as groundnut (*Arachis hypogaea*) and soybean (*Glycine max*) residues (Liu *et al.*, 2014; Singh *et al.*, 2019; Song *et al.*, 2019; Zhang *et al.*, 2020). Perhaps the residue biomass yield from cereals is not comparable to that from most legumes. Uvere *et al.* (1999) generated 60-76% residue yield from processing seeds of bambara groundnut (*Vigna subterranea* L. Verdc.), a leguminous crop. However, application of bambara seed residue (BSR) as a nutrient source

Please cite as: Okebalama C.B., Asogwa K.C., Uzoh I.M. and Marschner B. (2022). Impact of bambara seed residue biochar and NPK on soil fertility, aggregate carbon and nitrogen concentrations and yield of cucumber. *Agro-Science*, **21 (2),** 53-65.
DOI: https://dx.doi.org/10.4314/as.v21i2.6

for cucumber cultivation was found unsuitable for continuous application in an Ultisol (Okebalama *et al*., 2020a). In addition, cucumber yield obtained with 30 t ha^{-1} BSR was low compared to other organic amendments. Despite these limitations, the favourable potential of BSR to improve organic carbon (OC), nitrogen (N) and potassium (K) concentrations, and soil structure could hypothetically be maximized upon manipulation of its organic matter (OM) content for greater influence on soil chemical fertility and crop yield. It was on this background that the bambara seed biochar (BSB) study was designed to assess its impact on soil nutrient availability and retention as well as cucumber yield.

A number of studies have reported varying influence of biochar on soil quality and cucumber yields (Ali *et al*., 2019; Karimi *et al*., 2020; Zhou *et al*., 2021). Most reported positive effects resulted from biochar potential to improve soil nutrient retention (via sorption or stabilization of nutrient ions, decreased leaching), water holding capacity and sequestration of large recalcitrant C for centuries (Downie *et al*., 2009, Spokas *et al*., 2012; Ding *et al*., 2016). Considering its desirable properties, BSB could play a significant role towards soil fertility improvement and household/ national food and nutritional security. Bambara seed biochar showed a high OC (90%) and nitrogen (10%) composition but is deficient in phosphorus and some exchangeable cations (Table 1). Due to the recalcitrant nature of biochar, we envisaged that the C in BSB may not yield easily to microbial decomposition. With appropriate research efforts, supplementing major essential nutrients in BSB amended soils with NPK fertilizer could be highly advantageous in cucumber production because such valuable vegetable crop may generate more income for smallholder farmers than staple crops (Abewoy, 2018).

Integration of biochar and inorganic fertilizer has been reported to be more beneficial than the use of either biochar or inorganic alone (Peng *et al*., 2021; Zhang *et al*., 2021). Frimpong *et al*. (2021) showed improvement in total carbon (TC), total nitrogen (TN), available P, total exchangeable cations, effective cation exchange capacity and pH including tissue N, P and K in food crops with co-application of biochar and NPK. Enhancement in soil aggregate stability and the contents of C and N in macro- and micro-aggregates with sole biochar or in integration with NPK input under field crops abounds in the literature (Wang *et al*., 2017; Persaud *et al*., 2018; Joseph *et al*., 2020; Peng *et al*., 2021; Zhang *et al*., 2021). However, such data under cucumber cultivation is rare; especially with legume-based biochar amendment. Therefore, incorporating BSB and NPK fertilizer into an integrated nutrient management regime could be an important strategy for enhancing soil fertility and improving the overall productivity of cucumber in an Ultisol.

Since C sequestration in aggregates is central to conservation of C and N in biochar amended soils, there has been a continuous search for management systems that could sustain soil fertility and increase crop yield (Selim *et al*., 2019). Often, poor environmental and socio-economic conditions pose great challenge in the Derived Savanna regions of Nigeria, where improvements in soil quality and food security remain critical. The potential use of BSB, especially at locations where it is commonly produced, may offer maximum benefits to smallholder farmers in the locality. Soil aggregates are known to influence mineralization of organic materials and storage of soil nutrients, which in turn influences soil fertility. Evaluating the specific effect BSB would exhibit on soil aggregate C and N retention and release could be important in understanding the mechanism for their storage in soil aggregates. The aim of the study was therefore to examine the potential of BSB and its co-application with NPK fertilizer on aspects of sustainable soil quality and cucumber crop yield. The research also assessed the effect of BSB and/or NPK on soil C and N concentrations in hierarchical soil aggregates after four years of cucumber cultivation. We hypothesized that the co-application of BSB and NPK will maintain SOM buildup and sustainably provide higher essential soil nutrients needed for cucumber yield optimization than their sole application.

MATERIALS AND METHODS

Study Site Description

The year 2017 and 2018 (second phase) field experiments built on year 2015 and 2016 (first phase) study sited at the Department of Soil Science Teaching and Research Farm, University of Nigeria, Nsukka (UNN) (06^o 52′ N and 07^o 24′ E), Nigeria. The study area falls within the Derived Savannah agro-ecological zone of Nigeria and the climate is humid tropical. With a short dry spell in August, the location has a bimodal rainfall pattern with mean annual rainfall of 1719 mm and an average temperature of 26^oC (Climate-data, 2021). As described by Nwadialo (1989), the sandy loam textured Ultisol which originated from weathered sandstone is characterized by a deep, permeable and well-drained structure. The study field had previously been amended with bambara seed residue (BSR) during the two minor-cropping season experiments (first study phase). Before the establishment of the two seasons experiments with bambara seed biochar (BSB) and NPK treatments as reported herein, the field was cleared of weeds and the beds were raised using a hand hoe. Pre-cropping soil properties of the experimental site in 2015 and 2017 is shown in Table 1.

Experimental Set-Up and Treatment Description

The first phase of the field study consisted of a two-year continuous cultivation of cucumber under four rates (0, 10, 20 and 30 t ha^{-1}) of BSR with three

Table 1: Chemical properties of the previously cropped study soil and the bambara groundnut seed residues/biochar

Soil chemical properties	Study soil (2015)	Study soil (2017)	Bambara seed residue	Bambara seed biochar
pH (KCl)	4.00	4.40	5.70	9.30
Organic carbon (%)	1.26	0.97	53.21	89.78
Total nitrogen (%)	0.07	0.11	3.01	9.67
Carbon-Nitrogen ratio (C/N)	18.00	8.82	30.31	9.28
Available P (mg kg^{-1})	10.26	13.99	0.01	0.26
Exch. Na^{+} (cmol$_c$ kg^{-1})	0.04	0.01	not determined	0.33
Exch. K^{+} (cmol$_c$ kg^{-1})	0.05	0.07	0.02	1.34
Exch. Ca^{2+} (cmol$_c$ kg^{-1})	3.00	0.12	0.12	1.20
Exch. Mg^{2+} (cmol$_c$ kg^{-1})	0.40	0.06	0.22	0.40

Adapted from Okebalama *et al*. (2019; 2020a).

replications (Okebalama *et al*., 2020a) while the second phase included a modification of the previous 12 BSR treatment plots of 1.50 × 3.75 m^2 each, with 1 m spacing between blocks. The study was conducted on the same piece of land during the 2017 minor and 2018 major cropping seasons. As arranged in randomized complete block design (RCBD) with three replicates, the control plot was maintained all through the four-year study. Applications of 5, 10, and 15 t ha^{-1} BSB each with 350 kg ha^{-1} NPK 20:10:10 in 2017; and 300 kg ha^{-1} NPK 20:10:10, 20 t ha^{-1} BSB, and co-application of the NPK + BSB in 2018, were superimposed on the 10, 20 and 30 t ha^{-1} BSR plots of 2015/2016, respectively. The effect of the treatments on soil chemical fertility and cucumber fruit yield was determined only after crop harvest in 2018. The 2017 field experiment failed because NPK fertilizer application by broadcast adversely affected the growth of the cucumber plants. Selection of 350 kg ha^{-1} NPK 20:10:10 fertilizer was based on research report of cucumber yield response to NPK fertilizer application rates (Eifediyi and Remison, 2010) while the 20 t ha^{-1} BSB was based on previous performance of cucumber yield with BSR and BSB (2017) amendments. Further guidance was obtained by estimating the weight of BSR conversion to BSB; whereby 100 kg^{-1} BSR yielded an average of 44.35 kg^{-1} BSB.

Bambara seed biochar was prepared by pyrolysis of BSR feedstock using a metal barrel at the Farms and Operation Department, Faculty of Agriculture, UNN. The BSR was sourced from local commercial grinding mill at Ogige Market, Nsukka. The chemical composition of the biochar and the previously added BSR amendment are presented in Table 1. The biochar was uniformly spread on the beds and incorporated into the soil (0-20 cm depth) using a hand hoe, 2 and 4 weeks before planting, in 2017 and 2018, respectively. From 2017 experimental observation, seeding at two weeks after biochar application affected seed germination negatively (germination percentage was about 50%). Presumably, that may have resulted from heat generation at the onset of biochar degradation, or that the biochar contained some labile C which may have stimulated temporary upsurge in microbial activity and hence CO_2 demand. Perhaps, that resulted to creation of temporary anaerobic conditions which can also affect seed germination.

The NPK 20:10:10 fertilizer used in the study was sourced at Ogige Market, Nsukka. The fertilizer was applied by ring method, and in split doses of 1/3 and 2/3 at 2 and 4 weeks after planting, respectively. Ashley variety cucumber seeds was sourced from the Department of Crop Science, University of Nigeria Nsukka, and sown two seeds per hole at about 2.50 cm depth and at 75 × 75 cm spacing, giving a population of 35,556 plants ha^{-1}. Weeding was carried out using hand hoe and by hand picking. Harvesting of cucumber fruit was at physiological maturity, coinciding to 8-10 weeks after sowing. Cucumber fruit yield (weight in grams) was collected using a sensitive weighing balance, from an area of 5.63 m^2 per plot.

Soil Sampling and Preparations

Prior to crop establishment in 2017, the site was cleared and the beds raised and tagged appropriately. A composite sample (representative of the experimental area) from twelve observational points (treatment plots) at a depth of 0-20 cm was taken and air-dried. The soil samples were sieved with 2 mm mesh and used for the initial assessment of the soil chemical properties (Table 1) determined at the laboratory of the Department of Soil Science, UNN. After planting, soil samples were taken with an auger to a depth of 20 cm from each plot on weekly basis (from 1 to 8 weeks) and used for the determination of soil moisture content. At harvest in 2018, undisturbed soil samples were also taken from each treatment plot using a shovel (0-20 cm depth). The soil samples were allowed to air dry, and then packaged and transported for laboratory analyses at the Department of Soil Science/Soil Ecology, Ruhr-Universität Bochum (RUB), Germany. For initial characterization of the soils physio-chemical properties, a portion sieved with 2 mm mesh was used while the other sieved with 4.75 mm mesh was used for hierarchical aggregate size fractionation.

Laboratory Analysis

Soil moisture content was measured on plot basis and calculated thus:

$$\textit{Soil moisture content} = \frac{\textit{weight of wet soil} - \textit{weight of oven dry soil}}{\textit{weight of oven dry soil}} \times 100$$

Aggregate size fractionation was by dry-sieving method which provides better measure of the physically protected TC in aggregate fractions. A nest of three sieves (2.00, 1.00, and 0.25 mm) on an automated mechanical shaker (Retsch GmbH & Co. KG, Germany) was used to obtain four dry-stable aggregate fractions as follows: 4.75-2.00 mm (large macro-aggregates - lma), 1.00-2.00 mm (medium macro-aggregates - mma), 0.25-1.00 mm (small macro-aggregates - sma), and < 0.25 mm (micro-aggregates including silt and clay - mia). On the topmost 2.00 mm sieve, 25 g of 4.75 mm sieved soil was weighed in and allowed to shake for 5 min. at 45 revolutions per min. The suspended aggregate fractions on each sieve was carefully transferred into containers, weighed and expressed in percent (%) to the initial sample weight.

Chemical characterization of the BSB material and the previously cropped 2015/2016 soil collected at the onset of cultivation in 2017 were carried out at UNN while the post-harvest soil properties were determined at RUB. The pH of BSB and sampled soil were measured using a pH meter in a 1:2.5 soil to 0.1 N KCl suspension (McLean, 1982) and in 1:2.5 soil to $CaCl_2$ solution using a pH meter (pH 730 WTW series Lab) at UNN and RUB, respectively. At UNN, OC was determined by the Walkley and Black wet oxidation method (Nelson and Sommers, 1983) while TN was by the Kjeldahl distillation procedure (Bremner, 1996). Analysis of the bulk soil and aggregate associated TC and TN was by dry combustion (Vario EL Elementar Analysesysteme GmbH, Hanau, Germany) at RUB. At UNN, available phosphorus (P) was by Bray II bicarbonate extraction method (Olsen and Sommers, 1982) and exchangeable bases were extracted using NH_4OAC, while sodium (Na) and potassium (K) were measured by the flame photometer, and calcium (Ca) and magnesium (Mg) were by the complexometric EDTA titration (Thomas, 1982). Available P (Bray) was assessed by photometric measurement (Perkin Elmer uv/vis Spectrometer Lambda 2) while Na^+, K^+, Ca^{2+}, Mg^{2+} and aluminum (Al^{3+}) were extracted using NH_4Cl and measured by ICP-OES (Spectro Ametek-Spectroblue) at RUB.

Statistical Analysis

The data collected for the soil parameters and the cucumber fruit weight yield were subjected to one-way analysis of variance for RCBDs using GenStat for Windows (Lawes Agricultural Trust). The significant differences between treatment means were determined using the least significant difference at 5% probability level. Correlation analysis was carried out to evaluate the relationship between soil properties and cucumber fruit yield.

RESULTS

Chemical Characteristics of Previously Cropped Soil and Bambara Seed Biochar

As presented in Table 1, the study soil was strongly acid (pH 4.40) prior to the establishment of the field experiment. Except the moderate status of soil available P and Ca^{2+} concentrations, the contents of OC, N, Na^+, K^+ and Mg^{2+} were low.

The BSB material was strongly alkaline (pH 9.30) with high OC (89.78%) and N (9.67%) concentrations and a low C/N (9.28). Available P and basic cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) concentrations of the BSB were low though their values increased slightly as compared to their counterparts in BSR. In contrast to BSB also, the elemental properties of the BSR input as described in Okebalama *et al.* (2020a) showed major dissimilarities in pH 5.70, OC (53.21), TN (3.01) and C/N (30.31) parameters.

Changes in Soil Chemical Properties with Treatment

Treatment effects on the soil chemical properties indicated no significant change in soil pH (Table 2). However, BSB and NPK + BSB treatments significantly ($p \leq 0.05$) increased TC and TN concentrations of the soils. An enormous increase in available P was also evident in BSB and NPK + BSB soils, amounting to 39.18 and 74.26 mg kg^{-1}, respectively. Available P in NPK fertilized soil increased significantly as in BSB soil, but was not different from the control soil. The soil exchangeable Al^{3+} declined significantly with BSB and NPK + BSB, but remains similar with the NPK soil as the control. Amongst the exchangeable bases, the maximum and minimum soil exchangeable K^+ were recorded with BSB and NPK treatments, respectively, while K^+ with NPK + BSB was similar as the control. The BSB and NPK + BSB treatments increased ($p \leq 0.05$) the amounts of exchangeable Mg^{2+} but did not significantly influence exchangeable Ca^{2+} concentration.

Table 2: Post-harvest chemical properties of treated soils following a four-year consecutive cucumber cultivation

Treatment	pH $CaCl_2$	TC (%)	TN (%)	C/N	Avail. P (mg kg^{-1})	Al^{3+}	Ca^{2+}	K^+	Mg^{2+}
						(mmol$_c$ kg^{-1})			
Control	3.82	0.87	0.08	11.34	14.43	15.35	1.09	0.33	0.33
NPK	3.84	1.01	0.09	11.24	26.77	14.71	2.47	0.25	0.37
BSB	3.93	1.86	0.16	11.52	39.18	10.94	2.59	2.35	2.94
NPK + BSB	3.87	1.78	0.15	11.71	74.26	12.56	2.94	1.33	2.93
SED	0.05	0.12	0.01	0.37	21.88	0.87	0.69	0.43	0.39
$LSD_{0.05}$	NS	0.29	0.03	NS	14.55	2.12	NS	1.06	0.96

NPK - Nitrogen, phosphorus and potassium fertilizer, BSB - bambara seed residue biochar, SED - standard error of differences of mean; TC - total carbon, TN - total nitrogen, C/N - carbon:nitrogen ratio, Avail. P - available phosphorus; NS - not significant

Effect of Treatments on Soil Moisture Content

The soil moisture content (SMC) during the entire cucumber growth period ranged from 4.21 to 26.36% amongst the treated soils (Figure 1). At 1 and 3-6 weeks after planting (WAP), SMC differed significantly ($p \leq 0.05$) amongst the treatments, with higher content recorded mostly in the BSB and NPK + BSB than the control and NPK soils. Although the control soil showed the lowest SMC than the other treatments at 1 WAP, increasing trend in SMC was evident in the control as with NPK treatment from 1-5 WAP but from 2-4 WAP in the BSB and NPK + BSB soils. Nonetheless, SMC at 3 WAP was significantly greater in the NPK + BSB soil than in the other treated soils but the largest increase reaching 26.36, 24.51 and 20.66% at 4, 5 and 6 WAP, respectively, was obtained in the BSB soil. Thus, SMC at 4-6 WAP differed significantly amongst the treated soils with BSB > NPK + BSB > NPK = control.

Distribution of Aggregate Total C and N Concentrations in Treated Soils

The applied treatments exerted different effects on aggregate TC and TN concentrations in the soils (Figures 2-4). The TC concentration ranged from 0.68 to 2.62% across the treatments and aggregate fractions. Generally, significant differences ($p \leq 0.05$) in TC concentrations were evident amongst the aggregate fractions and the treatments. The sma fraction displayed the lowest TC concentration across all aggregate fractions and treatments. While there was no consistent trend with the highest aggregate TC concentration amongst the treatments, TC concentration increased in all aggregate fractions with BSB and NPK + BSB treatments. However, TC concentration across the aggregate hierarchies was similar with NPK treatment as the control. Total C concentration was significantly higher in the macro- than the micro- aggregate with the BSB treatment whereas maximal TC concentration was found in the lma, mma and mia fractions with NPK + BSB treatments. In the mia fraction, an additive increase in TC concentration was observed with NPK + BSB treatments.

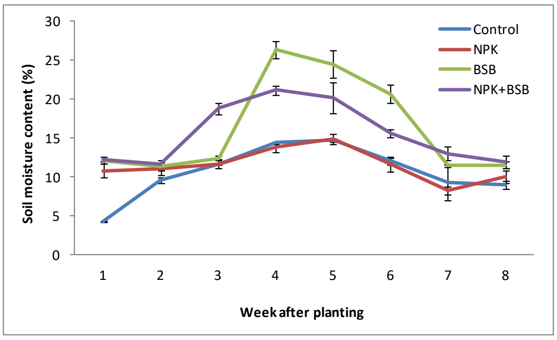

Figure 1: Soil moisture content during 8 weeks after planting of cucumber with bambara seed residue biochar and NPK treatments

Aggregate TN concentrations amongst the treatments and aggregate fractions ranged from 0.06 to 0.23%. While TN concentration was minimal in the sma across aggregate fractions and treatments, the maximum was found in the lma and mma fractions with BSB treatment but in the lma, mma and mia fractions with the NPK + BSB treatment. Similar to aggregate TC concentration, the TN concentrations across the aggregate fractions were significantly ($p \leq 0.05$) higher with BSB and NPK + BSB than with NPK and control treatments. In fact, the maximum TC and TN concentrations in the lma, mma and sma fractions as induced by the biochar treatments were about two-folds higher than that produced by the NPK and control treatments.

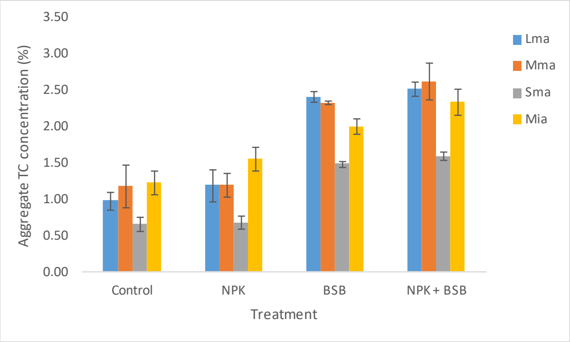

Figure 2: Total carbon (TC) concentration within soil aggregate hierarchies of the treatment soils

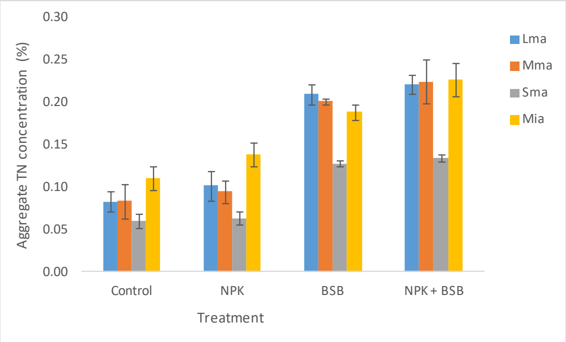

Figure 3: Total nitrogen (TN) concentration within soil aggregate hierarchies of the treatment soils

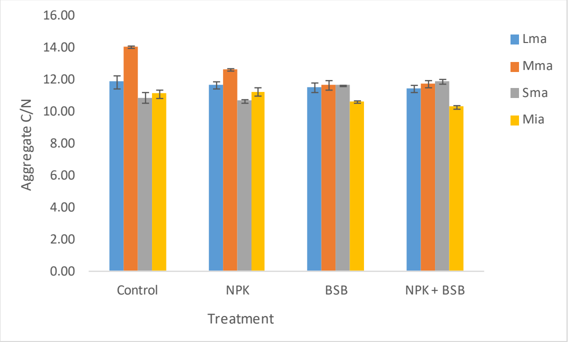

Figure 4: Soil C/N distribution within aggregate hierarchies of the treatment soils

The C/N ratio across aggregate fractions was generally low and ranged from 10.32 to 14.10 amongst the treatments. As such, the minimum C/N values across aggregate fractions were found in the sma fraction under NPK soil, but in the mia fraction with BSB and NPK + BSB treatments. The C/N ratio was maximal in the mma under the control and NPK soils, but in macro-aggregates (lma, mma and sma) under BSB and NPK + BSB soils. The lma had a similar C/N amongst the treatments, while the C/N of sma was significantly higher under the BSB and NPK + BSB soils than the control and NPK soils.

Effect of Treatments on Cucumber Crop Yield

Application of BSB and NPK + BSB treatments induced a significant ($p \leq 0.05$) increase in cucumber fruit weight (Figure 5). Whereas no cucumber yield was obtained in the control soil, the NPK fertilized plots produced 187.73 g plot^{-1} (equivalent to 0.33 t ha^{-1}) fruit weight yield. Compared to NPK treatment, about 12-fold higher (2322.47 g plot^{-1} = 4.13 t ha^{-1}) and 24-fold highest fruit yield (4585.83 g plot^{-1} = 8.15 t ha^{-1}) were produced with BSB and NPK + BSB treatments, respectively.

Relationship between Soil Properties and Cucumber Fruit Yield

Table 3 illustrates the correlation coefficients (*r*) of some soil fertility properties and cucumber fruit weight. Cucumber fruit yield showed a positive significant correlation with TC, TN, available P, and exchangeable- Ca^{2+}, K^{+}, and Mg^{2+} contents of the soils. Also, a negative significant correlation was obtained between cucumber fruit yield and exchangeable Al^{3+} concentration. Soil pH exhibited a similar relationship with Al^{3+} (r = -0.88**, p = 0.000) but had a positive significant correlation with Ca^{2+}, K^{+}, and Mg^{2+} soil nutrients.

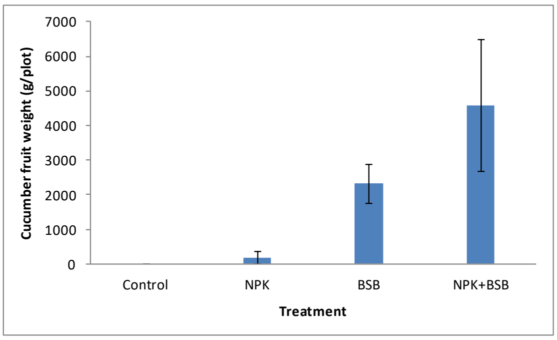

Figure 5: Effect of bambara seed residue biochar (BSB) and NPK treatments on cucumber fruit weight

DISCUSSION

Chemical Characteristics of Previously Cropped Soil and Bambara Seed Residue Biochar

The acidic pH of the study soil is typical to soils of the agro-ecological zone (Agim *et al.*, 2019; Okebalama *et al.*, 2022), attributable to leaching of base cations due to high rainfall regime. The prevailing high rainfall and temperature regimes which enhance SOM decomposition rate and OC loss (via erosion/runoff) could also explain the low OC content of the soil (Igwe, 2005). However, the soil available P concentration, indicating sufficient P availability suggests that P was preserved in the soil after the 2016 cropping. This is because after the two years of cucumber cropping with BSR amendment, slight increase in available P (by 3.99 of the initial value = 36% increase), was related to decomposition of native SOM and presumably, BSR input.

The recovery of alkaline BSB via pyrolysis of acid BSR feedstock is a common occurrence with most biochar yield. Resultant biochar pH range of 7.78 to 10.81 has been reported (Pandian *et al.*, 2016; Billa *et al.*, 2019). The alkaline pH of BSB was due to the pyrolysis temperature (not determined) which hydrolyzed carbonates and bicarbonates of base cations and as well releases organic and inorganic products from the feedstock (Yuan *et al.*, 2011a; Enders *et al.*, 2012). The relatively enhanced concentrations of the basic cation contents of BSB than BSR lend credence to the above assertion. Due to the alkaline pH, it could be reasonably assumed that application of BSB would increase the pH of the soil. The BSB contained more OC (90%) and TN (10%) than the BSB. Other leguminous biochar as groundnut husk contained about 59% OC and 11% TN (Billa *et al.*, 2019). Based on the study hypothesis, the purposive use of BSB in cucumber cultivation is to essentially maintain SOM buildup in the degraded and impoverished study soil. Owning to the considerably high OC and TN contents and the low C/N enabling rapid mineralization process, improvement in TC and TN concentrations of the BSB amended soil were expected.

Changes in Soil Chemical Properties with Treatment

The inability of BSB in reducing soil acidity was unexpected given the strongly alkaline pH (9.30) of the biochar. Yuan *et al.* (2011a) found that alkaline pH of biochar resulted from high pyrolysis temperature and content of ash, carbonates, and basic oxide of base cations. However, changes in soil pH were reported not to depend on the alkalinity

Table 3: Correlation coefficients (*r*) of cucumber fruit weight and some soil fertility parameters

Dependent variable	pH CaCl$_2$	TC (%)	TN (%)	C/N	Avail. P (mg kg^{-1})	Al^{3+}	Ca^{2+}	K^{+}	Mg^{2+}	SMC (%)
						(mmol$_c$ kg^{-1})				
Cucumber fruit weight	0.52	0.82**	0.82**	0.51	0.83**	–0.73*	0.58*	0.75*	0.89**	0.65*
Soil pH (CaCl$_2$)	-	0.49	0.49	0.39	0.26	–0.88**	0.70*	0.59*	0.64*	0.61*

TC - total carbon, TN - total nitrogen, C/N - carbon:nitrogen ratio, Avail. P - available phosphorus;
SMC - soil moisture content at 8 weeks after planting. **significant at 0.01 probability level

of biochar alone, but also on mineralization of organic N and nitrification of NH_4^+ (Yuan *et al*., 2011b; Saletnik *et al*., 2018). In addition, the low level of alkaline cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) in BSB input reflect a low buffering capacity and may have thus contributed to the non-ameliorating effect of BSB on the soil pH. Sun *et al*. (2021) obtained a significant increase in soil pH, and exchangeable K^+ and Mg^{2+} with maize stover biochar application. Yuan and Xu (2012) and Wan *et al*. (2014) also observed a pH increase with concomitant reduction in Al^{3+} concentration in soybean and peanut straw-derived biochar amended acid Ultisol. In our study, however, despite the appreciable improvement of more than seven-folds in soil exchangeable K^+ and Mg^{2+}, and the substantial reduction in exchangeable Al^{3+} with the added BSB, the reactions between oxygen-containing functional groups ($COOH^-$ or OH^-) with H^+ and metal cations were probably impeded due to high buffering capacity of the soil. The higher organic matter content of the BSB amended soil could explain the supposed increase in buffering capacity.

On the other hand, since the BSB and NPK + BSB treatments proved effective in reducing the exchangeable Al^{3+} concentration of the soil, it thus suggests that the BSB could be used for reducing exchangeable Al^{3+} toxicity under acidic soil conditions. Considering that the response of Al^{3+} to NPK + BSB addition was synergistic, it indicates that the observed decrease was mainly due to increase in soil organically complexed Al by oxygen-containing functional carboxylic and phenolic groups present on the biochar (Wan *et al*., 2014). Such beneficial role of biochar in alleviating Al toxicity in acid soils has been recognized (Xia *et al*., 2020). Yuan *et al*. (2011b) noted that Al^{3+} toxicity and soil infertility limit plant growth and crop yield in acid soils. Furthermore, Al^{3+} contributes chiefly to soil acidity as compared to H^+; and imposes a critical rhizotoxic effect as it solubilizes into the soil solution in soils of pH < 5 (Panda *et al*., 2017). Hence, if the target is to reduce Al^{3+} toxicity in acid soil, then the use of BSB could as well serve as a viable option for consideration. Nevertheless, the need to explore multiple soil/biochar/NPK/organic lime interactions and close the research gap that would help to compensate for ameliorating soil acidity and increasing base cations should not be overlooked.

There is a clear evidence of improved TC and TN concentrations with BSB amendment after the four-year cucumber cultivation, compared to the OC and TN concentrations of both 2015 and 2017 pre-cropped soils. In other study, similar increase in C was observed in biochar-amended soil over four years of cultivation (Joseph *et al*., 2020). The massive improvement in TC stock (114%) as influenced by BSB input is attributed to its substantial inherent TC concentration (89.78%) and the effective biochar-C storage stability against microbial decomposition. This is supported by the percentage TC increase (0.99 of the % value) in the BSB treated soil which exceeded the expected OC-input with BSB (0.62%). Total C concentration of biochar have also been found to depend on pyrolysis temperature and the feedstock material, and could amount up to 89% (Dume *et al*., 2015; Pandian *et al*., 2016; Shalini *et al*., 2017). Phares *et al*. (2020) obtained a significant increase in organic C and TN with biochar addition to a tropical sandy loam soil. A hundred-fold increased TN stock as contributed by the BSB was enabled by the porous and large surface area of the biochar which acted as a binder to efficiently adsorb and retain NO_3^- and NH_4^+ in the soil. The apparent N retention potential of biochar within agroecosystems as well as its N losses mitigation mechanisms has been extensively studied (Clough *et al*., 2013). This implies that BSB has the potential to increase N nutrient retention and thus reduce leaching of N.

Notably, conversion of BSR to BSB increased its TC concentration from 53.21 to 89.78%, with increased decomposition potential as indicated by the C/N from 30.31 to 9.28. This increase also applies to exchangeable K^+. Accordingly, part of the improved exchangeable K^+ in BSB amended soil are from mineralized biochar which contains both available and unavailable or insoluble nutrients. This implies that BSB is a better choice as soil amendment than BSR. Thus, applying BSB input would be more advantageous because post-harvest properties of the fertilized soils in years 2016 and 2018, suggest that N, P, K, and Mg nutrients were more available in the latter than in the former year (Okebalama *et al*., 2019; Okebalama *et al*., 2020a). As such, the maximal percent increase in TC, TN, K^+, and Mg^{2+} nutrients reserve with BSB than NPK + BSB proposes desirable agronomic benefits for farmers to boost OC and other nutrient reserves with BSB.

The percent increase in TC and TN concentrations amounting to 104.60 and 87.50%, respectively, with BSB + NPK addition may have resulted from the combined effect of the added BSB, increased plant biomass production and associated decomposition. Combined application of biochar and inorganic fertilizer often results in appreciable increase in soil organic C and N (Frimpong *et al*., 2021; Peng *et al*., 2021; Zhang *et al*., 2021). However, the influence of NPK + BSB on TC and TN produced a synergistic response, given the lacking effect of sole NPK fertilization. It therefore suggests that the observed improvement in TC and TN concentrations with NPK + BSB was chiefly from the added biochar. As such, the non-influence of NPK on soil TN could be related to N losses via leaching and nitrification as enhanced by the acid soil pH and the temperature and rainfall regimes that prevails in the study location. This is supported by the findings of Liu *et al*. (2017) and Norton and Ouyang, (2019). In addition, leaching of N and K nutrients in highly weathered soils has long been associated to NPK fertilization (Baligar and Bennett, 1986).

The great improvement in available P retention (+ 172%) with BSB signifies a large proportion of labile and easily absorbable forms of P in BSB than BSR. This suggests that the pyrolysis of BSR increased P bioavailability potential of BSB due to biochar's effectiveness in complexing soil exchangeable Al^{3+}. The potential of biochar in modifying available P retention in soils has been reported (Phares *et al*., 2020; Yang *et al*., 2020). Nonetheless, the similarity in P availability effect of BSB and NPK stems from the non-liming effect of the BSB since available P is highly dependent on soil reaction (Kahura *et al*., 2018). However, the low P retention with NPK treatment as the control soil may be attributed to erosion and leaching losses due to the soil texture and high rainfall regime of study area. Apparently, the low TC content in the NPK fertilized soil may have also contributed to the low available P retention.

Available P improvement with BSB may be related to degraded P nutrient from both residual P from 2017 application and the 2018 addition due to BSB slow release. It could have resulted from organic biomass P mineralization and retention due to biochar's ability to sorb nutrients; the superlative additive available P response to NPK + BSB possibly accrued from P fertilizer as complemented by the BSB chelating effect. Accumulation of inorganic forms of P in acidic soils of most cropping systems has been associated with Al, Ca and Fe ions (Beauchemin *et al*., 2003; McLaughlin *et al*., 2011). In our study, exchangeable Al^{3+}, a P complexing metal and an important determinant of the extent of sorption reactions in acid soils, was significantly reduced with BSB and NPK + BSB treatments. It thus implies that BSB can enhance inorganic P retention and consequently decreased leaching losses. Notably, the 414.62% improvement in available P retention shows the potential of NPK + BSB application to sustainably overcome P limitation and viably boost P fertility in acidic soils. Combined application of biochar and TSP has been found to significantly increase soil available P more than sole biochar addition (Phares *et al*., 2020).

Effect of Treatments on Soil Moisture Content

Biochar improves soil fertility not only by increasing the soil nutrient retention capacity (Gao and Deluca, 2016), but also by improving its capacity to retain soil moisture (Duku *et al*., 2011). Assessing the impact of biochar on increasing SMC is an important determinant of its potential to sustain crop growth under water stress (Singh *et al*., 2019). The lowest SMC in the control soil at 1 WAP indicates deterioration in soil physical properties due to continuous cultivation without soil amendment. Except at 3 WAP, SMC was moderated by NPK + BSB application while the improvement in SMC at 4-6 WAP with BSB indicates increased soil water holding capacity attributed to the large surface area of biochar which improves aggregation of organic/mineral complexes and thus porosity (Rillig and Mummey, 2006; Ding *et al*., 2016). Due to the high and well developed total porosity, biochar could retain water in small pores and enhance water infiltration from the ground surface to the topsoil through the larger pores after heavy rainfall (Asai *et al*., 2009). Singh *et al*. (2019) reported that the positive influence of biochar on the formation and stability of soil aggregates significantly improved soil porosity and hence water movement.

The overall improvement in water retention with the addition of BSB and NPK + BSB is indicative of enhanced soil physical fertility. Application of biochar to soil potentially results in long term soil fertility benefits through improved nutrient retention, gradual release of nutrients and therefore their availability to plants, improved soil water retention and water availability to crops, and enhanced microbial functions (Lehmann and Joseph, 2015). On the other hand, the medium SMC in the NPK + BSB soil at 4-6 WAP indicates saturation of the pore spaces with less water but more dissolved nutrients. Since water is required for the dissolution and ready supply of soluble nutrients from the applied NPK fertilizer, the water in the soil pores was less than that in the BSB soils where nutrient release was slow. The higher concentration of the soil solution amplifies the movement and uptake of water and nutrients by the plant roots for cucumber plant growth and reproduction. This could partially explain the improvement in higher fruit weight with NPK + BSB than BSB treatment.

Distribution of Aggregate Total C and N Concentrations in Treated Soils

The improved TC and TN concentrations with the application of NPK and NPK + BSB across all aggregate fractions as compared to NPK and control soils reveals the capacity of these treatments to enhance C and N in both macro and micro aggregates. It implies that these treatments have the potential to sequester C and N in all aggregate fractions. Zhang *et al*. (2021) reported significant increase in TC level of all aggregate fractions but the highest SOC and TN contents were found in 2-0.25 mm (corresponding to lma and sma) fraction of biochar amended soil. In our study, the maximal TC and TN concentrations in lma, mma and mia indicate higher association to BSB particles than in the sma. The remarkable influence of NPK + BSB on TC and TN may be chiefly BSB-induced because the sole application of NPK had no effect on the aggregate TC and TN concentrations as the control. More so, the improvement in aggregate TC and TN concentrations with

NPK + BSB and BSB treatments were quite similar, except the TN in mia fraction. As such, the 17% TC increment in mia fraction with NPK + BSB than BSB may have resulted from the complementary contribution of plant biomass decomposition due to higher association to flora particles. This also explains the 21% increased TN concentration in mia with NPK + BSB compared to BSB. Liu *et al.* (2013) reported that microbial plant residue decomposition forms organo-mineral associations that influence OM composition.

The increased TC concentration in macro- than micro- aggregates with BSB has similarly been reported with other biochar types (Du *et al*., 2017; Sun *et al*., 2021). The study result shows the potential of BSB to mainly induced C sequestration in the lma and mma fractions by about 122%; a confirmation of increased biochar-induced C storage in macro-aggregates (Wang *et al*., 2017). The high association of BSB to macro aggregates indicates optimized participation of BSB in soil macro aggregation; lending credence to the reported increased macro-aggregate stability with BSR (Okebalama *et al*., 2020a). Nevertheless, the overall TC improvement with BSB and NPK + RHB was substantial, amounting to 151, 110, 137 and 76% increase over the control in the lma, mma, sma and mia fractions, respectively. Such huge aggregate TC concentration suggests high interaction of the BSB with soil particles which would lead to the protection of biochar-C via aggregate formation. This interaction has been found to positively influence soil structural properties as aggregation, soil porosity, soil aeration and water retention (Du *et al*., 2017; Sun *et al*., 2021). Hence, the BSB and NPK + BSB treatments would influence soil physical fertility due to the critical role of soil structural aggregation in SOC turnover.

In somewhat similar manner, increment in aggregate TN concentrations with BSB and NPK + BSB was slightly higher than that of aggregate TC. The increase in TN concentrations of 169, 163, 117 and 91% in the lma, mma, sma and mia fractions, respectively, shows a decrease in N concentration with decreasing soil aggregate fractions. Zhang *et al.* (2014), Persaud *et al.* (2018) and Joseph *et al.* (2020) reported a significant increase in aggregate TN with different biochar application. Our study result further portrays the complementary contribution of applied NPK + BSB which resulted to an additive response of TN concentration in mia fraction. This could be related to improved plant biomass addition with NPK input, as well as enhanced N retention by the porous and large surface of biochar which could facilitate the adsorption of NO^{3-} and NH^{4+} in soils (Yao *et al*., 2012; Li *et al*., 2018). Even though the C/N ratio of the mia with NPK + BSB treatment diminished slightly, the BSB possibly stabilized N in mia fraction and thus slowed down nitrification processes and nitrate loss. Hence, the substantial stabilization of TC and TN in both macro and micro aggregates with the application of BSB or in combination with NPK is large enough to possibly sustain the fertility of the soil for the next cucumber cropping season.

Effect of Treatments on Cucumber Crop Yield

The inability of the control soil to produce cucumber fruits portrays the consequence of a 4-year continuous cultivation of an Ultisol without any soil amendments. Zhao *et al.* (2017) reported a yearly decrease in cucumber fruit yield under continuous cropping conditions. Over time, similar practice resulted to decline in soil quality and zero crop yields as shown in the study result. In contrast, the NPK + BSB treatment maximized cucumber fruit weight more than the individual application of the treatments. The study thus provides compelling evidence that the NPK + BSB was the most effective and sustainable amendment to improve cucumber crop productivity and as well, reduce the deleterious effects of continuous cultivation on soil fertility. Nonetheless, the obtained fruit weight (187.73 g plot^{-1} = 333.75 kg ha^{-1}) with NPK fertilizer was unexpectedly low and inconsistent with reportedly higher yields of 29,392.57 and 28,859.24 kg ha^{-1} with application of NPK 20:10:10 at the rate of 300 and 400 kg ha^{-1}, respectively (Eifediyi and Remison, 2010). Possible reason for the low yield achieved with NPK could be linked to the impoverished nature of the soil as exacerbated by accelerated erosion and leaching losses due to the soil texture (sandy loam) and the prevailing rainfall intensity in the study area. Thus, sole NPK fertilization for cucumber cultivation in the study soil implies loss of yield, representing a financial loss to the farmer. It is therefore crucial to consider organic source of P in maintaining the critical level of plant-available P required for improved cucumber yield.

Contrary to NPK, BSB treatment was effective in reducing free Al^{3+} in the soil solution by sorption and thus increases base saturation and high P retention effect in the soil. Since plants acquire inorganic P ($H_2PO^-_4$ and HPO_4^{2-}) from the soil solution via the roots, it implies that the reducing effect of BSB on exchangeable Al positively influenced the accessibility of P for root uptake. Available P uptake is partly controlled by plant root hairs and Al toxicity has been found to limit root growth in acid soils (Horst *et al*., 2001). Phosphorus is involved in several key plants physiological and biochemical processes, including enhancing plant root growth, crop response to N, and nutrient movement in plant cell among many others (Kirkby and Johnston, 2008). Besides the observed improvement in available P retention, microbial decomposition of BSB/organic biomass also released more nutrients (C, N, K and Mg), that were partitioned and utilized efficiently for plant growth and fruit development. Recent study has confirmed that biochar can increase C and N contents, available P and cations exchange capacity in soil, and consequently, enhanced plant nutrient uptake (Frimpong *et al.*, 2021). Although the substantially 12-fold fruit yield increment with BSB (4.13 t ha^{-1}) far outweigh the maximal yield of 0.46 t ha^{-1} with BSR (Okebalama *et al.*, 2020a), higher cucumber yield of 7.5 t ha^{-1} with 5 t ha^{-1} hardwood biochar was obtained in a sandy loam Ultisol (Mbah *et al.*, 2017). Even so, the 8.15 t ha^{-1} fruit yield with NPK + BSB is considerable when compared to the 10.28 t ha^{-1} achievable cucumber yield with 20 t ha^{-1} recommended poultry manure rate for the soil (Okebalama *et al.*, 2020b). Nonetheless, more research effort needed to be carried out on BSB to possibly bridge the gap between the observed yield and attainable yield of 45.2 t ha^{-1} as obtained with application of 20 t ha^{-1} biochar on a depleted loam soil (Ali *et al.*, 2019).

The huge 24-fold improvement with NPK + BSB indicates the importance of co-application of inorganic fertilizers and biochar for maximizing cucumber yield in the study soil. The treatment thus represents a suitable and sustainable strategy to increase plant nutrients and cucumber productivity. Remarkably, the cucumber fruit weight response to NPK + BSB exceeded the additive response of the individual application of NPK and BSB inputs; suggesting efficient uptake, partitioning and utilization of the available soil nutrients for fruit development. This could be associated to the complementary contribution of the BSB in reducing exchangeable Al^+ levels and maximizing C, N, P, K^+ and Mg^{2+} retention (due to its chelating influence) against erosive and leaching losses. A number of studies have reported positive effects of integrating biochar with inorganic fertilizers on soil properties and crop productivity (Kätterer *et al.*, 2019; Frimpong *et al.*, 2021; Peng *et al.*, 2021).

Considering the vital role of P in crop growth and reproduction, the enormous available P retention with NPK + BSB (which otherwise indicates adequate soil P supply) appears to be the most contributing factor to the obtained highest cucumber fruit yield. The weathered soils of the humid tropics are inherently low in available P, which together with high Al concentration in the soils solution limits crop growth and yields (Kirkby and Johnston, 2008). It thus becomes important to maintain a sufficient level of available P in the soil appropriate to optimize efficient use of plant-available P and yield potential of crops. Hypothetically, low P use efficiency of the previous application (residual P) was effective in improving the P use efficiency of the second application that translated to maximal fruit weight in the study soil where erosion and leaching is critical. Hence, a better understanding of the exceptional influence of NPK + BSB in reducing Al concentration, and maximizing available P retention and cucumber fruit weight beyond the effect of sole BSB addition is thus discovered in the study.

The huge difference in the percent fruit yield increase obtained between BSB and NPK + BSB represents the later treatment as the best option for yield optimization. However, before advocating the wide-scale adoption of the treatment to farmers within the study location, evidence of its economic benefits needed to be ascertained. This calls for a farm-profitability or cost-benefit analysis to provide agronomic and economic benefits of utilizing the treatment for sustaining a viable cucumber crop production and consequently increase farmer’s financial return. Overall, the study has demonstrated the potential of BSB and its co-application with NPK to induce short-term soil quality and cucumber crop yield benefits, nevertheless, the long-term benefits remain to be quantified.

Relationship between Soil Properties and Cucumber Fruit Yield

The negative significant correlation of Al^{3+} and cucumber fruit yield ($r = -0.73^*$; $p < 0.01$) indicates the relative importance of reduced Al^{3+} concentration for improvement in cucumber fruit weight. The strong correlation of soil pH and Al^{3+} ($r = - 0.88^*$; $p < 0.000$) lends credence to this as reduction of Al^{3+} concentration in soil solution could increase the soil pH. Accordingly, since exchangeable Al^{3+} is an acid forming cation, it implies that ameliorating soil acidity may further improve cucumber yield, and hence maximize its production in this and similar soils. Maintaining a soil pH of 6.0 to 6.5 reportedly improved cucurbits yield and quality as well as the availability of P, Mg and Ca nutrients (Warncke, 2007). Also, the positive association of the exchangeable bases (Ca^{2+}, K^+ and Mg^{2+}) with soil pH and cucumber yield establishes their involvement in reducing soil acidity and optimizing cucumber fruit yield. As such, application of cheaper and locally available liming material such as gypsum or firewood ash which may be attractive to smallholder farmers could be explored to quantify their effect when combined with BSB biochar. The relevance of the positive correlation of soil moisture content with cucumber fruit weight, and soil pH could be linked to solubilizing of soil nutrients for effective utilization by growing plants. Warncke (2007) noted the supportive role of adequate soil moisture in minimizing blossom-end-rot due to inadequate translocation of Ca to the blossom end of the young developing fruit.

Cucumber fruit weight correlates positively and strongly with TC, TN, available P, Ca^{2+}, K^+ and Mg^{2+} nutrients because of their essential functions in better growth and yield of cucumber. Specifically, N encourages vegetative growth; enhanced fruit set and crop yields, and contributes to organic matter build-up in the soil (Warncke, 2007; Moyin-Jesu, 2015).

Phosphorus affects vegetative growth and fruit production; K^+ is essential for high fruit quality (Papadopoulos, 1994); Ca^{2+} participates in plant cell wall structure, and cell division/enlargement (White and Broadly, 2003) while Mg^{2+}, a constituent of chlorophyll molecule affects production and supply of photo assimilates to other parts of plant (Siddique *et al*., 2017). Thus, the high correlation coefficient exhibited by the soils' TC, TN, available P and exchangeable Mg^{2+} nutrients suggests effective utilization of these nutrients since they accounted for more than 81% ($p < 0.001$) of the variability in cucumber fruit yield. Even though these parameters appear to be the most contributing factors to cucumber yield improvement, the correlation result shows that an overall improvement in soil quality would definitely boost and sustain productivity of cucumber fruits in a degraded Ultisol.

CONCLUSION

Sole biochar and its co-application with NPK generally improved soil properties and increased cucumber yield. These treatments proved most effective in increasing TC and TN concentrations, available P and exchangeable Mg^{2+} in the whole soil. The biochar amendment additionally improved soil exchangeable K^+. The BSB and NPK + BSB treatments have approximately 100% potential to sequester TC and TN in all aggregates fractions of the soil. Nonetheless, the individual contribution of the lma, mma and mia to TC and TN concentrations as influenced by the BSB and NPK + BSB treatments was more than that by the sma which contributed the least. As regards cucumber fruit weight, BSB and NPK + BSB produced 12 and 24-fold increase, respectively, over the NPK application. The study results have proved that BSB can provide a more sustainable input of C, N, P, K and Mg to the soil while NPK + BSB can in addition promote more intensely the productivity of cucumber. Hence, BSB has great potentials towards improved soil sustainability but additional potential for household/national food security lies more with NPK + BSB than BSB amendment.

ACKNOWLEDGMENT

Funding support from the 'Alexander von Humboldt Foundation' to the first author (CBO) through the 'Humboldt Research Fellowship for Postdoctoral Researchers' is hereby acknowledged.

REFERENCES

Abewoy D. (2018). Review on impacts of climate change on vegetable production and its management practices. *Adv. Crop Sci. Technol.,* **6,** 330

Agim L.C., Ahukaemere C.M., Onwudike S.U., *et al.* (2019). Distribution of selected soil nutrients in aggregate sizes of soils under different geologic formations in southeast Nigeria. *Bulg. J. Soil Sci.,* **4 (2),** 116-131

Ali A.B., Haofang Y., Hong L., *et al.* (2019). Enhancement of depleted loam soil as well as cucumber productivity utilizing biochar under water stress. *Comm. Soil Sci. Plant Analysis,* **50 (1),** 49-64

Asai H., Samson B.K., Stephan H.M., *et al.* (2009). Biochar amendment techniques for upland rice production in Northern Laos: Soil physical properties, leaf SPAD and grain yield. *Field Crops Res.,* **111 (1-2),** 81-84

Baligar V.C. and Bennett O.L. (1986). NPK-fertilizer efficiency-a situation analysis for the tropics. *Fert. Res.,* **10 (2),** 147-164

Beauchemin S., Hesterberg D., Chou J., Beauchemin M., Simard R.R. and Sayers D.E. (2003). Speciation of phosphorus in phosphorus-enriched agricultural soils using x-ray absorption near-edge structure spectroscopy and chemical fractionation. *J. Environ. Qual.,* **32 (5),** 1809-1819

Billa S.F., Angwafo T.E. and Ngome A.F. (2019). Agro-environmental characterization of biochar issued from crop wastes in the humid forest zone of Cameroon. *Int. J. Recycl. Org. Waste Agric.,* **8 (1),** 1-13

Bremner J.M. (1996). Nitrogen-total. *Methods of Soil Analysis, Part 3 - Chemical Methods,* 5, 1085-1121

Cha J.S., Park S.H., Jung S.C. *et al.* (2016). Production and utilization of biochar: A review. *J. Ind. Eng. Chem.,* **40,** 1-15

Clark M., Hastings M.G. and Ryals R. (2019). Soil carbon and nitrogen dynamics in two agricultural soils amended with manure-derived biochar. *J. Environ. Qual.,* **48 (3),** 727-734

Climate-data (2021). Climate: Enugu. Accessed 23/06/2021 https://en.climate-data.org/africa/nigeria/enugu-350/

Clough T.J., Condron L.M., Kammann C. and Müller C. (2013). A review of biochar and soil nitrogen dynamics. *Agron.,* **3 (2),** 275-293

Ding Y., Liu Y., Liu S., *et al.* (2016). Biochar to improve soil fertility: A review. *Agron. Sustainable Dev.,* **36 (2),** 1-18

Du Z.L., Zhao J.K., Wang Y.D. and Zhang Q.Z. (2017). Biochar addition drives soil aggregation and carbon sequestration in aggregate fractions from an intensive agricultural system. *J. Soils Sediments,* **17 (3),** 581-589

Duku M.H., Gu S. and Hagan E.B. (2011). Biochar production potential in Ghana-a review. *Renew. Sustain. Energy Rev.,* **15 (8),** 3539-3551

Dume B., Berecha G. and Tulu S. (2015). Characterization of biochar produced at different temperatures and its effect on acidic Nitosol of Jimma, Southwest Ethiopia. *Int. J. Soil Sci.,* **10 (2),** 63

Eifediyi E.K. and Remison S.U. (2010). Growth and yield of cucumber (*Cucumis sativus* L.) as influenced by farmyard manure and inorganic fertilizer. *J. Plant Breed. Crop Sci.,* **2 (7),** 216-220

Enders A., Hanley K., Whitman T., Joseph S. and Lehmann J. (2012). Characterization of biochars to evaluate recalcitrance and agronomic performance. *Bioresour. Technol.,* **114,** 644-653

Frimpong K.A., Phares C.A., Boateng I., Abban-Baidoo E., and Apuri L. (2021). One-time application of biochar influenced crop yield across three cropping cycles on tropical sandy loam soil in Ghana. *Heliyon*, **7 (2),** e06267

Gao S. and DeLuca T.H. (2016). Influence of biochar on soil nutrient transformations, nutrient leaching, and crop yield. *Adv. Plants Agric. Res.*, **4 (5),** 1-16

Horst W.J., Kamh M., Jibrin J.M. and Chude V.O. (2001). Agronomic measures for increasing P availability to crops. *Plant and Soil,* **237 (2),** 211-223

Igwe C.A. (2005). Erodibility in relation to water-dispersible clay for some soils of eastern Nigeria. *Land Degrad. Dev.,* **16 (1),** 87-96

Joseph S., Pow D., Dawson K. *et al.* (2020). Biochar increases soil organic carbon, avocado yields and economic return over 4 years of cultivation. *Sci. Total Environ.,* **724,** 138153

Kahura M.W., Min H., Kim M.S. and Kim J.G. (2018). Assessing phosphorus availability in a high pH, biochar amended soil under inorganic and organic fertilization. *Ecol. Resil. Infrastruct.,* **5 (1),** 11-18

Karimi A., Moezzi A., Chorom M. and Enayatizamir N. (2020). Application of biochar changed the status of nutrients and biological activity in a calcareous soil. *J. Soil Sci. Plant Nutr.,* **20 (2),** 450-459

Kätterer T., Roobroeck D., Andrén O., *et al.* (2019). Biochar addition persistently increased soil fertility and yields in maize-soybean rotations over 10 years in sub-humid regions of Kenya. *Field Crops Res.,* **235,** 18-26

Kirkby E.A. and Johnston A.E.J. (2008). Soil and fertilizer phosphorus in relation to crop nutrition. *Ecophysiol. Plant-Phosphorus Interact.,* 177-223

Lehmann J. and Joseph S. (2015). *Biochar for Environmental Management: An Introduction*. Routledge, pp. 33-46

Li S., Barreto V., Li R., Chen G. and Hsieh Y.P. (2018). Nitrogen retention of biochar derived from different feedstocks at variable pyrolysis temperatures. *J. Analyt. Appl. Pyroly.,* **133,** 136-146

Liu R., Hayden H.L., Suter H., *et al.* (2017). The effect of temperature and moisture on the source of N_2O and contributions from ammonia oxidizers in an agricultural soil. *Biol. Fert. Soils,* **53 (1),** 141-152

Liu X., Eusterhues K., Thieme J., *et al.* (2013). STXM and NanoSIMS investigations on EPS fractions before and after adsorption to goethite. *Environ. Sci. Technol.,* **47 (7),** 3158-3166

Liu Z., Chen X., Jing Y., Li Q., Zhang J. and Huang Q. (2014). Effects of biochar amendment on rapeseed and sweet potato yields and water stable aggregate in upland red soil. *Catena*, **123,** 45-51

Mbah C.N., Njoku C., Okolo C.C., Attoe E.E. and 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*). *Afr. J. Agric. Res.*, **12 (21),** 1781-1792

McLaughlin M.J., McBeath T.M., Smernik R., Stacey S.P., Ajiboye B. and Guppy C. (2011). The chemical nature of P accumulation in agricultural soils – implications for fertiliser management and design: An Australian perspective. *Plant Soil,* **349 (1),** 69-87

McLean E.O. (1982). Soil pH and lime requirement. In: Page A.L., Miller R.H. and Keeney D.R. (eds.), *Methods of Soil Analysis, Part 2* (pp. 199-224). Wisconsin: America Society of Agronomy Madison

Moyin-Jesu E.I. (2015) Use of different organic fertilizers on soil fertility improvement, growth and head yield parameters of cabbage (*Brassica oleraceae* L). *Int. J. Recycl. Organic. Waste Agric.*, **4 (4),** 291-298

Muhammad Y.Y. (2014). Exploring the potential of bambara groundnut, an underutilised African legume species, towards food security in Africa. *Afr. J. Agric. Sci. Technol.,* **2 (11),** 201-204

Nelson D.W. and Sommers L.E. (1983). Total carbon, organic carbon, and organic matter. In: *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties*, 9, 539-579

Norton J. and Ouyang Y. (2019). Controls and adaptive management of nitrification in agricultural soils. *Front. Microbiol.,* **10:** 1931

Nwadialo B.E. (1989). Soil-landscape relationship in the Udi-Nsukka plateau. *Catena*, **16,** 111-120

Okebalama C.B., Ibezim C.O., Ugwu V.U. and Marschner B. (2020a). Effects of amending an Ultisol with bambara groundnut seed residue on soil fertility, microbial nutrient cycling and yield of cucumber. *Biol. Agric. Hort.,* **36 (4),** 249-266

Okebalama C.B., Igwe C.A. and Onunwa A.O. (2022). Enumeration of carbon and nitrogen contents of water-stable aggregates in layers of topsoils from cultivated and adjacent bush-fallow loamy soils. Nigeria. *Agro-Science,* **21 (1),** 103-113

Okebalama C.B., Ogunezi K.C., Agbo I.C. and Asogwa K.C. (2020b). Influence of soil amendment with poultry droppings on the soil properties and productivity of cucumbers (*Cucumis sativus* L.) on a degraded Ultisol in Nsukka area, Southeast Nigeria. *Nig. J. Soil Sci.,* **30 (2),** 85-94

Okebalama C.B., Ugwu V.U. and Marschner B. (2019). Managing soil resources to secure our future: The edge. Annual Conference of the British Society of Soil science. Endcliffe Village, University of Sheffield, Sheffield UK, e-book of Abstracts

Olsen S.R. and Sommers L.E. (1982). Phosphorus. In: Page A.L., Miller R.H. and Keeney D.R. (eds.), *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties* (2nd ed., pp. 403-430). Madison Wisconsin: American Society of Agronomy & Soil Science Society of America

Panda A., Jha P., Kumar A. and Bajpai R.K. (2017). Impact of organic residues application as a soil amendment on response in soil acidity. *Int. J. Conserv. Sci.,* **5 (1),** 105-109

Pandian K., Subramaniayan P., Gnasekaran P. and Chitraputhirapillai S. (2016). Effect of biochar amendment on soil physical, chemical and biological properties and groundnut yield in rainfed Alfisol of semi-arid tropics. *Arch. Agron. Soil Sci.,* **62 (9),** 1293-1310

Papadopoulos A.P. (1994). Growing greenhouse seedless cucumbers in soil and in soilless media. Agriculture and Agri-Food Canada

Peng J., Han X., Li N. *et al.* (2021). Combined application of biochar with fertilizer promotes nitrogen uptake in maize by increasing nitrogen retention in soil. *Biochar*, 1-13

Persaud T., Homenauth O., Fredericks D. and Hamer S. (2018). Effect of rice husk biochar as an amendment on a marginal soil in Guyana. *World Environ.,* **8 (1),** 20-25

Phares C.A., Atiah K., Frimpong K.A., Danquah A., Asare A.T. and Aggor-Woananu S. (2020). Application of biochar and inorganic phosphorus fertilizer influenced rhizosphere soil characteristics, nodule formation and phytoconstituents of cowpea grown on tropical soil. *Heliyon*, **6 (10),** e05255

Riling M.C. and Mummey D.L. (2006). Mycorrhizas and soil structure. *New Phytologist*, **171 (1)**, 41-53

Saletnik B., Zagula G., Bajcar M., Czernicka M. and Puchalski C. (2018). Biochar and biomass ash as a soil ameliorant: The effect on selected soil properties and yield of Giant Miscanthus (*Miscanthus giganteus*). *Energies,* **11 (10),** 2535

Selim M.M., Al-Suhaibani N., El-Hendawy S. and Alderfasi A.A. (2019). Agronomic advancement in nutrients management for sustaining growth and crop contribution in wheat (*Triticum aestivum* L.). *Egypt. J. Agron.,* **41 (3),** 325-342

Shalini R., Pugalendhi S., Subramanian P. and Gopal N.O. (2017). Characteristic study on biochar production from biological substrates by slow pyrolysis for carbon sequestration. *Int. J. Curr. Microbiol. Appl. Sci.,* **6 (4),** 314-323

Siddique S., Ayub G., Nawaz Z., *et al.* (2017). Enhancement of growth and productivity of cucumber (*Cucumis sativus*) through foliar application of calcium and magnesium. *Pure Appl. Biol.,* **6 (2),** 402-411

Singh M., Saini R.K., Singh S. and Sharma S.P. (2019). Potential of integrating biochar and deficit irrigation strategies for sustaining vegetable production in water-limited regions: A review. *HortScience*, **54 (11),** 1872-1878

Song G.U.A.N., Liu S.J., Liu R.Y. *et al.* (2019). Soil organic carbon associated with aggregate-size and density fractions in a Mollisol amended with charred and uncharred maize straw. *J. Int. Agric.,* **18 (7),** 1496-1507

Sun Q., Meng J., Lan Y., *et al.* (2021). Long-term effects of biochar amendment on soil aggregate stability and biological binding agents in brown earth. *Catena*, **205,** 105460

Thomas G.W. (1982). Exchangeable cations. In: Page A.L. (ed.), *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties* (pp. 159-165). Madison WI: American Society of Agronomy

Uvere P., Uwaegbute A. and Adedeji E. (1999). Effects of malting on the milling performance and acceptability of Bambara groundnut (*Voandzeia subterranea* Thouars) seeds and products. *Plant Foods Hum. Nut*r., **54 (1),** 49-57

Wan Q., Yuan J.H., Xu R.K. and Li X.H. (2014). Pyrolysis temperature influences ameliorating effects of biochars on acidic soil. *Environ. Sci. Pollut. Res.,* **21 (4),** 2486-2495

Wang D., Fonte S.J., Parikh S.J., Six J. and Scow K.M. (2017). Biochar additions can enhance soil structure and the physical stabilization of C in aggregates. *Geoderma*, **303,** 110-117

Wang J. and Wang S. (2019). Preparation, modification and environmental application of biochar: a review. *J. Clean. Prod.,* **227,** 1002-1022

Warncke D.D. (2007). Nutrient management for cucurbits: Melons, pumpkin, cucumber, and squash. In: Indiana CCA Conf. Proc., Indianapolis, India

White P.J. and Broadly M.R. (2003). Calcium in plant. *Ann. Bot.,* **92,** 487-511

Xia H., Riaz M., Zhang M., Liu B., El-Desouki Z. and Jiang C. (2020). Biochar increases nitrogen use efficiency of maize by relieving aluminum toxicity and improving soil quality in acidic soil. *Ecotoxicol. Environ. Safety,* **196,** 110531

Yang C.D., Zong Y.T. and Lu S.G. (2020). Dynamic effects of different biochars on soil properties and crop yield of acid farmland. *Huan Jing ke Xue/Huanjing Kexue*, **41 (4),** 1914-1920

Yao Y., Gao B., Zhang M., Inyang M. and Zimmerman A.R. (2012). Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. *Chemosphere,* **89 (11),** 1467-1471

Yuan J.H. and Xu R.K. (2012). Effects of biochars generated from crop residues on chemical properties of acid soils from tropical and subtropical China. *Soil Res.,* **50 (7),** 570-578

Yuan J.H., Xu R.K. and Zhang H. (2011a). The forms of alkalis in the biochar produced from crop residues at different temperatures. *Bioresour. Technol.,* **102 (3),** 3488-3497

Yuan J.H., Xu R.K., Qian W. and Wang R.H. (2011b). Comparison of the ameliorating effects on an acidic Ultisol between four crop straws and their biochars. *J. Soils Sediments,* **11 (5),** 741-750

Zhang C., Li X., Yan H. *et al.* (2020). Effects of irrigation quantity and biochar on soil physical properties, growth characteristics, yield and quality of greenhouse tomato. *Agric. Water Manage.,* **241,** 106263

Zhang Q.Z., Dijkstra F.A., Liu X.R., Wang Y.D., Huang J., and Lu N. (2014). Effects of biochar on soil microbial biomass after four years of consecutive application in the North China plain. *PloS one*, **9 (7),** e102062

Zhang S., Cui J., Wu H., *et al.* (2021). Organic carbon, total nitrogen, and microbial community distributions within aggregates of calcareous soil treated with biochar. *Agric. Ecosys. Environ.,* **314,** 107408

Zhao H.T., Li T.P., Zhang Y., *et al.* (2017). Effects of vermicompost amendment as a basal fertilizer on soil properties and cucumber yield and quality under continuous cropping conditions in a greenhouse. *J. Soils Sediments,* **17 (12),** 2718-2730

Zhou R., Wang Y., Tian M., *et al.* (2021). Mixing of biochar, vinegar and mushroom residues regulates soil microbial community and increases cucumber yield under continuous cropping regime. *Appl. Soil Ecol.,* **161:** 103883