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Effects of Maize-Straw Biochar and NPK Fertiliser on Groundnut (*Arachis Hypogaea* L.) Yield and Soil Loss During Harvesting

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ABSTRACT
Information on the effects of biochar on soil loss associated with groundnut harvesting remains limited. Hence, a 3 × 3 factorial field experiment arranged in a Randomised Complete Block Design (RCBD) with three replications, consisting of three rates of maize-straw biochar (0, 3 and 6 t ha^{-1}) and NPK 15:15:15 fertiliser (0, 30 and 60 kg N ha^{-1}), was conducted at the Teaching and Research Farm, University of Ibadan, Ibadan, Nigeria, to examine the effects of biochar, NPK 15:15:15 fertiliser and their interaction on groundnut yield, soil loss associated with crop harvesting, soil nutrient loss and post-harvest soil physical properties. The results showed that biochar application did not significantly (P > 0.05) affect groundnut pod yield, specific soil loss due to crop harvesting (SLCHspec), total soil nutrient loss or post-harvest soil physical properties. NPK 15:15:15 fertiliser significantly (P < 0.05) affected groundnut pod yield and total soil loss due to crop harvesting (SLCHcrop), while the interaction between biochar and NPK 15:15:15 fertiliser significantly influenced groundnut pod yield and SLCHcrop. The highest pod yield (2.97 t ha^{-1}) was obtained from the combined application of 6 t ha^{-1} maize-straw biochar and 0 kg ha^{-1} NPK 15:15:15 fertiliser, whereas the highest SLCHcrop (8.13 kg ha^{-1}) was recorded under the same treatment combination. Biochar application produced numerical improvements in field capacity, bulk density and saturated hydraulic conductivity. The interaction between biochar and NPK fertiliser significantly influenced saturated hydraulic conductivity. The study demonstrated that biochar alone had limited short-term effects under the conditions of the study, whereas its interaction with NPK fertiliser influenced selected crop and soil responses.

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INTRODUCTION

Soil is a fundamental component of terrestrial ecosystems and provides the medium required for plant growth and agricultural production. Among the forms of soil degradation, soil loss due to crop harvesting (SLCH) has received relatively little attention despite its potential to contribute to soil and nutrient depletion (Kuhwald *et al*., 2022). SLCH occurs when loose soil particles, clods and stones adhering to harvested crops are removed from the field. Continuous removal of soil during harvesting can reduce topsoil depth and nutrient availability, thereby threatening long-term soil productivity (Oshunsanya *et al*., 2018; Panagos *et al*., 2019). The magnitude of SLCH varies with crop type, harvesting method, soil properties and crop conditions. Groundnut (*Arachis hypogaea* L.) is particularly susceptible to SLCH because its pods develop below the soil surface. Consequently, soil adhering to the pods and roots can be removed from the field during harvesting. Groundnut harvesting has been shown to result in measurable soil loss, with soil compaction and other soil conditions influencing the amount of soil removed (Ewetola, 2020; Parlak *et al*., 2022). Such losses are important because the soil exported during harvesting may contain organic matter and plant nutrients, representing both a physical loss of soil and a potential loss of valuable soil resources. Groundnut requires adequate supplies of essential nutrients for optimum growth, pod development and yield. Although biological nitrogen fixation contributes substantially to its nitrogen requirement, the availability of other essential nutrients remains important for productive growth. Mineral fertilisers are therefore commonly used to improve nutrient availability and crop yield. However, reliance on mineral fertilisers alone may not adequately address soil fertility and nutrient-retention challenges in highly weathered tropical soils (Basak *et al*., 2022). This has encouraged interest in integrated nutrient management involving mineral fertilisers and organic or carbon-based amendments. Biochar is a carbon-rich material produced through the thermal decomposition of biomass under limited oxygen conditions. Its application can influence soil chemical and physical properties, nutrient retention and plant productivity (Joseph *et al.*, 2021). Biochar application has shown particular potential for improving the quality and productivity of degraded tropical soils (Basak *et al*., 2022). Moreover, a meta-analysis showed that combining biochar with inorganic fertiliser can enhance crop yield compared with the corresponding fertiliser treatments alone (Bai *et al.*, 2022). These benefits suggest that biochar–NPK combinations may improve crop productivity while enhancing nutrient retention in the soil. Despite increasing research on biochar and SLCH, limited information is available on the combined effects of biochar and NPK fertiliser on soil and nutrient losses associated with groundnut harvesting, particularly under Nigerian conditions. Previous studies have established the importance of crop harvesting as a pathway of soil loss (Panagos *et al*., 2019), while evidence from groundnut demonstrates that harvesting can result in substantial soil removal (Parlak *et al.*, 2022). However, limited attention has been given to whether integrated biochar–NPK management can reduce soil and nutrient losses during groundnut harvesting while maintaining or improving crop yield. Therefore, this study was conducted to determine the combined effects of biochar and NPK fertiliser on soil and nutrient loss due to groundnut harvesting and to evaluate their effects on groundnut yield.

MATERIALS AND METHODS

Experimental Site

The experiment was conducted at the Teaching and Research Farm, University of Ibadan, Ibadan, Oyo State, Nigeria, along Parry Road. The experimental site is located at 7°27′07″ N latitude and 3°53′29″ E longitude. The area receives an average annual rainfall of approximately 1,250 mm, with a bimodal rainfall distribution. The soil at the experimental site is an Alfisol classified as Typic Kandiustalf and developed from basement-complex rocks. Locally, the soil belongs to the Iwo series.

Experimental Design and Treatments

The experiment was laid out as a 3 × 3 factorial arrangement in a randomized complete block design (RCBD) with three replicates., giving a total of 27 lots. Each plot measured 2 m × 3 m, with 1 m spacing between adjacent plots and 1 m spacing between blocks. The factors consisted of three rates of maize-straw biochar (0, 3 and 6 t ha^{-1}) and three rates of NPK 15:15:15 15:15:15 fertiliser equivalent to 0, 30 and 60 kg N ha^{-1}. The factorial combination resulted in nine treatment combinations: 0 t ha^{-1} biochar + 0 kg N ha^{-1} NPK 15:15:15, 0 t ha^{-1} biochar + 30 kg N ha^{-1} NPK 15:15:15, 0 t ha^{-1} biochar + 60 kg N ha^{-1} NPK 15:15:15, 3 t ha^{-1} biochar + 0 kg N ha^{-1} NPK 15:15:15, 3 t ha^{-1} biochar + 30 kg N ha^{-1} NPK 15:15:15, 3 t ha^{-1} biochar + 60 kg N ha^{-1} NPK 15:15:15, 6 t ha^{-1} biochar + 0 kg N ha^{-1} NPK 15:15:15, 6 t ha^{-1} biochar + 30 kg N ha^{-1} NPK 15:15:15, and 6 t ha^{-1} biochar + 60 kg N ha^{-1} NPK 15:15:15.

Land Preparation and Plot Establishment

The experimental field was manually cleared and tilled using a cutlass and hoe. The field was subsequently divided into 27 experimental plots, each measuring 2 m × 3 m. The plots were arranged according to the randomized complete block design, with each block containing the nine treatment combinations. Treatments were randomly assigned within each block to minimize the effects of field variability.

Planting Material and Crop Establishment

Groundnut (*Arachis hypogaea* L.) seeds of SAMNUT-26 obtained from the Teaching and Research Farm, University of Ibadan, were used as the planting material. The seeds were sorted to remove damaged and malformed seeds and treated with Apron Plus 50 DS before planting to protect them against seed-borne and soil-borne pathogens.

The treated seeds were sown in January 2024 at a spacing of 0.75 m × 0.45 m and at a depth of approximately 5 cm. Following sowing, the beds were temporarily covered with straw to protect the seeds and reduce exposure to excessive heat. The straw covering was removed six days after sowing to facilitate normal seedling emergence and establishment.

Preparation and Application of Maize-Straw Biochar

The biochar used in this study was produced using a locally fabricated pyrolysis unit consisting of three main compartments: an insulated outer metal box with a cover, an inner cylindrical chamber with its own lid and a lower outlet for collecting the charred material. maize-straw feedstock was loaded into the inner chamber and securely sealed. Pre-heated charcoal was then introduced into the space surrounding the inner cylinder to initiate the pyrolysis process, after which the entire reactor was covered. A timer was set to monitor the duration of the charring process, which lasted approximately five hours at 550^0C. Upon completion, the residual material inside the inner chamber, which was fully charred was identified as biochar. This biochar was discharged through the lower outlet and water was immediately sprinkled over the hot char to prevent further combustion. The resulting biochar was then air-dried for one week before being applied in the experimental treatments.

Application of NPK 15:15:15 Fertiliser

NPK 15:15:15 fertiliser was applied according to the assigned treatment rates of 0, 30 and 60 kg N ha^{-1}. The quantity of fertiliser required for each plot was calculated from the nitrogen concentration of the fertiliser and the corresponding treatment rate. The calculated amount was weighed and applied to the designated plots.

Cultural Practices

Standard cultural practices were carried out uniformly across all treatments throughout the growing period, except where treatments differed in the amount of biochar and NPK 15:15:15 fertiliser applied. Weed management was carried out manually using a hoe. Weeding was performed twice after crop establishment to minimise competition between the groundnut plants and weeds for water, nutrients, light and space. The experimental plots were regularly monitored throughout the growing period for proper crop establishment and general field conditions. The straw used to cover the beds after sowing was removed six days after planting. Other management activities were carried out uniformly across the experimental plots to minimise variation arising from management practices.

Soil Sampling and Laboratory Analysis

Soil samples were collected from the 0–15 cm depth using a soil auger. Two soil samples were randomly collected from each plot and bulked to form one composite sample. The composite samples were air-dried, gently crushed and passed through the appropriate sieve before laboratory analysis. The samples were analysed for selected physical and chemical properties, including particle-size distribution, bulk density, soil-water retention, saturated hydraulic conductivity, pH, organic carbon, available phosphorus, total nitrogen, exchangeable bases and selected micronutrients.

Particle-Size Distribution

For each soil sample, the relative amounts of sand, silt, and clay were ascertained by particle size analysis using Bouyouco's hydrometer method (Day, 1965). Fifty grams of air-dried soil was weighed into a dispersion cup, and sodium hexametaphosphate solution was added as the dispersing agent. Water was added and the suspension was mechanically stirred to disperse the soil particles. The suspension was transferred into a sedimentation cylinder through a 210-µm sieve. The coarse sand fraction retained on the sieve was collected, oven-dried at 105 °C and weighed. The suspension in the sedimentation cylinder was made up to the 1-L mark with distilled water and thoroughly mixed. Hydrometer and temperature readings were taken at specified settling times to determine the proportions of silt and clay. The proportions of sand, silt and clay were subsequently calculated and used to determine the soil textural class.

Bulk Density

Undisturbed soil samples were collected using soil core samplers. The soil cores were oven-dried at 105 °C to constant weight. Bulk density was calculated as the ratio of the mass of oven-dried soil to the volume of the soil core:

$$BD = \frac{Md}{V} \quad (1)$$

where BD is bulk density (g cm^{-3}), Md is the mass of oven-dried soil (g), and V is the volume of the soil core (cm^3).

Soil-Water Retention
Soil-water retention was determined using a tension table. Soil cores were saturated with water for 24 h before being placed on the tension table. Suction was applied at 10, 20, 30, 40, 50 and 60 cm. The samples were weighed after equilibration at each suction level, and the corresponding soil-water contents were determined.

Saturated Hydraulic Conductivity
Saturated hydraulic conductivity was determined using a permeameter under saturated conditions. Water was supplied continuously to the soil cores, and the volume of water passing through the cores was collected and measured after the flow reached equilibrium. Saturated hydraulic conductivity was calculated using:

$$K = \frac{QL}{Aht} \quad (2)$$

Where; K is saturated hydraulic conductivity (cm min^{-1}), Q is the quantity of water discharged at equilibrium (cm^3), L is the length of the soil core (cm), A is the cross-sectional area of the soil core (cm^2), h is the hydraulic head above the soil core (cm), and t is the time taken for the measured discharge (min).

Soil pH
Soil pH was determined in a 1:1 soil-to-distilled-water suspension using a glass electrode pH meter (Udo and Ogunwale, 1986). 10 grams of air-dried soil passed through a 2-mm sieve was weighed into a 50-mL beaker, and 20 mL of distilled water was added. The suspension was thoroughly stirred and allowed to equilibrate before the pH was measured using a glass-electrode pH meter.

Soil Organic Carbon and Organic Matter
Using the Walkley Black wet oxidisation method, the soil's organic carbon content was ascertained. Soil organic carbon was determined using the wet-oxidation procedure. Air-dried soil was reacted with potassium dichromate and concentrated sulphuric acid, after which the excess oxidising agent was determined by titration with ferrous sulphate using an appropriate indicator. A reagent blank was included in the determination. Organic carbon was calculated from the difference between the blank and sample titres, while organic matter was estimated from the organic carbon concentration using the appropriate conversion factor.

Available Phosphorus
Available phosphorus was determined by extracting the soil using Bray-1 extractant. Two grams of soil was weighed into a shaking bottle, and 20 mL of the extracting solution was added. The mixture was mechanically shaken for 5 min and filtered through Whatman No. 42 filter paper. Phosphorus in the extract was developed using the appropriate colour reagent and quantified colorimetrically at 882 nm.

Total Nitrogen
Total nitrogen was determined using the micro-Kjeldahl digestion and distillation procedure. Approximately 0.5 g of air-dried and sieved soil was weighed into a digestion flask, followed by the addition of concentrated sulphuric acid and a selenium catalyst. The sample was digested until a clear digest was obtained. The digest was subsequently distilled, and the liberated ammonia was collected in boric acid solution. The amount of nitrogen was determined by titration with standard hydrochloric acid. Total nitrogen concentration was calculated from the titre value, blank value, acid concentration, dilution factor and soil weight.

Exchangeable Bases
Exchangeable bases were extracted using neutral 1 M ammonium acetate. Five grams of air-dried soil was weighed into a plastic bottle and 100 mL of the extracting solution was added. The mixture was mechanically shaken for 10 min and filtered. Calcium and magnesium in the extract were determined by EDTA titration, while sodium and potassium were determined using a flame photometer. The concentrations were calculated using the appropriate dilution factors, extract volume and soil weight.

Soil Micronutrients
Soil micronutrients, including iron, copper, manganese and zinc, were extracted using dilute hydrochloric acid. Ten grams of air-dried soil was weighed into a plastic bottle, and 100 mL of the extracting solution was added. The mixture was shaken for 10 min and filtered through Whatman No. 42 filter paper. The concentrations of the extracted micronutrients were determined using an atomic absorption spectrometer.

Growth Parameters
Ten plants were randomly selected from the middle rows of each plot and tagged for data collection. Plant height was measured at two-week intervals using a metre rule, with measurements taken from the soil surface to the apex of the longest leaf. Leaf area was determined using a leaf-area meter.

Harvesting and Yield Parameters
At harvest, the entire plot area was harvested, no border rows or plants were excluded from the harvested area. Groundnut was harvested manually at five months after planting by carefully uprooting the plants from the soil. Harvested plants from each plot were kept separate to prevent mixing among treatments. The pods were detached from the shoots and weighed to determine pod yield. Total plant biomass was determined by weighing the harvested plant material after removing adhering soil, while shoot biomass was determined by weighing the above-ground plant material after pod removal.

Determination of Soil Loss Due to Crop Harvesting
The harvested groundnut material from each plot was handled separately. All harvested pods and associated root material from each plot were washed in clean water for approximately 10 min to remove soil adhering to the harvested material. Particular care was taken during washing to recover soil particles trapped around the root-hair zone. The washings containing the detached soil were collected separately using filtration method for each plot. The recovered soil was separated from the water, and visible organic debris were carefully removed before drying. The soil was then oven-dried at 105^0C for 24 hours, cooled in a desiccator before weighing. The resulting dry mass represented the soil removed from the field with the harvested crop.
Soil loss due to crop harvesting was expressed as specific soil loss per unit groundnut mass (SLCHspec) and total soil loss per unit land area per harvest (SLCHcrop). Specific soil loss was calculated as:

$$SLCH_{spec}\ (kg\ kg^{-1}) = \frac{M_{ds}(kg)}{M_{groundnut}(kg)} \quad (3)$$

where M_{ds} is the mass of oven-dried soil recovered from the harvested groundnut material (g), and Mgroundnut is the corresponding mass of harvested groundnut (kg). Specific soil loss was expressed as g kg^{-1} harvested groundnut.

Total soil loss per hectare per harvest was calculated from specific soil loss and groundnut yield, with appropriate unit conversion:

$$SLCH_{crop} = SLCH\ spec\ (kg\ kg^{-1}) \times M_{cy}\ (kg\ ha^{-1}) \quad (4)$$

where SLCHcrop is soil loss due to crop harvesting (kg ha^{-1} $harvest^{-1}$), SLCHspec is specific soil loss (g kg^{-1}), and Mcy is groundnut yield expressed on a hectare basis (t ha^{-1} $harvest^{-1}$).

Statistical Analysis

Data obtained for soil properties, growth parameters, biomass, pod yield, soil loss due to crop harvesting and nutrient loss were subjected to analysis of variance using the factorial treatment structure in a randomized complete block design. The main effects of biochar rate and NPK 15:15:15 fertiliser rate and their interaction were evaluated. Where significant differences occurred among treatment means, means were separated using the least significant difference test at the 5% probability level. Pearson's correlation analysis was further conducted among selected variable to assess relationships. All statistical analyses were performed using GenStat Discovery Edition & R statistical package.

RESULTS AND DISCUSSION

Table 1 presents the soil nutrient composition of the experimental site and the soil was classified as a sandy loam, containing 83.8% sand, 4.6% silt and 11.6% clay. The soil had a pH of 6.80, organic carbon content of 15.2 g/kg, total nitrogen of 0.28 g/kg and available phosphorus of 4.0 mg/kg. The exchangeable bases comprised 3.54, 1.06, 0.20 and 0.70 cmol/kg of calcium, magnesium, potassium and sodium, respectively. The bulk density was 1.53 Mg/m^3, while saturated hydraulic conductivity was 10.76 cm/h. The relatively high sand content and low clay fraction indicate that the soil had limited capacity for nutrient retention and aggregation. Sandy soils are also generally more susceptible to structural instability, rapid drainage and nutrient leaching. These characteristics may increase the likelihood of soil detachment and removal during the harvesting of crops with underground reproductive structures. The relatively low available phosphorus and total nitrogen contents further suggest that nutrient availability could constrain groundnut productivity without external nutrient inputs.

Table 1: Soil Physical and Chemical Properties of the Experimental Site Before Cropping

Parameters	Values
pH (H_2O)	6.80
Organic carbon (g/kg)	15.2
Total nitrogen (g/kg)	0.28
Available p (mg/kg)	4.0
Extractable cations (cmol/kg)	
Ca	3.54
Mg	1.06
K	0.20
Na	0.70
Exchangeable acidity (cmol/kg)	0.45
Bulk density (Mg m^{-3})	1.53
Saturated hydraulic conductivity (cm/hr)	10.76
Particle size distribution (g/kg)	
Sand	838
Silt	46
Clay	116
Textural class	Sandy loam

Table 2 shows the analysis of maize-straw biochar which contained 205.0 g/kg total carbon, 0.28 g/kg total nitrogen and 176.0 mg/kg total phosphorus. The exchangeable calcium, magnesium, potassium and sodium contents were 7.61, 3.47, 24.80 and 6.50 cmol/kg respectively. The relatively high carbon content indicates the potential of the biochar to contribute to soil carbon accumulation, while its exchangeable nutrient contents suggest that it could act as a supplementary source of plant nutrients. However, the nutrient contribution of biochar depends not only on its total nutrient concentration but also on the chemical form, solubility and accessibility of the nutrients after incorporation into the soil.

Table 2: Chemical Analysis of Biochar Used for the Experiment

Parameters	Values
Total carbon (g/kg)	205.0
Total nitrogen (g/kg)	0.28
Total phosphorus (mg/kg)	176.0
Exchangeable cation (cmol/kg)	
Ca	7.61
Mg	3.47
K	24.8
Na	6.5

As shown in Table 3, groundnut pod yield was not significantly affected by the main effect of biochar application ($P = 0.131$). Pod yield increased numerically from 2.01 t ha^{-1} in the control treatment to 2.12 and 2.40 t ha^{-1} under 3 and 6 t ha^{-1} biochar, respectively. Although the increase was not statistically significant, the numerical improvement suggests that the higher biochar rate may have enhanced soil conditions, including moisture retention, nutrient availability and root development, thereby supporting pod formation. The absence of a significant biochar effect may be attributed to the relatively short period between biochar incorporation and crop harvesting, since the beneficial effects of biochar often become more pronounced with time. Joseph *et al.* (2021) reported that crop responses to biochar depend largely on soil properties, biochar characteristics, application rate and duration after application. NPK 15:15:15 fertiliser application significantly affected pod yield (P = 0.031). Contrary to the expectation of increasing yield with increasing fertiliser rate, the highest mean pod yield (2.35 t ha⁻¹) was obtained in the NPK0 treatment, followed by NPK30 (2.31 t ha⁻¹), while the NPK60 treatment produced the lowest yield (1.86 t ha⁻¹). These results suggest that the highest fertiliser rate may not have been optimum under the prevailing soil and environmental conditions, possibly because of nutrient imbalance, excessive vegetative growth or reduced nutrient-use efficiency. Similar observations have been reported by Orji *et al.* (2022), who showed that optimum rather than maximum NPK application improved groundnut productivity.

The interaction between biochar and NPK fertiliser significantly influenced pod yield (P = 0.024). The highest pod yield (2.97 t ha⁻¹) was obtained from the combination of 6 t ha⁻¹ biochar and NPK0, whereas the lowest yield (1.56 t ha⁻¹) occurred under 3 t ha⁻¹ biochar combined with NPK60. These results indicate that the response of groundnut to fertiliser depended on the level of biochar applied. The superior performance of the 6 t ha⁻¹ biochar without NPK fertiliser suggests that biochar alone may have improved nutrient retention and soil physical conditions sufficiently to support crop growth under the experimental conditions. Bai *et al.* (2022) similarly reported that the interaction between biochar and mineral fertiliser depends on soil characteristics, nutrient status, biochar properties and fertiliser management practices.

Specific soil loss due to crop harvesting (SLCHspec) was not significantly affected by either biochar application (P = 0.663), NPK fertiliser application (P = 0.449) or their interaction (P = 0.262). Although numerical differences were observed among treatments, these differences were not statistically significant, indicating that neither biochar nor NPK fertiliser consistently altered the quantity of soil adhering to harvested groundnut pods. Soil adhering to harvested pods is influenced primarily by soil moisture content at harvest, soil texture, root morphology, pod characteristics and harvesting conditions rather than by soil amendments alone. Kuhwald *et al.* (2022) described harvest erosion as a distinct soil-loss process controlled largely by crop and soil characteristics rather than conventional erosion-control practices. Total soil loss due to crop harvesting (SLCHcrop) was not significantly affected by biochar application (P = 0.417), although soil loss increased numerically from 4.22 kg ha⁻¹ in the control to 4.50 and 5.07 kg ha⁻¹ under 3 and 6 t ha⁻¹ biochar, respectively. The numerical increase in soil loss may be associated with the corresponding increase in pod yield, since greater harvested biomass may remove more adhering soil even when soil loss per unit of harvested crop remains unchanged. Therefore, the higher values should not be interpreted as evidence that biochar increased soil erodibility.

NPK fertiliser application significantly affected SLCHcrop (P = 0.030). The highest soil loss (5.68 kg ha⁻¹) occurred in the NPK0 treatment, whereas significantly lower soil losses were recorded under NPK30 (4.15 kg ha⁻¹) and NPK60 (3.95 kg ha⁻¹). This suggests that fertiliser application reduced the amount of soil removed during harvesting, possibly through improved root development and soil aggregation. Similarly, the interaction between biochar and NPK fertiliser significantly influenced SLCHcrop (P < 0.001). The highest soil loss (8.13 kg ha⁻¹) occurred under 6 t ha⁻¹ biochar combined with NPK0, whereas the lowest value (2.56 kg ha⁻¹) was recorded under 0 t ha⁻¹ biochar combined with NPK0. These results demonstrate that harvest soil loss depended on the combined effects of biochar and fertiliser rather than on either factor alone. Panagos *et al.* (2019) identified crop harvesting as an important geomorphic process capable of removing considerable quantities of fertile topsoil, while Oshunsanya *et al.* (2022) showed that harvest-induced soil loss can contribute to economically important nutrient losses in root and pod crops.

Table 3: Effects of Maize-Straw Biochar, NPK 15:15:15 Fertiliser and their Interaction on Groundnut Pod Yield and Soil Loss Due to Crop Harvesting

Treatment	Pod yield (t ha⁻¹)	SLCHcrop (kg ha⁻¹)	SLCHspec (g kg⁻¹)
Biochar			
B0 (0 t ha⁻¹)	2.01	4.22	2.32
B3 (3 t ha⁻¹)	2.12	4.50	2.35
B6 (6 t ha⁻¹)	2.40	5.07	3.50
NPK fertiliser			
NPK0 (0 kg ha⁻¹)	2.35 a	5.68 a	2.32
NPK30 (30 kg ha⁻¹)	2.31 a	4.15 b	2.05
NPK60 (60 kg ha⁻¹)	1.86 b	3.95 b	3.81
Biochar × NPK			
B0 × NPK0	1.67 cd	2.56 c	2.36
B0 × NPK30	2.22 bcd	5.51 b	2.45
B0 × NPK60	2.13 bcd	4.59 bc	2.15
B3 × NPK0	2.42 ab	6.35 ab	2.63
B3 × NPK30	2.39 ab	4.33 bc	2.59
B3 × NPK60	1.56 d	2.81 c	1.85
B6 × NPK0	2.97 a	8.13 a	1.96
B6 × NPK30	2.33 abc	2.61 c	1.11
B6 × NPK60	1.89 bcd	4.47 bc	7.42
ANOVA p-value			

Treatment	Pod yield (t ha^{-1})	SLCHcrop (kg ha^{-1})	SLCHspec (g kg^{-1})
Biochar (B)	0.131	0.417	0.663
NPK (N)	0.031*	0.030*	0.449
B × N	0.024*	<0.001*	0.262
LSD (0.05), N	0.40	1.35	ns
LSD (0.05), B × N	0.69	2.34	ns

SLCHcrop = Soil Loss Due to Crop Harvesting (kg ha^{-1}); SLCHspec = Specific Soil Loss Due to Crop Harvesting (g kg^{-1} Pod Yield). Biochar Rates: B0 = 0, B3 = 3, and B6 = 6 t ha^{-1}; NPK rates: NPK0 = 0, NPK30 = 30, and NPK60 = 60 kg N ha^{-1}. * Significant at $P < 0.05$; ns = not Significant. Means Followed by the Same Letter Within a Column are Not Significantly Different According to Fisher's LSD test ($P < 0.05$). Letters are Shown only where the ANOVA F-Test was Significant

Table 4 presents the relationship between soil loss due to harvesting and crop and soil properties. Specific soil loss was strongly and positively correlated with total soil loss due to harvesting, with a correlation coefficient of 0.798. This relationship indicates that plots with greater soil loss per unit mass of harvested groundnut also tended to record higher total soil loss. Above-ground biomass was also strongly and positively correlated with total soil loss, with a correlation coefficient of 0.808. This suggests that plots producing greater above-ground biomass tended to experience greater total soil loss during harvesting. A positive relationship was also observed between below-ground biomass and total soil loss, although the association was weaker, with a correlation coefficient of 0.387. The relationship between below-ground biomass and soil loss may be associated with the development of roots and root hairs, which can increase soil attachment around the harvested plant.

Table 4: Correlation Analysis Between SLCH, and Crop Parameters

Parameters	SLCHspec	SLCHcrop	BGB	AGB
SLCHspec	1			
SLCHcrop	0.798**	1		
BGB	-0.197ns	0.387*	1	
AGB	-0.206ns	0.302ns	0.808**	1

* - Correlation is Significant at the 0.05 Level, ** - Correlation is Significant at the 0.01 Level, ns – not Significant, AGB - Above-Ground Biomass, BG -: Below Ground Biomass

Table 5 presents the effect of biochar and NPK 15:15:15 fertiliser on soil nutrient losses following groundnut harvesting. The results showed that biochar application had no significant effect ($P > 0.05$) on organic carbon (OC), total nitrogen (TN), phosphorus (P), calcium (Ca), magnesium (Mg) or potassium (K) losses. Although numerical differences were observed among the biochar treatments, these differences were not statistically significant. Organic carbon loss ranged from 8.36 to 13.95 g ha^{-1}, TN loss ranged from 36.5 to 53.2 g ha^{-1}, while P, Ca, Mg and K losses also varied slightly among treatments. These numerical variations may be attributed to differences in soil loss associated with harvesting rather than to the direct effect of biochar on nutrient removal. Biochar has been widely reported to improve nutrient retention and soil fertility; however, such benefits are often expressed through reduced nutrient leaching and improved nutrient availability rather than through immediate reductions in nutrient loss associated with crop harvesting. Similarly, NPK 15:15:15 fertiliser application had no significant effect ($P > 0.05$) on OC, TN, P, Ca, Mg or K losses. Although the NPK30 treatment recorded numerically higher OC and TN losses than the other fertiliser treatments, whereas NPK60 generally produced lower nutrient losses, these differences were not statistically significant. The absence of significant differences suggests that fertiliser application did not consistently influence nutrient removal through harvest-induced soil loss under the conditions of this study. The amount of nutrient removed appeared to depend more on the quantity of soil adhering to harvested pods than on fertiliser application itself. The interaction between biochar and NPK fertiliser also did not significantly influence ($P > 0.05$) losses of OC, TN, P, Ca, Mg or K, although considerable numerical variation occurred among treatment combinations. For example, the B0 × NPK30 treatment recorded the highest OC and TN losses, whereas B6 × NPK60 generally recorded the lowest nutrient losses. Likewise, Ca, Mg and K losses varied among the interaction treatments but the observed differences were not statistically significant. These results indicate that the combined application of biochar and NPK fertiliser did not consistently alter nutrient loss through harvested soil. The numerical differences observed among treatments were likely associated with differences in harvested soil mass and natural field variability rather than treatment effects. The absence of significant treatment effects suggests that nutrient loss through soil adhering to harvested groundnut pods was influenced primarily by the quantity of soil removed during harvesting rather than by biochar or fertiliser application. Harvest soil loss is largely controlled by factors such as soil moisture content at harvest, soil texture, pod and root morphology, and soil adhesion to pods. Consequently, although biochar and fertiliser may improve soil fertility and crop growth, their influence on nutrient loss through harvest erosion may be limited during a single cropping season. Similar observations have been reported by Kuhwald *et al*. (2022), who showed that harvest erosion is governed mainly by crop characteristics and harvesting conditions, and by Panagos et al. (2019), who identified crop harvesting as an important mechanism of soil and nutrient removal from agricultural land. The findings also agree with Oshunsanya *et al.* (2022), who reported that nutrient losses associated with harvest erosion are closely related to the amount of soil adhering to harvested crops rather than solely to soil fertility management practices.

Table 5: Effects of Maize-Straw Biochar, NPK 15:15:15 Fertiliser and their Interaction on Soil Nutrient Losses

Treatments	**OC loss†**	**TN loss†**	**P loss**	**Ca loss†**	**Mg loss**	**K loss**
Biochar						
B0 (0 t ha⁻¹)	13.80	53.2	0.503	7.85	2.30	3.41
B3 (3 t ha⁻¹)	13.95	44.2	0.450	7.46	2.16	3.10
B6 (6 t ha⁻¹)	8.36	36.5	0.368	6.16	1.78	2.58
NPK fertiliser						
NPK0 (0 kg ha⁻¹)	8.68	44.3	0.488	7.55	2.23	3.27
NPK30 (30 kg ha⁻¹)	16.37	77.3	0.458	6.83	1.97	2.99
NPK60 (60 kg ha⁻¹)	11.0	12.4	0.375	7.09	2.04	2.82
Biochar × NPK						
B0 × NPK0	10.19	15.0	0.471	7.28	2.23	3.30
B0 × NPK30	25.93	127.6	0.526	6.47	1.89	3.30
B0 × NPK60	5.27	17.1	0.512	9.81	2.79	3.64
B3 × NPK0	2.33	102.1	0.428	5.41	1.56	2.11
B3 × NPK30	17.44	15.1	0.535	8.97	2.62	3.77
B3 × NPK60	22.08	15.6	0.386	8.00	2.29	3.40
B6 × NPK0	13.50	15.9	0.565	9.95	2.90	4.40
B6 × NPK30	5.75	89.2	0.314	5.07	1.40	1.91
B6 × NPK60	5.83	4.4	0.225	3.47	1.05	1.43
ANOVA p-value						
Biochar (B)	0.726	0.901	0.486	0.208	0.524	0.588
NPK (N)	0.620	0.461	0.581	0.857	0.847	0.856
B × N	0.071	0.698	0.576	0.058	0.117	0.211
LSD (0.05)	Ns	ns	ns	ns	ns	ns

OC = Organic Carbon; TN = total Nitrogen; P = Phosphorus; Ca = Calcium; Mg = Magnesium; K = Potassium. All Nutrient Losses are Expressed as g ha⁻¹. †ANOVA was Performed on $\log_{10}$-Transformed Data Because Residuals of the Untransformed Data did Not Satisfy the Assumption of Normality. * Significant at $P < 0.05$; ns = Not Significant

Biochar application resulted in numerical improvements in several post-harvest soil physical properties as shown in Table 6. Field capacity increased from 8.06% in the control treatment to 14.87% under 6 t ha⁻¹ biochar, while bulk density decreased slightly from 1.42 to 1.38 Mg m⁻³. Saturated hydraulic conductivity (Ksat) also varied among the biochar treatments, although no consistent trend was observed. However, none of these differences was statistically significant (P > 0.05). The numerical increase in field capacity observed at the highest biochar rate may be attributed to the porous nature of biochar, which has been reported to improve soil water retention and pore continuity. Similarly, the slight reduction in bulk density may reflect the relatively low density of biochar compared with mineral soil. Edeh *et al.* (2020) reported that biochar application can improve soil water-holding capacity and total porosity while reducing soil bulk density, whereas Razzaghi *et al.* (2020) observed that improvements in soil physical properties following biochar application depend on soil texture, biochar characteristics and application rate. The absence of significant effects in the present study suggests that a single cropping season may not have been sufficient for these improvements to become statistically detectable.

The effects of NPK fertiliser application on post-harvest soil physical properties were also not statistically significant (P > 0.05). Field capacity ranged from 9.62 to 11.60%, saturated hydraulic conductivity ranged from 7.50 to 9.12 cm h⁻¹, and bulk density varied only slightly among the NPK treatments. These findings indicate that mineral fertiliser alone had little influence on soil physical properties during the experimental period. This observation agrees with the general understanding that NPK fertilisers primarily improve soil fertility through nutrient supply rather than by directly modifying soil physical characteristics.

The interaction between biochar and NPK fertiliser significantly affected saturated hydraulic conductivity (P = 0.036) but had no significant effect on field capacity or bulk density. The highest Ksat (14.07 cm h⁻¹) was recorded under the B0 × NPK0 treatment, whereas the lowest value (4.69 cm h⁻¹) occurred under B6 × NPK30. Although the combination of 6 t ha⁻¹ biochar and 60 kg N ha⁻¹ NPK produced the highest numerical field capacity (17.00%) and one of the lowest bulk density values (1.22 Mg m⁻³), these differences were not statistically significant. The significant interaction observed for Ksat indicates that the influence of biochar on water movement through the soil depended on the level of NPK fertiliser applied. Such interaction effects may arise from changes in soil pore continuity, aggregation and root activity resulting from the combined application of organic and inorganic amendments. Despite the numerical improvements observed in some soil physical properties, particularly field capacity, these changes did not translate into significant reductions in specific soil loss during groundnut harvesting. This suggests that improvements in soil water retention, bulk density and hydraulic conductivity alone are insufficient to reduce harvest-induced soil loss. Soil adhering to harvested groundnut pods is influenced by several interacting factors, including soil moisture content at harvest, soil texture, root architecture, root-hair development and the degree of soil adhesion to pods. Consequently, improvements in soil physical quality do not necessarily result in reduced harvest erosion during a single growing season. This observation agrees with Kuhwald *et al.* (2022), who reported that harvest erosion is controlled largely by crop characteristics and harvesting conditions rather than by soil physical properties alone.

Table 6: Effects of Maize-Straw Biochar, NPK 15:15:15 Fertiliser and their Interaction on Post-Harvest Soil Physical Properties

Treatments	Field capacity (%)	Ksat (cm h^{-1})	Bulk density (Mg m^{-3})
Biochar			
B0 (0 t ha^{-1})	8.06	9.84	1.42
B3 (3 t ha^{-1})	9.28	7.56	1.39
B6 (6 t ha^{-1})	14.87	7.88	1.38
NPK fertiliser			
NPK0 (0 kg ha^{-1})	9.62	8.67	1.33
NPK30 (30 kg ha^{-1})	11.60	7.50	1.50
NPK60 (60 kg ha^{-1})	10.99	9.12	1.36
Biochar × NPK			
B0 × NPK0	8.15	14.07 a	1.22
B0 × NPK30	7.76	10.70 abc	1.48
B0 × NPK60	8.26	4.75 c	1.54
B3 × NPK0	9.39	5.27 bc	1.42
B3 × NPK30	10.73	7.11 abc	1.44
B3 × NPK60	7.73	10.30 abc	1.30
B6 × NPK0	11.31	6.65 abc	1.34
B6 × NPK30	16.31	4.69 c	1.57
B6 × NPK60	17.00	12.31 ab	1.22
ANOVA p-value			
Biochar (B)	0.080	0.500	0.896
NPK (N)	0.795	0.723	0.104
B × N	0.852	0.036*	0.112
LSD (0.05), B × N	ns	7.53	ns

Ksat = Saturated Hydraulic Conductivity. Biochar Rates: B0 = 0, B3 = 3 and B6 = 6 t ha^{-1}; NPK rates: NPK0 = 0, NPK30 = 30 and NPK60 = 60 kg N ha^{-1}. Data were Obtained from a Randomized Complete Block Design with three Replicates. * Significant at $P < 0.05$; ns = Not Significant. Means Followed by the Same Letter within the Ksat Column are not Significantly Different According to Fisher's LSD test ($P < 0.05$). Letters are Shown only Where the ANOVA F-test was Significant

CONCLUSION

The results indicated that biochar application rates of 3 and 6 t ha^{-1} did not significantly affect groundnut pod yield, soil loss due to crop harvesting, soil nutrient loss, or post-harvest soil physical properties. However, NPK 15:15:15 fertiliser application significantly affected groundnut pod yield and total soil loss due to crop harvesting. The interaction between biochar and NPK 15:15:15 fertiliser significantly influenced groundnut pod yield, total soil loss due to crop harvesting, and saturated hydraulic conductivity. The highest pod yield was obtained from the combined application of 6 t ha^{-1} maize-straw biochar and 0 kg N ha^{-1} NPK 15:15:15 fertiliser. Overall, the combined application of biochar and NPK 15:15:15 fertiliser produced varying responses depending on the treatment combination.

Further studies on different fertiliser combinations should be undertaken to identify treatment combinations that produce higher groundnut yield with minimal soil loss due to crop harvesting. In addition, biochar produced from other feedstocks should be evaluated, while studies over multiple cropping seasons, different soil types, varying soil-moisture conditions at harvest, and detailed nutrient-loss quantification are recommended.

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