Off-Season Heavy Application of Poultry Manure to Droughty-Acid Soils under Heavily Protective Organic Mulch Later Burnt to Ash Improves Their Productivity

C.J. Onah[1], A.L. Nnadi[2], N.U. Eyibio[1], J.O. Obi[2], A.I. Orah[1], C.F. Amuji[2] and S.E. Obalum[1,3*]

[1] *Department of Soil Science, University of Nigeria, Nsukka, Enugu State, Nigeria*

[2] *Department of Crop Science, University of Nigeria, Nsukka, Enugu State, Nigeria*

[3] *Department of Soil & Environmental Management, Kogi State University, Anyigba, PMB 1008 Anyigba, Kogi State, Nigeria*

*Corresponding Author: *sunday.obalum@unn.edu.ng*

Abstract

The effects of poultry-droppings manure at high rates (up to and > 50 t/ha), termed heavy application, on soil productivity indices of sandy-loam Ultisols were evaluated on okra, under conditions of heavily protecting the amended soil with dry-grass mulch and subsequent burning of same. The plots, prepared in dry season, were saturated weekly by manual irrigation. Two months after manuring, the protective surface mulch was completely burnt to ash. Weekly irrigation continued till the rains stabilized in the next rainy season, 7 months later, okra was sown. The soil was sampled before sowing and after harvest of okra, in-between which gravimetric water content was determined twice some 5-9 h after rain events ≥ 30 mm. Just before cropping, soil organic matter steadily increased while soil bulk density decreased with increasing manure rate. Total porosity, aggregate stability indices and saturated hydraulic conductivity of the soil all showed higher values in 75 t/ha than the rest at both sampling periods. Macro- and microporosity tended to decrease and increase, respectively with manure rate. Soil water content was not affected during okra growth, but treatment enhanced post-cropping microporosity. Treatment optimally enhanced pre-cropping soil pH and available phosphorus including okra vegetative growth at 50 t/ha, and pre-cropping total nitrogen and cation exchange properties including okra fruiting at 25 t/ha. Adding poultry manure at ≥ 25 t/ha to droughty-acid tropical soils with a heap of protective organic mulch to be ashed later can improve their productivity in the following rainy season, most likely due to enhanced pre-cropping soil pH and phosphorus fertility and post-cropping water availability relative to no-manure soil.

Keywords: high manure rate, burnt organic mulch, residual effects, water retention, soil productivity

Introduction

The fertility and productivity of soils are influenced by animal manure, which is an efficient reservoir of nutrients. Poultry-droppings manure (poultry manure) not only supplies nitrogen, phosphorus, potassium and other macronutrients as well as micronutrients (Ibeawuchi et al., 2010), but also improves soil structure and hydraulic properties (Adeyemo et al., 2019; Ogunezi et al., 2019; Obalum et al., 2020). These nutrients are slowly released and stored for longer durations in the soil, resulting in residual effects. Due to the prevailing high temperatures in the tropics, the effects of manures on soil organic matter (SOM) and soil productivity diminish rapidly (Onah et al., 2022). The tropical temperature can cause a massive loss in SOM, thereby reducing the fertility and productivity of the soil. By accelerating SOM loss, high temperatures adversely influence surface soil structure, manifesting in decreased water retention and storage capacity of the soil (Stoof et al., 2015), including reduced infiltration and hence increased runoff and erosion leading to decreased crop productivity (Moody and Ebel, 2014). When tillage exposes the soil to extremely high temperatures, the population of microorganisms involved in soil nutrients recycling and maintenance often goes down (Ogumba et al., 2020), and the soil tends to also lose its fertility. Soils of the humid tropics affected by fire may thus have numerous alterations in their physical, chemical and biological properties.

Burning alters the geomorphological and hydrological processes of tropical soils. However, ash residues from burnt dry leaves can be rich in carbon, potassium, calcium and magnesium (Nwite et al., 2011a, b), and so can have compensatory effects in fire-affected soils. Due to its high contents of nutrient elements which help to raise the pH of soils, ash helps to ameliorate soil acidity (Nwite et al., 2011a, b, 2012; Akinmutimi et al., 2013). Leaf ashes are rich in nitrogen and phosphorus (Nwite et al., 2011a), the two most essential elements for plant growth and often the most limiting nutrients in crop production. Burnt soils contain greater amounts of nitrogen and phosphorus than unburnt ones due to the presence of ash (Caon et al., 2014). Nitrogen-rich organic soils cause increases in plant growth, despite the fact that organic carbon content can be depleted in such soils (Ntia et al., 2017). Jansone et al. (2020) reported a 21% increase in available phosphorus due to the effect of ash; additionally, an increase in nitrogen was observed in the ash-treated potted soils compared to the control.

Poultry manure at 20 t/ha has been proposed to restore the productivity of droughty Ultisols in southeastern Nigeria (Ogunezi et al., 2019; Nnadi et al., 2020). Under long-term fallow, however, 50 and 75 t/ha were found to improve SOM content and mean-weight diameter (MWD) of soil aggregates over the control after one month. At only 75 t/ha SOM, soil bulk density, water retentivity including field-capacity water content were increased after 7 months when treatment residual effects were tested (Onah et al., 2022). Also, 25 t/ha of the manure raised soil pH and available phosphorus levels, but it took 50 t/ha as the optimum rate for its residual effects on these critical indices of fertility of the soils to be evident (Onah et al., 2022). These observations even with the heavy rates of the poultry manure cast doubt on its ability to have residual effects on productivity of the soils. Nwite et al. (2013) posited that rice-husk ash may induce nutrients immobilization in poultry manure, translating into further deceleration of mineralization. This, coupled with the aforestated benefits of ash, suggests that its presence in acid tropical soils could be a way to realize the residual effects of poultry manure in them.

Increases in crop growth and yields in soils amended with poultry manure are often attributed to the increased microbial activities and mineralization (Ntia et al., 2017). This situation is associated with the relatively low-carbon content and hence low C:N ratio of poultry manure, as this manure and ash may not always complement each other, depending on location and/or indices of soil productivity considered. Co-application of poultry manure and rice-husk ash at half their rates in sole use was reported to be similar to sole use of the manure in terms of soil organic carbon and exchangeable potassium, superior in terms of total nitrogen and available phosphorus, but inferior in terms of soil pH and leaf yield of *Telfeiria occidentalis* on sandy-loam Ultisols in southeastern Nigeria (Nwite et al., 2013). By contrast, Agbede and Adekiya (2012) found that such co-application of the manure and ash was superior to such sole use as regards soil chemical properties and the growth and pod yield of okra (*Abelmoschus esculentus*) on sandy-loam Alfisols in southwestern Nigeria. The opined deceleration of nutrients releases from poultry manure in the soil when co-applied with ash (Nwite et al., 2013) and the indication that the two soil amendments can complement each other (Agbede and Adekiya, 2012) may imply lasting effects of the manure in the soil in the presence of ash.

Based on the available data on complementarity of manure and ash applied at conventional rates (Agbede and Adekiya, 2012; Nwite et al., 2013) and the inconsistencies typifying the residual effects of higher rates of the former (Onah et al., 2022), we hypothesize that such heavy addition of the manure and heaping of organic mulch on the soil to decelerate its mineralization and subsequently burning the mulch to enrich the soil with ash could help to stabilize the effects of the manure in the soil in tropical environments. This hypothesis, however, is still without empirical support. The aim of this study, therefore, was to assess the residual effects of heavy addition of poultry manure in the dry season, under conditions of heavily protecting the amended soil with dry-grass mulch to be later burnt to ashes, on productivity of droughty, acid tropical soils (indexed here by selected soil structural/ hydraulic and chemical properties) evaluated by okra vegetative growth and fruit yield during the following rainy growing season.

Materials and Methods

Site Description

The study was carried out at the University of Nigeria (UNN) Teaching & Research Farm, located at Nsukka campus of the University (06° 52'N and 07º 24'E). The Farm is on an elevation of ca. 447 m asl. The study location is in the Derived Savanna agro-ecological zone in southeastern Nigeria. The climate is humid tropical, with two distinct seasons, the rainy season (April to October) and the dry season (November to March). Mean annual rainfall is about 1600 mm, and the rainfall shows a bimodal distribution pattern with peaks usually in July and October. The mean minimum and maximum daily temperatures are 21 and 31 ºC, respectively. Relative humidity can be variable yearly, often in the range of 55-90%.

The soil at the experimental site has been derived from false-bedded sandstones and is deeply weathered and Fe-oxidic (hence coarse-textured and brownish red), with kaolinite as the dominant clay mineral. It belongs to the order Ultisols of the Soil Taxonomy. Mean topsoil contents of sand, silt and clay at the site are 760, 80 and 160 g/kg, respectively, placing the soil in the textural class of Sandy Loam. The soil is mostly low in SOM but with granular surface occasioned by its mineralogy. The soil's coarse texture, low SOM and surface structure together confer to it the attribute of being excessively 'porous' and well-drained and hence droughty (Obalum and Obi, 2014). In its control section, the soil has an ustic moisture regime and an isohyperthermic thermal regime. Soil moisture storage in the core of the rainy season could range between 180 and 240 mm/m (Obalum et al., 2012). The soil is characterized further by low fertility status, due partly to its low content of SOM and partly to its occurrence in a high-rainfall zone vis-à-vis its 'porous' attribute, for which it is highly leached of basic cations as evident in its being strongly acid and of low base saturation (Obalum et al., 2011a). Rainfed, subsistence crop production is widely practiced in the area.

Experimental Design and Treatment Set-Up

The field study involved poultry-droppings manure (poultry manure) application at four incrementally high rates viz. 0, 25, 50 and 75 t/ha, termed heavy application and serving as treatments of the study, designated PM0 (or control), PM_{25}, PM_{50} and PM_{75}, respectively. Treatments were replicated three times in a randomized complete block design (RCBD), giving 12 plots. The site for the study was manually cleared and an area, ca. 6.25 m × 4.50 m, mapped out and demarcated into treatment plots each plot (each, 1 m × 1 m) using earthen bunds, leaving a 0.75-m space between every two adjoining plots in a block and every two blocks. The manure, sourced from the battery cage system of the Poultry Unit of Animal Science Section of the UNN Teaching & Research Farm, was cured by air-drying for four weeks, crushed, sieved and thoroughly mixed to ensure homogeneity before application.

The poultry manure had a pH of 9.5 and organic matter content of 562 g/kg, and was applied at the different rates to the plots meant to receive them. Thereafter, the plots were tilled by hoeing to about 20-cm depth, incorporating the amendments into the soil and making flatbeds to ensure uniform water distribution during irrigation and rainfall. Two weeks after manuring, the plots were individually covered with a thick translucent polythene material about the size of the plots. This was followed by surface mulching using dry-grass material at a uniformly high rate of 100 t/ha (heaping of 10 kg of dry grass mulch per plot) to minimize mineralization of the added manure and also prevent water loss to evaporation.

The experimental plots were set up in early December 2019, when they were saturated with artificially applied water twice a week. Two months after adding manure, the mulches were burnt to ashes while the routine saturation continued till 5 months after treatment (MAT), corresponding to early May 2020, when rains had fully returned. Thereafter, natural rains sustained the plots till 7 MAT when the agronomic trial was initiated. Both the routine saturation and the natural rain helped the integration of the ash with the soil. At this 7 MAT, okra was grown to evaluate treatment effects in the presence of ash obtained from the biomass combustion. After manual tillage to ca. 20-cm depth, two seeds of Clemson Spineless variety of okra were sown per 2-cm hole at a plant spacing of 50 × 30 cm, giving six plant stands per plot.

Agronomic Data Collection

Crop data collection was done at one-week intervals starting from 5 weeks after sowing (WAS) of okra. Data were collected on the two middle plant stands in a plot, as these two middle plants were the only ones among the six stands experiencing the least border effects, and so represented treatment effects on okra growth better than the remaining four. Agronomic data collected were vegetative growth parameters specifically plant height, number of leaves per plant and leaf area, as well as number of fruits per plant and fresh fruit weight per plot. Plant height was measured starting from the soil level and progressing to the youngest outgrowth at the tip. Number of leaves per plant was obtained by counting/recording the number of leaves including the leaf bud for cases of fallen leaves. After measuring the length (L) and the width (W) of the broadest leaves, leaf area was calculated as L × W × 0.45 (Ogoke et al., 2003).

Fruit (pod) harvest was done over a two-week period, starting from 8 WAS till end of 9 WAS. Cumulative number of fruits plucked per plant over the course of each week was recorded, and the mean for the two middle plant stands taken to obtain number of fruits per plant. The corresponding cumulative fresh fruit weight per plant was also recorded, and converted to fruit weight per plot by extrapolating the values for the two middle plant stands to the supposed values for the six stands in a plot. This fresh fruit weight per plot was averaged for 8 and 9 WAS and, again, extrapolated to its hectarage equivalent, designated mean fresh pod yield, representing treatments' weekly average fresh pod yields of okra during its fruiting stage.

Soil Data Collection and Analysis

The soil was sampled at the beginning of July 2020, corresponding to 7 MAT. Undisturbed and disturbed soil samples were taken from the topsoil (0-10 cm) to assess treatment effects in the soil before cropping. The undisturbed soil samples, collected using 100-cm^3 soil core samplers, were used to assess soil hydraulic properties, while the disturbed ones were used to assess soil aggregate stability and chemical properties. Gravimetric water content of the topsoil was determined at two different occasions during 7-8 MAT. These two occasions were synchronized with rain events ≥ 30 mm, an amount deemed to sufficiently wet the soil. The sampling was done some 8.5 and 5.4 h after rainfall in the 1st and 2nd occasions, respectively.

Soil sampling involving undisturbed and disturbed soils was repeated at the final harvest of okra fruits marking the end of the experiment about 9 MAT, corresponding to 10 WAS. Physical analyses were performed on both the pre- and post-cropping soil samples, whereas chemical analyses were performed on only the pre-cropping ones. The disturbed soil samples were air-dried to constant weight at the prevailing temperature and manually dry-sieved to separate them into 4.75-2.00 and <-2.00 mm aggregate size fractions for the determination of aggregate stability and chemical properties, respectively.

The 4.75-2.00 mm soil aggregates were wet-sieved into water-stable and unstable size fractions using the wet-sieving machine (Kemper and Rosenau, 1986). In this method, 25 g of these soil aggregates was placed on top of four sieves (2.00, 1.00, 0.50 and 0.25 mm) nested in the order listed and hanging inside the three-quatre water-filled machine. It was slightly lowered to pre-soak in the water for 5 min., after which the nested set of sieves was vertically oscillated at 4-cm amplitude for 35 times in 1 min. The resistant, water-stable aggregates retained on the >-0.50-mm sieves were oven-dried at 105 °C for 24 h and weighed. Then, they were pooled, dispersed with 0.1N NaOH and wash to obtain the mass of sand > 0.50 mm.

Two aggregate stability indices, mean-weight diameter (MWD) of soil aggregates and percent water-stable aggregates corrected for sand (%WSAcfs), were derived by Obalum et al. (2011b):

i. $MWD = \sum_{i=1}^{n}(X_i W_i)$ and (ii) $\%WSA_{cfs} = (\frac{WSAs - M_{s>0.50}}{M_i - M_{s>0.50}}) \times 100$;

where X_i is the mean diameter of a given size fraction (mm), W_i is the proportion by weight of aggregates in the size fraction (g g^{-1}), n is the total number of aggregate size fractions including the water-stable aggregates (WSAs) retained on the four sieves and the water-unstable ones passing through the last sieve (totaling 5), *WSAs* is the mass of these WSAs (g), M_i is the initial mass of aggregates (g), and $M_s > 0.50$ is the mass of sand > 0.50 mm (g).

The hydraulic properties determined on the undisturbed soil samples (soil cores) were soil bulk density, total porosity, macro- and microporosity, and saturated hydraulic conductivity (K_s). First, the steady state volume of water flowing through the soil was measured by the constant head permeameter method (Klute and Dirksen, 1986), after which K_s was calculated using the transposed Darcy's equation for vertical flows of liquids. Then, pore size distribution was determined by re-saturating and weighing the undisturbed samples before subjecting them to 60-cm water-tension for 24 h; macroporosity was computed as the volume ratio of water drained out of the soil core (taken as hypothetically occupying the macropores) and the volume of its sampler (Obalum et al., 2011b). To determine the soil bulk density, the soil cores were oven-dried at 105ºC for 24 h (Grossman and Reinsch, 2002). Standard laboratory procedures were used to determine soil pH-H_2O; soil contents of SOM, total nitrogen and Bray-2 available phosphorus; as well as 1N NH_4OAc-pH7 apparent cation exchange capacity (CEC) including exchangeable calcium and magnesium (Sparks, 1996).

Data were analyzed using the software *R*. A one-way analysis of variance was performed on the soil and agronomic data, following the procedure for RCBD experiments. To compensate for the relatively small number of observations ($n = 12$), the analysis was done using the Kruskal Wallis test. This test accepted differences to be significant at the 5% probability level ($p < 0.05$). Bonferonni test was used to distinguish between means. In presenting the data, different letters of the alphabet were used to denote significantly different means.

Results and Discussion

Effects of Treatments on Soil Organic Matter and Soil Structural and Hydraulic Properties

The effects of heavy application of poultry manure on the concentration of soil organic matter (SOM) in the drought-prone soil are presented in Table 1, for the sampling done 7 MAT, corresponding to five months after burning of the heavily protective dry-grass mulch to ash and the time just before sowing of okra. The data show that poultry manure has to applied at the rate of 50 t/ha (PM_{50}) for its residual effect on SOM to be evident in the soil, but that the application rate 75 t/ha (PM_{75}) would produce superior residual effect on SOM.

Table 1 also shows the effects of treatment on some structural and hydraulic properties of the drought-prone soil 7 MAT, just before okra sowing, and at the end of the study about 9 MAT, corresponding to 10 WAS. At 7 MAT, both MWD of soil aggregates and %WSA$_{cfs}$ of the soil showed higher values in PM$_{75}$ than lower application rates of the poultry manure. At 9 MAT, however, MWD was unaffected by treatment while %WSAcfs was higher in PM$_{75}$/PM$_{50}$ than PM$_{25}$/control. These two indices of soil aggregate stability showed higher values at 7 than 9 MAT. The expected decreases in aggregate stability with progressive soil wetness as the rainy season advances would explain this observation. Also, though the tillage just before sampling and okra sowing 7 MAT was not expected to affect aggregate stability of this soil investigated (Obalum and Obi, 2010), the present data show the possibility of such. This is considering biomass ash-induced improvement in aggregate stability of degraded soils (Huang et al., 2017), as well as the short interval (just two months) between tillage and sampling. With enhanced SOM status and slow mineralization rate, tillage effects on soil aggregate stability could even persist for more than two years (Obalum et al., 2019). The present results may, therefore, be attributed to the heavy application of poultry manure, its mulch-provided initial protection from fast mineralization in the soil, and the biomass combustion of the organic mulch done later.

Treatment affected soil bulk density only at 7 MAT, with higher values in the control compared to the rest, differences of which reflect manure-induced varying SOM levels. When assessed within the season of application, poultry manure at 10 t/ha can increase SOM and decrease bulk density of the soil of this study (Obi and Ebo, 1995; Obalum et al., 2020), but conventional tillage may not (Obalum and Obi, 2010; Obalum et al., 2020). The decreases in bulk density even in PM$_{25}$ (the lowest rate) at 7 but not 9 MAT suggest that application rates higher than 25 t/ha may not be needed for poultry manure effects to linger in these droughty soils, but that such residual effects can be obliterated once the soil is tilled to tamper with the ash-induced aggregation (Huang et al., 2017) and expose SOM (which relates inversely with bulk density).

TABLE 1

Soil organic matter concentration and some structural and hydraulic properties of the soil before sowing of okra seven months after treatment (corresponding to five months after burning of the heavily protective grass mulch) and after okra harvest nine months after treatment

Treatment of PM rate	SOM (g/kg)	MWD (mm)	% WSA$_{cfs}$	BD (g/cm^3)	% Total porosity	% Macro-porosity	% Micro-porosity	K_s (cm/h)
	7 months after treatment (MAT)							
PM$_0$ (0 t/ha)	15.60 ^{a}	0.61 ^{a}	20.24 ^{a}	1.54 ^{b}	48.80	4.75	44.05	7.66 ^{a}
PM$_{25}$ (25 t/ha)	20.50 ^{ab}	0.62 ^{a}	19.55 ^{a}	1.36 ^{a}	46.15	6.58	39.57	9.45 ^{a}
PM$_{50}$ (50 t/ha)	27.10 ^{b}	0.61 ^{a}	17.93 ^{a}	1.35 ^{a}	46.50	4.32	42.17	11.92 ^{a}
PM$_{75}$ (75 t/ha)	37.10 ^{c}	1.18 ^{b}	39.70 ^{b}	1.21 ^{a}	50.75	4.04	46.71	20.38 ^{b}
Sig. Level	*	*	*	*	ns	ns	ns	*
	9 months after treatment (MAT)							
PM$_0$ (0 t/ha)	-	0.48	8.32 ^{a}	1.47	40.83 ^{a}	5.03	35.80 ^{a}	3.45 ^{a}
PM$_{25}$ (25 t/ha)	-	0.50	6.98 ^{a}	1.52	45.98 ^{ab}	3.65	42.32 ^{b}	5.78 ^{b}
PM$_{50}$ (50 t/ha)	-	0.56	11.03 ^{b}	1.51	47.23 ^{b}	5.87	41.36 ^{b}	4.90 ^{b}
PM$_{75}$ (75 t/ha)	-	0.61	12.60 ^{b}	1.43	48.93 ^{bc}	5.20	43.73 ^{b}	10.54 ^{c}
Sig. Level		ns	*	ns	*	ns	*	*

PM - poultry manure, SOM - soil organic matter, BD - bulk density, TP - total porosity, MWD - mean-weight diameter of soil aggregates, WSA$_{cfs}$ - water-stable aggregate corrected for sand, K_s - saturated hydraulic conductivity, ns - not significant

By contrast, treatment affected soil total and microporosity only at 9 MAT, when values were generally higher in manure-amended than the control plots. These results suggest that the labile SOM species are the ones mostly lost following soil exposure, thus weakening their influence on bulk density, and that their loss creates an enabling environment for the microaggregate-protected recalcitrant SOM to promote microaggregation and water retentivity of droughty soils. Soil hydraulic conductivity (K_s) differed in a pattern indicating the superiority of PM_{75} over the rest with a tendency of increases with manure rate at both sampling periods. Because ash could reduce K_s due to pore-clogging (Moragues-Saitua et al., 2017), its increases with manure rate may be due to the associated SOM (Oguike et al., 2022), and point at the potential of heavy addition of manure for countering ash's negative effects on soil hydraulic properties.

Treatment had no effects on the gravimetric soil water content determined between 7 and 9 MAT; the values only tended to increase with manure rate from 0.03 to 0.05 (1st sampling) and from 0.05 to 0.07 (2nd sampling). These no effects was also found for microporosity 7 MAT are despite the treatment-induced differences in SOM (Obalum and Obi, 2013), thus pointing at the dependence of water retentivity of droughty tropical soils not on the status of SOM itself, but on its underlying influence on their microporosity. Similar to this observation, differences in SOM concentration and associated water repellency were found not to influence water retention at field capacity (Onah et al., 2022; Sheppard et al., 2022).

Effects of Treatments on Key Soil Fertility Indices

Table 2 shows some chemical properties of the soil 7 MAT, corresponding to five months after burning of the heavily protective dry-grass mulch to ash, before sowing of okra. Treatment affected soil pH which was lower in PM_0 (control) compared to the rest involving actual addition of the poultry-droppings manure. This observation aligns with the widely known effectiveness of poultry manure in raising soil pH (Opala et al., 2012; Igwe et al., 2013; Duruigbo et al., 2017; Ndzeshala et al., 2023), but suggests that application rates higher than 25 t/ha may not be needed for residual effects in this regard in these droughty-acid soils. The soil pH was near neutral in the control while alkaline in the manured treatments. Ash produces liming effect in the soil (Nwite et al., 2011a, b, 2012; Akinmutimi et al., 2013). The near-neutral values in these acid soils imply that the acidity-ameliorating effect of the ash from burning of the dry-grass mulch done seven months earlier persisted in the soil. Such a conversion of organic residue to ash long before the cropping season could, therefore, be a promising soil management practice for ameliorating the acidity problem of the soils.

Soil total nitrogen tended to increase with poultry-droppings manure rate 7 MAT (Table 2). The values were, however, slightly above the range of 0.42-0.90 g/kg found by some

TABLE 2

Some chemical properties of the soil before planting of okra seven months after treatment (corresponding to five months after burning of the heavily protective grass mulch)

Treatment of PM rate	Soil pH	Total N (g/kg)	Available P (mg/kg)	CEC	Ca^{2+}	Mg^{2+}
					cmol/kg	
PM_0 (0 t/ha)	6.9 ^{a}	0.90	31.37 ^{a}	5.20 ^{a}	1.13 ^{a}	0.60 ^{a}
PM_{25} (25 t/ha)	7.7 ^{bc}	1.00	103.68 ^{b}	5.20 ^{a}	2.60 ^{ab}	1.13 ^{ab}
PM_{50} (50 t/ha)	8.0 ^{c}	1.30	145.39 ^{b}	8.27 ^{b}	3.87 ^{b}	1.67 ^{b}
PM_{75} (75 t/ha)	7.9 ^{c}	1.30	116.65 ^{b}	7.60 ^{b}	6.53 ^{c}	1.80 ^{bc}
Sig. Level	*	ns	*	*	*	*

PM - poultry manure, CEC - cation exchange capacity, ns - not significant studies in the same season of adding manure or biochar to the sandy-loam Ultisols under investigation (Asadu and Igboka, 2014; Ebido et al., 2021; Ndzeshala et al., 2023), probably because of the biomass burning done after manuring (Caon et al., 2014). The lack of residual effect of the manure, despite its heavy rates, on total nitrogen may be attributed to high losses of soil nitrogen in the core tropical climates relative to sub-tropical climates as well as to the inherently low fertility status of the soil under investigation (Shahzad et al., 2015).

Treatment had a residual effect on available phosphorus content of the soil, being higher in the manured plots than the control (Table 2). The data show that application rates higher than 25 t/ha may not be needed for treatment residual effects on available phosphorus to be evident in these soils. Poultry manure promotes phosphorus availability by increasing the population of phosphorus-solubilizing microorganisms in the soil (Kumar and Nair, 2011; Yu et al., 2013; Yang et al., 2019; Jansone et al., 2020). The values of available phosphorus in the control plots exceed its typical values in the same season of adding manure or biochar to the sandy-loam Ultisols studied (Asadu and Igboka, 2014; Okebalama et al., 2020; Ndzeshala et al., 2023). Considering the peculiar problem of phosphorus fixation in acid tropical soils, and the potential of poultry manure even at low rates of 10-20 t/ha to give three- to five-fold increases in its availability in these soils (Ogunezi et al., 2019; Obalum et al., 2020; Umeugokwe et al., 2021; Ndzeshala et al., 2023), the ‘high’ available phosphorus in the control plots more than the average of four-fold increases in the manure-amended plots is an important finding of this study. This observation is attributed to the biomass burning and the associated presence of ash.

The residual effects of treatment on the cation exchange capacity (CEC), exchangeable calcium (Ca^{2+}) and exchangeable magnesium (Mg^{2+}) of the soil were such that their values generally increased with application rate of the manure. Treatment PM_{75} was thus the best. The results reflect the influence of SOM on CEC of the soils (Obalum et al., 2013). Notably, the values of CEC, the index of soil fertility which apparently integrates all the basic and acidic cations into one number, may be adjudged low when related to its threshold value often taken to be that of kaolinite (15 cmol/kg) for kaolinitic tropical soils (Obalum et al., 2013). The true situation, however, was that the treatment-induced high soil pH (6.9-8.0) in this kaolinitic soil permitted little or no proton displacement during the required leaching of soil sample in the CEC determination, giving virtually no room for the phenomenon of low soil pH leading to elevated CEC values. (Aprile and Lorandi, 2012; Obalum et al., 2013).

With the understanding that the high soil pH in the present study would explain the observed low values of the apparent CEC, the treatment of heavy rates of poultry manure and the subsequent biomass burning cannot be said to have adversely affected the cation exchange behaviour of the studied soil. This supposition draws credence from relating the values attained in this study for Ca^{2+} and Mg^{2+} to the commonly reported values in the same season of adding manure or biochar to the sandy-loam Ultisols under investigation, including ranges of values of 0.50-7.00 and 0.30-3.00 cmol/kg, respectively (Asadu and Igboka, 2014; Ogunezi et al., 2019; Okebalama et al., 2020; Ndzeshala et al., 2023).

Residual Effects of Treatment on Okra Plant Productivity

Table 3 shows the effect of poultry-droppings manure rates on plant height, number of leaves and leaf area of okra during 5-9 WAS. Okra plants grew taller with increasing manure rate. This treatment effect on plant height was significant at all the sampling stages of okra growth, except at 5 WAS. Also, the okra plant progressively grew taller from 5 to 8 WAS, after which the rate of growth slowed down between 8 and 9 WAS. The slowing down of growth at this later growth stage of the crop may be attributed to yield effect. Number of leaves per plant exhibited a similar trend of increases in growth with increasing manure rate, though the differences were significant only at 7 and 9 WAS. Treatment consistently affected leaf area, being broader as manure rate increased. This leaf area also progressively became broader from 5 to 8 WAS, after which it generally became smaller at 9 WAS, attributed again to yield effect. Interpreting the effects of the four treatments in the light of all three vegetative growth indices considered together across the growth stages, treatment PM_{50} would appear to be the best.

Treatment residual effects on fruiting indices of the okra plant at 8 and 9 WAS are shown (Table 4). Number of fruits produced per the okra plant was lower in the control plots compared to the manure-amended plots at 9 WAS. Fresh fruit weight per plot exhibited a similar pattern of differences among treatments at 8 and 9 WAS. These results may be attributed to poultry manure solubilization to improve soil nutrient status. The observed increases in growth and productivity of okra with increasing manure rate align with the responses of okra to different manure combinations, as reported from Coimbatore, India (Premsekhar and Rajashree, 2009) and from Moyamba District, Southern Sierra Leone (Nyande et al., 2021).

Treatment PM_{50} appeared to be the best for enhancing the vegetative growth of okra. However, the trio of PM_{25}, PM_{50} and PM_{75} produced similar effects for both number of fruits per plant and fresh fruit weight per plot (and hence the computed mean fresh pod yield), thus supporting the recommendation of PM_{25} (25 t/ha) as the optimum rate for realizing the residual agronomic effects of poultry manure in droughty tropical soils. Application of poultry manure at 15 t/ha was found to be superior to lower application rates in terms of residual effects on okra growth and productivity at Makurdi, North-Central Nigeria (Onwu et al., 2018). Differences in environmental and experimental conditions make our recommendation and that of Onwu et al. (2018) difficult to compare. For instance, our lowest non-control manure rate was the proposed 25 t/ha, whereas Onwu et al.'s

TABLE 3

Effect of poultry manure rates and ash on plant height, number of leaves and leaf area of okra plant during 1-5 weeks after sowing (WAS)

Treatment of PM rate	5 WAS			6 WAS			7 WAS			8 WAS			9 WAS		
	Plant height (cm)	No. of leaves/ plant	Leaf area (cm^2)	Plant height (cm)	No. of leaves/ plant	Leaf area (cm^2)	Plant height (cm)	No. of leaves/ plant	Leaf area (cm^2)	Plant height (cm)	No. of leaves/ plant	Leaf area (cm^2)	Plant height (cm)	No. of leaves/ plant	Leaf area (cm^2)
PM_0 (0 t/ha)	2.73	3	1.59 ^{a}	4.05 a	4	4.10 ^{a}	6.08 ^{a}	3 ^{a}	10.3 ^{a}	7.33 ^{a}	3	13.4 ^{a}	7.50 a	3 a	19.0 a
PM_{25} (25 t/ha)	3.70	4	4.06 ^{a}	6.83 a	5	17.72 ^{b}	11.50 ^{b}	5 ^{b}	46.9 ^{b}	17.08 ^{b}	5	61.0 ^{b}	20.33 b	7 b	33.0 b
PM_{50} (50 t/ha)	4.38	4	5.70 ^{b}	8.42 b	6	24.44 ^{b}	15.25 ^{c}	6 ^{bc}	68.5 ^{b}	24.92 ^{b}	4	71.5 ^{c}	24.50 b	6 b	67.0 b
PM_{75} (75 t/ha)	4.45	4	6.37 ^{b}	9.00 b	5	27.93 ^{b}	15.50 ^{c}	7 ^{c}	97.2 ^{b}	25.58 ^{b}	6	87.0 ^{c}	28.42 b	7 b	47.0 b
Sig. Level	ns	ns	*	*	ns	*	*	*	*	*	ns	*	*	*	*

PM - poultry manure

TABLE 4

Treatment effects on number of fruits of okra and fresh fruit weight and as assessed during four-five weeks after sowing (WAS)

Treatment	8 WAS		9 WAS		Mean fresh pod yield (t/ha)
	No. of fruits/ plant	Fresh fruit weight (g/plot)	No. of fruits/ plant	Fresh fruit weight (g/plot)	
PM_0 (0 t/ha)	1	18.90 ^{a}	1 ^{a}	13.74 ^{a}	0.15
PM_{25} (25 t/ha)	2	54.27 ^{b}	3 ^{b}	68.16 ^{b}	0.60
PM_{50} (50 t/ha)	3	60.90 ^{b}	3 ^{b}	66.27 ^{b}	0.63
PM_{75} (75 t/ha)	3	69.42 ^{b}	4 ^{b}	67.44 ^{b}	0.69
Sig. Level	ns	*	*	*	

PM - poultry manure, ns - not significant

(2018) highest rate was the 15 t/ha found to give the best results.

In this study, the soil properties also showing optimal residual effects of poultry manure to be at 25 t/ha are soil pH and available phosphorus as determined 7 MAT just before okra sowing, as well as microporosity as determined 9 MAT corresponding to when the okra plants were fruiting. Optimal residual agronomic effects of the manure being at 25 t/ha could, therefore, be linked to its positive effects at this application rate on pre-sowing soil pH and available phosphorus as well as on water availability to the okra plant during fruiting. The acidic and droughty nature of the soil lends credence to this supposition.

Conclusion/Recommendation

This study was conducted to assess the effects of heavy addition of poultry-droppings manure (rates in excess of 25 t/ha) on the productivity of droughty tropical soils after burning to ashes of heavily protective grass-residue surface mulch. The data attained demonstrate that such heavy rates of the poultry manure improved some physicochemical properties and productivity indices of the soil as well as okra growth and yield, with the degree of improvement increasing with application rate of the manure in most of the cases. Poultry-droppings manure at ≥ 75 t/ha may be needed before converting heavily protective grass-residue surface mulch to ashes in order to realize the residual effects on soil organic matter (SOM) and most structural/hydraulic properties of droughty tropical soils. The rates 50 and 25 t/ha may be needed for the same purpose when considering the fertility of the soils, depending on the soil fertility index of interest. Overall, however, 25 t/ha would be the rate to adopt if the ultimate aim is to optimally increase the agronomic productivity of the soils. This is postulated to be due to this rate also producing optimal residual effects on soil pH and available phosphorus before cropping and on water retentivity and availability to the crop during its critical growth stages.

Acknowledgement

The authors wish to thank their colleague in the Department of Soil Science of the University of Nigeria Nsukka, Mr. David C. Enemo who assisted with the data analysis by applying on the data the appropriate test for limited number of observations using the *R* software.

References

Adeyemo A. J., Akingbola O. O. and Ojeniyi S. O. (2019). Effects of poultry manure on soil infiltration, organic matter contents and maize performance on two contrasting degraded Alfisols in south-western Nigeria. *International Journal of Recycling of*

Organic Waste in Agriculture, **8**:73-80. https://doi.org/10.1007/s40093-019-0273-7

Agbede, T. M. and Adekiya, A. O. (2012). Effect of Wood Ash, Poultry Manure and NPK Fertilizer on Soil and Leaf Nutrient Composition, Growth and Yield of Okra (Abelmoschus esculentus). *Emirate Journal Food Agriculture*, **24 (4)**:314-321. http://eprints.lmu.edu.ng/916/1/my%20paper%20EM%20Wood%20Ash.pdf

Akinmutimi, A. L., Osodeke, V. E. and Ano, A. O. (2013). Yield and nutrient composition of sweet potato (*Ipomea batatas* L Lam) as influenced by application of three different sources of ash. *Greener Journal of Agricultural Sciences*, **3(2)**:101-109. https://doi.org/10.15580/GJAS.2013.2.112212281

Aprile, F. and Lorandi, R. (2012). Evaluation of cation exchange capacity (CEC) in tropical soils using four different analytical methods. *Journal of Agricultural Science*, **4(6)**:278-289. DOI: 10.5539/jas.v4n6p278

Asadu, C. L. A. and Igboka, C. R. (2014). Effects of animal faeces and their extracts on maize yield in an Ultisol of Eastern Nigeria. *Journal of Agricultural Sustainability*, **5(1)**: 1-13

Caon, L., Vallejo, V. R., Ritsema, C. J. and Geissen, V. (2014). Effects of wildfire on soil nutrients in Mediterranean ecosystems. *Earth-Science Reviews*, **139**:47-58. https://doi.org/10.1016/j.earscirev.2014.09.001

Duruigbo, C., Obiefuna, J. and Onweremadu, E. (2017). Effect of poultry manure rates on soil acidity in an Ultisol. *International Journal of Soil Science*, **2**:154-158. https://doi.org/10.3923/ijss.2007.154.158

Ebido, N. E., Edeh, I. G., Unagwu, B. O., Nnadi, A. L., Ozongwu, O. V., Obalum, S. E. and Igwe, C. A. (2021). Rice-husk biochar effects on organic carbon, aggregate stability and nitrogen-fertility of coarse-textured Ultisols evaluated using Celosia argentea growth. SAINS TANAH - *Journal of Soil Science and Agroclimatology*, **18(2)**: 177-187. https://dx.doi.org/10.20961/stjssa.v18i2.56330

Grossman, R. and Reinsch, T. (2002). *Bulk density and linear extensibility*. SSSA Book Series. https://doi.org/10.2136/sssabookser5.4.c9

Huang, R., Gao, M. and Liu, J. (2017). Effects of soil conditioners on aggregate stability in a clay loam soil: A comparison study of biomass ash with other four conditioners. *Communications in Soil Science and Plant Analysi*, **48 (19)**: 2294-2313, DOI: 10.1080/00103624.2017.1411506

Igwe, C. A., Nwite, J. C., Agharanya, K. U., Watanabe, Y., Obalum, S. E., Okebalama, C. B. and Wakatsuki T. (2013). Aggregate-associated soil organic carbon and total nitrogen following amendment of puddled and sawah-managed rice soils in southeastern Nigeria. *Archives of Agronomy and Soil Science*, **59(6)**: 859-874. https://doi.org/10.1080/03650340.2012.684877

Jansone, B., Samariks, V., Okmanis, M., Klavina, D. and Lazdina, D. (2020). Effect of high concentration of wood ash on soil properties and development of young Norway spruce (*Picea abies* (L.) Karst) and scots pine (*Pinus sylvestris* L.). *Sustainability*, **12**:79-94. https://doi.org/3390/su12229479

Klute, A. and Dirksen, C. (1986). Hydraulic conductivity and diffusivity. In: Klute A. (ed.) Methods of Soil Analysis Part 1 (pp. 694-783), Madison WI, *American Society of Agronomy*, 271. https://doi.org/10.2136/sssabookser5.1.2ed.c28

Kumar, B. M. and Nair, P. R. (2011). Carbon sequestration potential of agroforestry systems: Opportunities and challenges. *Advances in Agroforestry*, **8**: 10-16. https://doi.org/10.1007/978-94-007-1630-8

Moody, J. A. and Ebel, B. A (2014). Infiltration and Runoff Generation Processes in Fire Affected Soils. *Hydrological Process*, **28**:3432-2402. https: // doi. org /10.1002/hyp.9857

Moragues-Saitua, L. Arias-González, A. and Gartzia-Bengoetxea N. (2017). Effects of biochar and wood ash on soil hydraulic properties: A field experiment involving contrasting temperate soils. *Geoderma*, **305**: 144-152. https://doi.org/10.1016/j.

geoderma.2017.05.041

Ndzeshala, S. D., Obalum, S. E. and Igwe, C. A. (2023). Some utilisation options for cattle dung as soil amendment and their effects in coarse-textured Ultisols and maize growth. *International Journal of Recycling of Organic Waste in Agriculture*, **12 (1)**:123-139. DOI: 10.30486/ijrowa.2022.1934239.1284

Nnadi, A. L., Nnanna, P. I., Onyia, V. N., Obalum, S. E. and Igwe, C. A. (2020). Growth and yield responses of high-density coverage sweet potato to liming and fertilizer combinations for sandy-loam Ultisols at Nsukka, southeastern Nigeria. In: Climate-Smart Soil Management, Soil Health/ quality and Land Management Synergies for Sustainable Ecosystem Services (pp. 263-269), *Proceedings of the 44th Conference of Soil Science Society of Nigeria*

Ntia, J. D., Shiyam, J. O. and Etim, E. D. (2017). Effect of lime and rate of application of poultry manure on the growth and yield of okra (*Abelmoschus esculentus* (L) Moench) in the Cross River Rain Forest Area, Nigeria. *Asian Journal of Soil Science and Plant Nutrition*, 1(2):1-6. https://doi.org/10.9734/AJSSPN/2017/35184

Nwite, J. C., Essien, B. A., Anaele, M. U., Obalum, S. E., Keke, C. I. and Igwe, C. A. (2012). Supplementary use of poultry droppings and rice-husk waste as organic amendments in southeastern Nigeria. 1. soil chemical properties and maize yield. *Libyan Agricultural Research Centre Journal International*, **3(2)**: 90-97

Nwite, J. C., Igwe, C. A. and Obalum, S. E. (2011a). The contributions of different ash sources to the improvement in properties of a degraded Ultisol and maize production in southeastern Nigeria. *American-Eurasian Journal of Sustainable Agriculture*, **5(1)**: 34-41

Nwite, J. C., Keke, C. I., Obalum, S. E., Essien, J. B., Anaele, M. U. and Igwe, C. A. (2013). Organo-mineral amendment options for enhancing soil fertility and nutrient composition and yield of fluted pumpkin. *International Journal of Vegetable Science*, **18(2)**:188-199. https://doi.org/10.1080/19315260.2012.705233

Nwite, J. C., Obalum, S. E., Igwe, C. A. and Wakatsuki, T. (2011b). Properties and potential of selected ash sources for improving soil condition and sawah rice yields in a degraded inland valley in southeastern Nigeria. *World Journal of Agricultural Sciences*, **7(3)**: 304-310

Nyande, A., George, M. S., Kassoh F. A. and Bah, A. M. (2021). Growth and yield response of okra (*Ablemochus esculentus*) to varying rates of different sources of organic soil amendments at Njala, Moyamba District, Southern Sierra Leone. *African Journal of Agricultural Research*, **17 (8)**: 1144-1154. DOI: 10.5897/AJAR2021.15656

Obalum, S. E. and Obi, M. E. (2010). Physical properties of a sandy loam Ultisol as affected by tillage-mulch management practices and cropping systems. *Soil and Tillage Research*, **108(1-2)**: 30-36. https://doi.org/10.1016/j.still.2010.03.009

Obalum, S. E. and Obi, M. E. (2013). Moisture characteristics and their point pedotransfer functions for coarse-textured tropical soils differing in structural degradation status. *Hydrological Processes*, **27(19)**: 2731-2735. https://doi.org/10.1002/hyp.9398

Obalum, S. E. and Obi, M. E. (2014). Measured versus estimated total porosity along structure-stability gradients of coarse-textured tropical soils with low-activity clay,. *Environmental Earth Sciences*, **72 (6)**: 1953-1963. DOI: 10.1007/s12665-014-3102-3

Obalum, S. E., Igwe, C. A. and Obi, M. E. (2012). Soil moisture dynamics under rainfed sorghum and soybean on contrasting tillage-mulch seedbeds in a mineral sandy loam at derived savanna of south-eastern Nigeria. *Archives of Agronomy and Soil Science*, **58(11)**: 1205-1227. https://doi.org/10.1080/03650340.2011.575065

Obalum, S. E., Nwite, J. C., Oppong, J., Igwe, C. A. and Wakatsuki, T. (2011b). Comparative topsoil characterization of Sawah rice fields in selected inland valleys around Bida, North-Central Nigeria:

Textural, structural and hydrophysical properties. *Paddy and Water Environment*, **9(3)**: 291-299. https://doi.org/10.1007/s10333-010-0233-3

Obalum, S. E., Ogumba, P. O. and Uzoh, I. M. (2020). Influence of tillage-seedbed and manure-NPK-micronutrient management options on selected soil properties of sandy-loam Ultisols evaluated using sweet potato. *Nigerian Journal of Soil Science*, **30(3)**: 117-125

Obalum, S. E., Okpara, I. M., Obi, M. E. and Wakatsuki, T. (2011a). Short-term effects of tillage-mulch practices under sorghum and soybean on organic carbon and eutrophic status of a degraded Ultisol in southeastern Nigeria. *Tropical and Subtropical Agroecosystems*, **14(2)**:393-403

Obalum, S. E., Uteau-Puschmann, D. and Peth, S. (2019). Reduced tillage and compost effects on soil aggregate stability of a silt-loam Luvisol using different aggregate stability tests. *Soil and Tillage Research*, **189 (1-2)**: 217-228. https://doi.org/10.1016/j.still.2019.02.002

Obalum, S. E., Watanabe, Y., Igwe, C. A., Obi, M. E. and Wakatsuki, T. (2013). Improving on the prediction of cation exchange capacity for highly weathered and structurally contrasting tropical soils from their fine-earth fractions. *Communications in Soil Science and Plant Analysis*, **44 (12)**: 1831-1848. https://doi.org/10.1080/00103624.2013.790401

Obi, M. E. and Ebo, P. O. (1995). The effects of different application rates of organic and inorganic fertilizers on soil physical properties and maize production on a severally degraded Ultisol in southern Nigeria. *Bioresource Technology*, **51**: Il7-123

Ogoke, I., Egesi, C. and Obiefuna, J. (2003). A Review of Some Non-destructive Linear Measurement Procedures for Leaf Area Determination in Crops. *International Journal of Agricultural Rural Development*, **4**:74-80. https://doi.org/10.4314/ijard.v4i1.2548

Oguike, P. C., Onwuka, B. M. and Obalum, S. E. (2022). Soil organic matter control of water transmission properties of coarse-textured soils under contrasting land-use types in tropical rainforest. *International Journal of Hydrology Science and Technology*, In Press. DOI: 10.1504/IJHST.2022.10046853

Ogumba, P. O., Obalum, S. E. and Uzoh, I. M. (2020). Soil biochemical and microbial properties of sandy loam Ultisols as affected by some tillage and nutrient management practices. *International Journal of Agriculture and Rural Development*, **23(2)**:5184-5195

Ogunezi, K. C., Okebalama, C. B. and Obalum, S. E. (2019). Optimum poultry droppings rate for coarse-loamy Ultisols based on soil macro-aggregation and fertility indices and evaluation using cucumber (*Cucumis sativus*). Presented under Understanding Nigerian Soils for Sustainable Food & Nutrition Security and Healthy Environment, the 43rd Conference of Soil Science Society of Nigeria on (SSSN), 15-19 July 2019, University of Agriculture, Makurdi, Benue State, Nigeria

Okebalama, C. B., Ibezim, C. O., Ugwu, V. U. and Marschner, B. (2020). Effects of amending an Ultisol with bambara groundnut seed residue on soil fertility, microbial nutrient cycling and yield of cucumber. *Biological Agriculture and Horticulture*, **36(4)**:249-266. DOI: https://doi.org/10.1080/01448765.2020.1808067

Onah, C. J., Obalum, S. E. and Eyibio, N. U. (2022). Any residual effects of heavy application of poultry-droppings manure on soil organic matter and field capacity attainment in droughty Ultisols? In: *Sustaining Living Soil Ecosystem through Adoption of Soil Management Practices for Mitigating Climate Change for National Development* (in press), Proceedings of the 46th Annual Conference of Soil Science Society of Nigeria

Onwu, A. C., Unah, P. O. and Abubakar, J. R. (2018). Residual effect of poultry manure on growth and yield of okra. *African Journal of Agriculture Technology and Environment*,

7(2):110-118

Opala, P., Okalebo, J. and Othieno, C. (2012). Effects of organic and inorganic materials on soil acidity and phosphorus availability in a soil incubation study. *International Scholarly Research Notices*, **Volume 2012**, Article ID 597216. https://doi.org/10.5402/2012/597216

Premsekhar, M. and Rajashree, V. (2009). Influence of organic manures on growth, yield and quality of okra. American-Eurasian *Journal of Sustainable Agriculture* **3 (1)**: 6-8

Shahzad, K. Khan, A., Smith, J. U., Saeed, M., Khan, S. A. and Khan, S. M. (2015). Residual effects of different tillage systems, bioslurry and poultry manure on soil properties and subsequent wheat productivity under humid subtropical conditions of Pakistan. *International Journal of Biosciences*, **6(11)**:99-108. DOI: 10.12692/ijb/6.11.99-108

Sheppard, J., Hoyle, F. and Murphy, D. (2022). *Facts Sheets: Water Repellency*. Accessed 08 April 2022, from https://soilquality.org.au/factsheets/water-repellency

Sparks, D. L. (ed.). (1996). Methods of Soil Analysis Part 3: Chemical Methods. Soil Science Society of America Book Series, Inc. Madison, WI, Volume 14 of SSSA Book Series. https://doi.org/102136/sssabookser5.3

Stoof, C. R., Ferreira, A. J., Mol, W., Van den Berg, De Kort, Drooger S., Slingerland, E. C., Mansholt, A. U., Ferreira, C. S. and Ritsema, C. J. (2015). Soil surface changes increase runoff and erosion risk after a low-moderate severity fire. *Geoderma*, **239**-240:58-67. https://doi.org/10.1016/j.geoderma.2014.09.020

Umeugokwe, C. P., Ugwu, V. U., Umeugochukwu, O. P., Uzoh, I. M., Obalum, S. E., Ddamulira, G., Karwani, G. M. and Alenoma, G. (2021). Soil fertility indices of tropical loamy sand as influenced by bambara groundnut variety, plant spacing and fertilizer type. *Agro-Science*, **20(1)**:65-71. https://dx.doi.org/10.4314/as.v20i1.11

Yang, X., Chen, X. and Yang, X. (2019). Effect of organic matter on phosphorus adsorption and desorption in a black soil from Northeast China. *Soil and Tillage Research*, **187**:85-91, https://doi.org/10.1016/j.still.2018.11.016

Yu, W., Ding, X., Xue, S., Li, S., Liao, X. and Wang, R. (2013). Effects of organic-matter application on phosphorus adsorption of three soil parent materials. *Journal of Soil Science and Plant Nutrition*, **13(4)**: 1003-1017. https://doi.org/10.4067/S0718-95162013005000079