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Original Article

Improving physical properties of degraded soil: Potential of poultry manure and biochar

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A B S T R A C T

The application of organic materials for soil amendment plays important roles in reclaiming and improving the physical quality (SPQ) of degraded soils. This study assessed the effects of composted and non-composted poultry manures and biochar on the SPQ indicators of a degraded soil. A randomized complete block design was applied with four replications using five treatments: 1) veticompost (composted poultry manure + vetiver grass prunes), 2) poultry tea (non-composted poultry slurry), 3) solid non-composted poultry manure, 4) poultry biochar and 5) an unamended control. The soil physical quality indicators were determined after four consecutive growing seasons, with maize (*Zea mays* var. DMR-ESR-Y) planted as the test crop in each season. In comparison with the other treatments, poultry biochar consistently retained 3.3–31.3% more water at lower suctions (0–500 kPa). The saturated hydraulic conductivity following the application of poultry biochar (9.2 mm/hr) was significantly lower ($p < 0.05$) than for other organic amendments (16.5–18.2 mm/hr). The increase in water stable aggregates under the veticompost treatment was 3.4–26.7% greater than for the other treatments. The comparison of the SPQ indices indicated positive effects from the amendments on the soil physical properties in the order: unamended control < poultry biochar < poultry tea < non-composted poultry manure < veticompost. Composted and non-composted manures and biochar favored better maize growth and resulted in significantly higher grain yields (1.48–1.73 t/ha) than the unamended control treatments (0.87 t/ha). These results suggest that composted and non-composted manures may be more worthwhile than biochar for improving the physical quality of degraded soil.

Introduction

The capacity of a soil to function within ecosystem and land use boundaries, sustain productivity, maintain environmental quality and promote plant and animal health can be defined as soil quality (Doran and Parkin, 1994). It integrates the physical, chemical and biological components and processes and the interactions among them within the soil (Karlen et al., 2001; Dexter, 2004a). Though much attention has been given to the chemical and biological components in several studies, little attention has been given to the physical quality of the soil. The physical quality of agricultural soil refers primarily to the soil's strength and fluid transmission and storage characteristics in the crop root zone (Topp et al., 1997). It plays an integral role in controlling chemical and biological processes and determines the suitability of soil for sustaining plant growth (Dexter and Czyz, 2000; Dexter, 2004b; Hillel, 2004). Soil properties such as soil texture, aggregate stability and size distribution, plant available water content, strength and maximum rooting depth have been proposed by Larson and Pierce (1991) for the assessment of physical indicators of soil quality. However, the majority of farmers in sub-Saharan Africa (SSA) are ignorant of the fragility of the soils they cultivate, thus engaging in activities that impair the physical quality indicators of the fertile topsoil (Babalola, 2000). Perhaps they are not convinced that physically impaired soil brings about reduction in plant response to soil fertility and decrease in crop productivity. Studies by Aina (1979) and Meyer et al. (1985) have shown that physically degraded soils do not respond positively to chemical fertilizer.

Smallholder farmers in SSA usually lack sufficient capital to apply inorganic fertilizers at the recommended rates (Kapkiyai et al., 1999). Sometimes, the distribution systems often do not function efficiently, because fertilizer will be available at the wrong

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times (Shapiro and Sanders, 1998). It is therefore, imperative to intensify research on improving soil productivity with organic manures, which are a cost-effective method of fertilizing a crop, especially if the manure is produced on-farm (Radke et al., 1988). In Nigeria, large quantities (about 932.5 t) of poultry manures are annually produced by commercial farms (Adewumi et al., 2011). These manures are being disposed of in either a solid or liquid mixture of water and insoluble solid (poultry slurry) form. This has created ample opportunity for crop farmers to make use of poultry manure in different forms from other animal manures such as swine, cattle and turkey. Adekiya and Agbede (2017) considered that the attraction to poultry manure for crop production in Nigeria, apart from its accessibility, was its rich source of plant nutrients. However, the use of composted poultry manure and vetiver clippings tagged as veticompost (Are et al., 2012), has attracted the interest of researchers and also the demand by farmers for poultry manure since grass increases its carbon content when composted poultry manure is applied. Large quantities (approximately 2.6–10.4 t/ha) of material in the form of vetiver grass clippings are produced as prunings when vetiver grass strips are established as hedges around farm within 3 mth (Babalola et al., 2007), and this has made it easy for the production of veticompost. Apart from the high capital outlay of inorganic fertilizer, Aina (1979) reported that long-term chemical fertilization caused soil physical quality degradation while such soil is also prone to acidification (Ogbodo, 2013) and surface soil hardening (Lai et al., 1992). For these reasons, Nyakatawa et al. (2001) considered that it was impossible to increase crop yields on physically degraded soil without using organic resources. Several researchers (Li and Zhang, 2007; Ludwig et al., 2007; Liu et al., 2009) have also reported that the traditional organic manure (such as farmyard manure) can be potentially beneficial for soil physical, chemical and biological properties. However, there is still insufficient information on the effect of animal manure on soil physical quality indicators in SSA.

Recently, biochar, the carbonaceous product of biomass combusted under oxygen-limited conditions, has been studied for its effects as a soil amendment. Inal et al. (2015) and Zheng et al. (2012) documented that biochar could reduce soil acidity, while either increasing or retaining soil nutrients in field and pot experiments. Biochars are characteristically very light materials with a high porosity and surface area, which alter some soil physical properties such as the bulk density (BD), water-holding capacity (WHC), surface area and penetration resistance (PR) (Mukherjee and Lal, 2013). While a lot of attention has been given to the effects of biochar on soil chemical properties, data are scarce on biochar impacts on soil physical quality indicators, especially at the field scale (Mukherjee and Lal, 2014). Several studies have documented the influence of organic manures and biochars on soil fertility and other soil properties. However, available information on the effects of poultry biochar on SPQ indicators compared with those of composted and non-composted poultry manures is scant. Therefore, this study compared the potential of composted and non-composted poultry manures with that of poultry biochar on soil physical quality indicators and their influence on maize grain yield.

Materials and methods

Study site and soil

The study was conducted at the Institute of Agricultural Research and Training, Ibadan (7°23′ N, 3°51′ E), Nigeria. Ibadan has a tropical humid climate with a bimodal rainfall distribution; the mean annual rainfall is 1381.6 mm based on records over a period of 10 yr (Institute of Agricultural Research and Training, 2010). Rainfall peaks occur in June and September; the temperature ranges from 21.3 °C to 31.2 °C. There are two cropping seasons, with an early (March/April to early August) and late (mid-August to October/November) season. The soil on which the experiment was carried out was a degraded soil with no apparent spatial difference in soil properties, on a relatively flat terrain that has been under continuous cultivation for more than 15 yr. The initial properties of the studied soil are shown in Table 1. The soil has a coarse-grained texture belonging to the alfisols, classified as Typic Kanhaplustalf (Soil Survey Staff, 2014) and classified locally as Iwo series (Smyth and Montgomery, 1962).

Layouts and treatments

The experimental plot was plowed and harrowed before application of the treatments and sowing of the test crop. Each plot size was 4.0 m × 3.0 m with plots separated by a 1.0 m path. The five organic amendments were: 1) veticompost (composted poultry manure + vetiver grass prunes), 2) poultry tea (non-composted poultry slurry), 3) solid non-composted poultry manure, 4) poultry biochar and 5) unamended control. The treatments were arranged in a randomized complete block design (RCBD) with four replications. All amendments were applied at a rate of 5 t/ha based on the recommendation of Adediran et al. (2003) for southwestern Nigeria. The solid poultry manures and biochar were broadcasted uniformly on each treated plot while the poultry slurry was sprinkled using a watering can and manually incorporated into the soil to a depth of 0–10 cm with a garden rake. Veticompost was prepared by composting vetiver grass pruning waste with poultry manure collected from a deep litter broiler pen. Poultry tea was prepared by dissolving an equivalent weight of 5 t/ha of solid, dry poultry manure in water of the same volume to form a slurry. The slurry was left for 24 h, stirred and filtered to remove the wood waste that might have mixed with the manure before application. Poultry biochar was prepared using pyrolysis by burning the solid, dry poultry manure in a pyrolyzer at 450 °C in the absence of oxygen for 3 h. The chemical analyses of the organic materials for amendments are shown in Table 2.

Maize (*Zea mays* var. DMR-ESR-Y) was planted as the test crop four cropping seasons (early and late seasons of 2013 and 2014). The maize crop was harvested at physiological maturity (85 d after sowing) and the total above-ground biomass and grain yield were determined on each plot at 15% moisture content.

Table 1
Soil properties of the experimental site (0–15 cm depth).

Soil property	Value
Sand (g/kg)	705
Silt (g/kg)	183
Clay (g/kg)	112
Textural class	Sandy Loam
Bulk density (Mg/m^3)	1.51
K_{sat} (mm/hr)	11.32
Total pores (m^3/m^3)	0.430
Transmission pores (m^3/m^3)	0.069
Storage pores (m^3/m^3)	0.173
Residual pores (m^3/m^3)	0.188
WSA > 250 μm (%)	51.7
MWD (mm)	0.87
pH (1:1 soil:water suspension)	6.05
SOC (g C/kg soil)	12.1
Total N (g/kg)	1.09
Available (Bray 1) P (mg/kg)	7.88
Exch. K (cmol/kg)	0.30

K_{sat} = saturated hydraulic conductivity, WSA = water stable aggregates, MWD = mean weight diameter, SOC = soil organic carbon.

Soil sampling and analysis

Initial soil sampling was carried out on the soil to ascertain its baseline soil properties (Table 1). In addition, three replicated soil samples were collected from each plot after harvest following the four maize cropping seasons to determine the changes in the soil physical quality indicators. The soil samples (collected at 0–15 cm depth) were air dried and allowed to pass through a 2.00 mm sieve. Thereafter, sand, silt and clay particles were determined using a modified Boyoucos hydrometer method as described by Gee and Or (2002). The bulk density was determined using the core method as described by Grossman and Reinsch (2002). Total porosity was extrapolated from the bulk density using the relationship described by Hillel (2004) in Equation (1):

$$POR_t = 1 - \frac{\rho_b}{\rho_s} \quad (1)$$

where, POR_t is the soil total porosity, ρ_b is the soil bulk density and ρ_s is the particle density assumed to be 2.65 Mg/m^3

Soil organic carbon was determined using the loss-on-ignition method as described by Cambardella et al. (2001). Soil water stable aggregates (WSA) and the mean weight diameter (MWD) were determined using a modified Kemper and Rosenau wet sieving method as described by Nimmo and Perkins (2002). Core samples were also obtained to determine the saturated hydraulic conductivity (K_{sat}) in the laboratory using a constant head permeameter (Reynolds et al., 2002). The soil moisture retention characteristics of the core samples were determined in the laboratory using a tension plate assembly (Topp and Zebchuk, 1979) for the lower suction values (0–6 kPa) and a pressure plate apparatus following Dane and Hopmans (2002) for higher matrix suction values (10, 50, 100, 500, and 1500 kPa). The available water capacity (AWC) expressed on a gravimetric basis was estimated as the difference between the field capacity (FC) obtained at 10 kPa (100 cm water) and the permanent wilting point (PWP) determined at 1500 kPa (15,000 cm water) as described in Equation (2):

$$AWC = (\Theta_{FC} - \Theta_{PWP}) \quad (2)$$

where, Θ_{FC} is the gravimetric moisture content (%) at field capacity and Θ_{PWP} is the gravimetric moisture content (%) at permanent wilting point.

Pore size distributions were calculated using the water retention data and capillary rise equation as described by Flint and Flint (2002) in Equation (3):

$$r = \frac{2\gamma \cos \alpha}{h \rho_w g} \quad (3)$$

where, r is the mean equivalent radius of pores (meters), γ is the surface tension of the water against the wetting surface (millijoules per square meter) at laboratory temperature, α is the contact angle between the solid and water interface (assumed to be zero), h is the matrix suction or pressure head (centimeters of water) applied to drain the water; ρ_w is the density of water (megagrams per cubic meter) and g is acceleration due to gravity (meters per second squared). However, in this study, the pores were grouped as suggested by Greenland (1981) into transmission pores (P_T, 50–500 μm equivalent cylindrical radius, (ECR) corresponding to 20–100 cm of water), storage pores (P_S, 0.5–50 μm ECR corresponding to 100–15,000 cm of water) and residual pores (P_R, less than 0.5 μm ECR corresponding to more than 15,000 cm matrix suction).

The soil physical quality index was assessed by adopting a modified Soil Management Assessment Framework design (SMAF) as described by Andrews et al. (2004). This framework was based on the integration and transformation of observed indicators using non-linear scoring functions. The measured values of indicators were transformed into dimensionless values (ranging between 0 and 1) based on the critical values of the indicators (Lal, 1994) for easy combination into a single value. The overall soil physical quality index as influenced by the various treatments with regard to soil physical properties was computed as shown in Equation (4):

$$SQ_{phy} = \sum_{i=1}^{n} WS = \text{q.rp x wt} + \text{q.rd x wt} + \text{q.wr x wt} \quad (4)$$

where SQ_{phy} is the soil physical quality index, W is the total weighted average of the soil physical processes, S is the relative scores of the factors; q.rp is the soil quality rating for the root penetration process; q.rd is the soil quality rating for the ability to resist structural degradation process; q.wr is the soil quality rating for water transport and retention, and wt is the weighting factor for each function.

Data analysis

Data collected were subjected to analysis of variance using statistical software (Statistical Analysis System (SAS), 2002). All data were presented as mean ± standard deviation of three measurements. Where the F value was found to be significant, the means were separated at the $p \leq 0.05$ level of significance, using

Table 2
Properties of different forms of poultry manure.

Parameter	Veticompost	Non-composted poultry manure	Poultry tea	Poultry biochar
pH	6.95	7.05	7.05	9.32
Nitrogen (%)	6.78	5.46	4.68	2.53
Phosphorus (%)	5.34	3.75	3.69	2.82
Potassium (%)	1.56	1.29	1.34	2.13
Sodium (%)	0.53	0.45	0.44	0.39
SO_4-S (%)	0.17	0.19	0.18	0.17
Carbon (%)	25.4	20.5	18.7	33.4
Ash (%)	19.2	18.5	14.2	58.2
Cellulose (%)	42.7	41.0	22.7	19.8
Lignin (%)	29.4	28.2	15.6	13.6
Carbon/Nitrogen	3.75	3.75	4.00	13.20
Calcium (%)	4.03	4.13	3.54	6.83
Magnesium (%)	0.63	0.62	0.65	0.75
Iron (mg/kg)	2915	2465	2437	1987
Boron (mg/kg)	12.1	13.2	12.6	13.5

Fisher least significant differences (LSD). Pearson's linear correlation was used to assess the relationship between soil moisture retention and parameters related to the pore space and between the soil physical quality and SOC, pore fractions, aggregation indices, K_{sat} and bulk density.

Results and discussion

Effects of amendments on particle size distribution and soil bulk density

The relative distribution of sand, clay and silt sizes at 0–15 cm soil depth is shown in Table 3. Although there were variations among the particle sizes following the addition of the different forms of poultry manure, the changes were not statistically significant nor were the differences among the treatments with regard to the distribution of different particle sizes. The textural class (sandy loam) of the soils among the treatments were not significantly different. The lack of a change in the soil texture following the various treatments confirmed Hulugalle (1994) who asserted that changes in the soil texture do not occur easily and take many years to occur irrespective of the management practices implemented.

The mean bulk density (ρ_b) ranged from 1.44 Mg/m^3 to 1.60 Mg/m^3 among treatments (Table 3). The soil bulk densities of the veticompost, poultry tea, poultry manure and biochar plots were lower by 8.8%, 6.9%, 8.1% and 10.0%, respectively. Compared to the initial bulk density (1.51 Mg/m^3) of the study site, veticompost, poultry tea, poultry manure and biochar reduced the bulk density by 3.1%, 1.3%, 2.5% and 4.4%, respectively whereas the bulk density increased by 6.0% on the unamended control plot. A number of studies, at both the field and lab scale, have also reported that manure addition reduces the soil bulk density (Jones et al., 2011; Are et al., 2012; Ojeniyi et al., 2013). For instance, research conducted by Ojeniyi et al. (2013) at Akure, Nigeria, on sandy loam soil found that 5 t/ha of poultry manure reduced the soil bulk density by 13.9%. Furthermore, Are et al. (2012) reported an 18.6% reduction in soil bulk density of a sandy loam soil using veticompost in a maize field after five cropping seasons. Elsewhere in India, Mankasingh et al. (2011) reported a 7.8% reduction in the soil bulk density in an experiment involving biochar-amended. However, with the addition of 50 t/ha of biochar, Jones et al. (2012) recorded an increase of 3.8% in the bulk density in a sandy clay loam-textured soil. In the present study, the addition of poultry biochar reduced the soil bulk density by 1.4%, 3.4% and 2.0% more than with veticompost, poultry tea and poultry manure, respectively.

Soil organic carbon and aggregate stability

The result indicated that the application of different forms of poultry manures (either as composted or non-composted poultry manures) and biochar increased the soil organic carbon (SOC) contents of amended soils (Table 3). In comparison with the baseline, veticompost, non-composted poultry manure, poultry tea and biochar increased the accumulation of SOC by 44.5%, 43.8%, 9.1% and 9.1%, respectively, whereas the SOC of the unamended control reduced by 31.4% after four cropping seasons. It was also observed that veticompost and poultry manure had comparable SOC values that were higher than those of the poultry tea, biochar and control treatments (Table 3). After four cropping seasons, the SOC of the veticompost, poultry tea, poultry manure and biochar treatments were higher than the unamended control by 2.1-folds, 1.6-folds, 2.1-folds and 1.6-folds, respectively. The beneficial effects of organic amendments in SOC accumulation and enhancing carbon sequestration have been reported in some field trials (Reeves, 1997; Purakayastha et al., 2008; Gong et al., 2009; Adeleye et al., 2010; Puttaso et al., 2011; Are et al., 2012). For instance, Adeleye et al. (2010) found that the application of 10 t/ha poultry manure increased the SOC by 37.8% while Are et al. (2012) reported an increase of 44.5% in the SOC after 3 yr continuous application of composted poultry manure + vetiver grass (veticompost). In the present study, the higher percentage increase in the SOC following the application of veticompost and non-composted poultry manure might have been associated with the presence of grass and wood wastes respectively, which perhaps increased the carbon and lignin contents relative to other amendments (Table 2). In contrast, poultry tea and biochar with neither grass nor wood residues produced SOC values lower than for the veticompost and poultry manure. Puttaso et al. (2011) observed that the differences in residue quality (cellulose, lignin content or C/N ratio) might have influenced the level of C accumulation in soils. This assertion is supported by a similar observation by Fließbach et al. (2007), who reported that the differences in manure quality (in terms of lignin and C/N ratios) influenced C storage in soils.

The strength and size of aggregates are shown by the water stable aggregates (WSA) and mean weight diameter (MWD) in Table 3. Both the WSA and MWD gave a clear indication of the potential of organic amendments in re-building soil structural quality after an initial degradation. In the present study, soils treated with organic amendments favored a better structure with increases of 17.5–26.7% in the WSA after four cropping seasons of maize. The MWD of the soils treated with organic amendments followed a similar trend to that of the WSA (Table 3). However, the WSA of the unamended control treatments reduced by 10.1% while the MWD reduced by 17.0% relative to those before the experiment. The increase in macroaggregate formation was probably a reflection of the level of increase in SOM under the different organic amendments. Previous studies (Li and Zhang, 2007; Manna et al., 2007; Li et al., 2011; Ouyang et al., 2013) established a close relationship between the soil aggregate stability index and SOM content. For instance, Manna et al. (2007) cited SOM as a major cause of improvements in soil tilt and structural quality. On the other hand, the hydrophobicity of organic matter sources, especially biochar (Jeffery et al., 2015), may also have increased the resistance of

Table 3
Soil physical quality indicators as affected by different forms of poultry.

Treatments	Sand	Silt	Clay	Bulk density	POR_t	K_{sat}	SOC	WSA	MWD
	g/kg	g/kg	g/kg	Mg/m^3	%	mm/hr	g/kg	%	mm
Veticompost	642 ± 11.0^{a}[a]	245 ± 4.6^{a}	113 ± 3.0^{a}	1.46 ± 0.02^{b}	44.9 ± 0.6^{a}	16.5 ± 0.7^{a}	17.5 ± 0.3^{a}	68.3 ± 1.9^{a}	1.24 ± 0.03^{a}
Poultry tea	702 ± 1.1^{a}	205 ± 6.1^{a}	93 ± 3.6^{a}	1.49 ± 0.02^{b}	43.7 ± 0.8^{a}	18.1 ± 0.5^{a}	13.2 ± 0.2^{b}	60.2 ± 0.9^{a}	1.12 ± 0.02^{b}
Poultry manure	702 ± 11.0^{a}	225 ± 5.1^{a}	73 ± 2.0^{a}	1.47 ± 0.04^{b}	44.4 ± 1.4^{a}	18.2 ± 0.3^{a}	17.4 ± 0.3^{a}	64.9 ± 1.7^{a}	1.22 ± 0.04^{a}
Poultry biochar	709 ± 8.2^{a}	165 ± 2.9^{a}	126 ± 2.0^{a}	1.44 ± 0.01^{b}	45.7 ± 0.4^{a}	9.2 ± 0.2^{b}	13.2 ± 0.2^{b}	59.1 ± 1.3^{a}	1.02 ± 0.03^{b}
Control	688 ± 2.6^{a}	219 ± 2.8^{a}	93 ± 1.7^{a}	1.60 ± 0.02^{a}	39.7 ± 0.8^{a}	9.9 ± 0.3^{b}	8.3 ± 0.2^{c}	41.6 ± 1.6^{b}	0.72 ± 0.04^{c}
$LSD_{(0.05)}$	89.3	106.1	56.4	0.09	6.9	5.8	3.2	12.6	0.11

POR_t = total porosity, K_{sat} = saturated hydraulic conductivity, SOC = soil organic carbon, WSA = water stable aggregates, MWD = mean weight diameter.
[a] Means (±standard error of the mean) in the same column with different lowercase, superscript letters (a, b, c) are significantly ($p \leq 0.05$) different.

aggregates to slaking in water (Piccolo and Mbagwu, 1999), which ultimately increased the aggregate stability.

Saturated hydraulic conductivity and pore size distribution

The K_{sat} results (Table 3) revealed that the application of organic amendments was effective in increasing the soil hydraulic conductivity, where non-composted poultry manure recorded the highest water conductivity. Nevertheless, the differences between the saturated hydraulic conductivities of non-composted poultry manure, poultry tea and veticompost were not significant. Khalid et al. (2014) also observed a distinct increase in K_{sat} when poultry manure was applied to a sandy soil in Ghana. The soil hydraulic conductivity of poultry biochar (9.2 mm/hr) was significantly lower than the other organic amendments (16.5–18.2 mm/hr), but not significantly different from the unamended control (9.9 mm/hr). The reduction in the K_{sat} of poultry biochar treatments might be attributed to the ash deposited by the biochar, which perhaps reduced the larger soil pores and thus led to reduction in pore space and volumes. Several studies (Major et al., 2012; Uzoma et al., 2011; Deveraux et al., 2012; Barnes et al., 2014) have linked the reduction in soil hydraulic conductivity of sandy soil to a reduction in porosity imposed by the fine-grained particles of biochar. Uzoma et al. (2011) also found that the K_{sat} in the field decreased in a sandy soil as the biochar concentration increased from 0 t/ha to 20 t/ha. The decrease was thought to be due to biochar's large surface area and the high number of pores which had to be filled up before water drained under the force of gravity, meaning that more biochar in the soil might lead to the retention of more water in the storage pores (Deveraux et al., 2012). Barnes et al. (2014) were of the opinion that the shifts in K_{sat} could be related to the physical mechanisms of the biochar, such as swelling and grain segregation, leading to the clogging of pores, a decrease in pore radii and possibly a variation in the bulk density and sample heterogeneity over the course of the experiment. Contrasting results have been reported on K_{sat} following the application of biochar, with Asai et al. (2009) reporting significant increases following the application of biochar on a clay loam soil in Laos, whereas Major et al. (2012) reported no significant effect in a clay soil following the addition of 20 t/ha biochar produced from wood. In a study by Barnes et al. (2014), K_{sat} significantly increased in clay soil, decreased in sandy soil and had no significant effect for sandy loam rich in organic matter following the incorporation of biochar. These results demonstrate that the interactions between applied biochar and soil amended with biochar, and the resulting effects on hydraulic conductivity are dependent on soil texture.

The soil total porosity expectedly followed inverse trends in the bulk density, and varied with amendments. Although there were no significant differences among the treatments, the total porosities of amended soils were consistently higher than the unamended control (Table 3). Transmission pores increased significantly following the application of veticompost, poultry tea and poultry manure for four cropping seasons, but reduced under poultry biochar and unamended control (Fig. 1). The ash deposit within the pores might have been more effective in reducing the transmission pores of the soil ameliorated with poultry biochar than for the other treatments, where the pore space had to be filled with water before it drained under gravity. Pagliai et al. (1981) reported that as a result of the decreased bulk density, the pore size distribution was altered and the relative number of small pores (less than 30 μm diameter) increased in a coarse-textured soil. The highest storage pores were recorded with the poultry biochar, perhaps due to ash deposits as described by Deveraux et al. (2012), and this was significantly higher than those recorded under the veticompost (0.188 m^3/m^3), poultry tea (0.179 m^3/m^3) and poultry manure

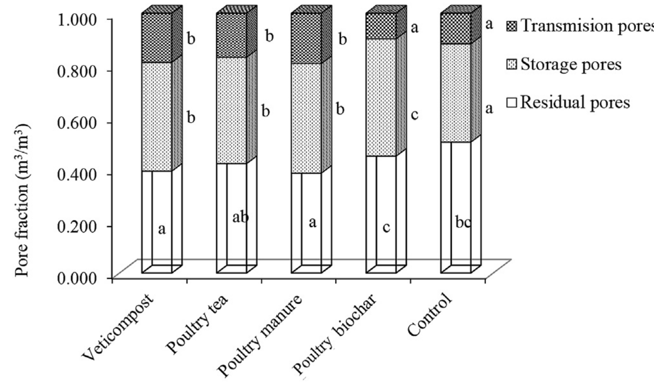

Fig. 1. Pore size distribution as affected by different forms of poultry manure. Means across the bars for a particular pore fraction containing a common lowercase letter are not significantly different ($p \leq 0.05$).

(0.187 m^3/m^3). However, the storage pores in the unamended control soil (0.150 m^3/m^3) were significantly ($p \leq 0.05$) lower than for any of the organically amended soils, which perhaps resulted in its low soil water retention. Haynes and Naidu (1998) stated that increasing the soil organic matter content might improve the soil pore structure following the addition of organic manure. In the present study, poor soil aggregation, as a consequence of a reduction in intra-aggregate and inter-aggregate pore spaces, might have led to the breakdown of transmission and storage pores in the unamended control treatments. This was in line with Chakraborty et al. (2010) who linked soil pore size distribution and structural development to intra-aggregate and inter-aggregate pore spaces.

Soil water characteristics and relationship between soil moisture retention and some parameters related to pore space

The soil water retention characteristics as influenced by soil amendments are shown in Fig. 2. Poultry biochar and veticompost had comparable soil moisture retentions, especially at lower suctions (0–500 kPa), that were higher than those of other treatments. However, the differences in moisture retention among the treatments became increasingly smaller with increased suction. At lower suctions (0–500 kPa), the effects of poultry biochar, veticompost and non-composted poultry manure on moisture retention were distinctly visible and significantly higher than for the

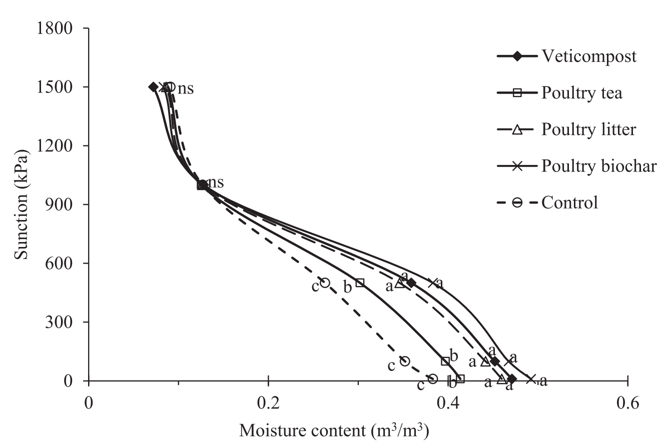

Fig. 2. Soil moisture characteristics as affected by different forms of poultry manure. Moisture contents with a common lowercase letter at the same suction value are not significantly different ($p \leq 0.05$). ns = non-significant at $p \leq 0.05$.

Table 4
Linear correlation between soil moisture retention and parameters related to pore structure.

Parameter	R	R^2	Regression equation for the relationship
SOC	0.733*	0.537	y = 156.74x − 19.83
WSA	0.767*	0.589	y = 419.4x − 32.10
MWD	0.606*	0.367	y = 5.17x − 0.02
Bulk density	− 0.625*	0.391	y = − 2.303x + 1.72
Sand	− 0.370ns[a]	0.138	y = − 56.8x + 81.08
Silt	− 0.079ns	0.006	y = − 13.35x + 24.08
Clay	0.603*	0.363	y = 70.35x − 5.20
Total porosity	0.625*	0.391	y = 86.9x + 35.19
Residual pores	− 0.196ns	0.039	y = − 0.169x + 0.22
Storage pores	0.881**	0.776	y = 1.02x − 0.04
Transmission pores	0.306ns	0.091	y = 0.35x − 0.007

SOC = soil organic carbon; WSA = water stable aggregates; MWD = mean weight diameter.
[a] ns = not significant; *, ** significantly different at 0.05 and 0.01 probability levels.

poultry tea and control treatments. In comparison with other treatments, poultry biochar consistently retained between 3.3% and 31.3% more water than the other treatments at 0–500 kPa. However, at higher tensions (>500 kPa), there were no significant differences among the treatments in relation to soil moisture retention. The increased soil moisture retention in soils amended with poultry manures and biochar might be attributed to the organic matter build up in the soil which improved the structure and pore space. This was evident in the correlation analyses between results obtained for moisture retention and parameters related to pore space in this study (Table 4). Soil moisture retention was positively and significantly correlated to SOC (r = 0.73*), WSA (r = 0.77*), MWD (r = 0.61*), clay particles (r = 0.60*), storage pores (r = 0.88**) and total porosity (r = 0.63*) but negatively correlated with bulk density (r = −0.63*). However, there were no significant correlations between soil moisture retention and sand, silt, residual and transmission pores. Adeleye et al. (2010) reported that soil moisture retention following the application of poultry manure was attributed to the colloidal and hydrophobic nature of the poultry manure which perhaps improved the soil structure and increased the resistance of soil aggregates to slaking water (Piccolo and Mbagwu, 1999). Gaskin et al. (2007) also confirmed that biochar could improve soil water retention, reporting a doubling in the mean volumetric water content of a loamy sandy soil at 2 kPa following the application of peanut hull biochar at a rate of 88 t/ha. However, Basso et al. (2013) was of the opinion that the increase in soil water retention might be associated with the water stored within the pore space of the biochar applied to the soil, which was generally highly porous (van Zwieten et al., 2009).

Soil physical quality index

Fig. 3 shows the soil physical quality index as influenced by different forms of poultry material added. Veticompost had the highest soil physical quality rating (73.5%), closely followed by non-composted poultry manure (72.4%). However, there were no significant differences between the quality ratings for the poultry biochar (59.4%) and unamended control (52.3%) treatments, although the latter was less by 7.1%. The observed increases in soil physical quality indices under composted and non-composted poultry manures and biochar might have been associated with the influence of SOM, which enhanced better soil and pore structures, transmission and storage characteristics. The use of organic amendments has been recognized generally as an effective means for improving soil aggregation, structure and improving the moisture-holding capacity of soils (Walsh and McDonell, 2012). Although, SOC is not a true soil physical quality parameter, research has established a close relationship between SOC and many soil physical properties (Kay, 1998; Reynolds et al., 2002; Dexter, 2004a; b; Chakraborty et al., 2010). For instance, Chakraborty et al. (2010) obtained significant positive correlations between SOC and basic soil properties including bulk density and aggregation indices, water retention, pore fractions and K_{sat}. In the present study however, the application of organic amendments improved the SOC and consequently influenced the physical properties significantly as observed in the K_{sat}, transmission and storage pore fractions, soil aggregation indices and moisture retention of the sandy loam soil (Table 5). The degradation in these properties however, led to the observed decrease in the soil physical quality index for the unamended control.

Maize grain yield

The maize grain yields as influenced by different organic amendments are shown in Table 6. The differences between any of the organic amendments and the unamended control were statistically highly significant in all the cropping seasons. The pooled grain yields of the four cropping seasons ranged from 0.51 t/ha to 1.84 t/ha with the highest yield in the veticompost-treated plots, closely followed by that of poultry manure and the least grain yield was recorded for the unamended control. Organic amendments increased the pooled grain yields by 93.1–261.4% compared to the unamended control treatments. However, in the early 2013 season, the grain yields for veticompost (1.72 t/ha), poultry manure

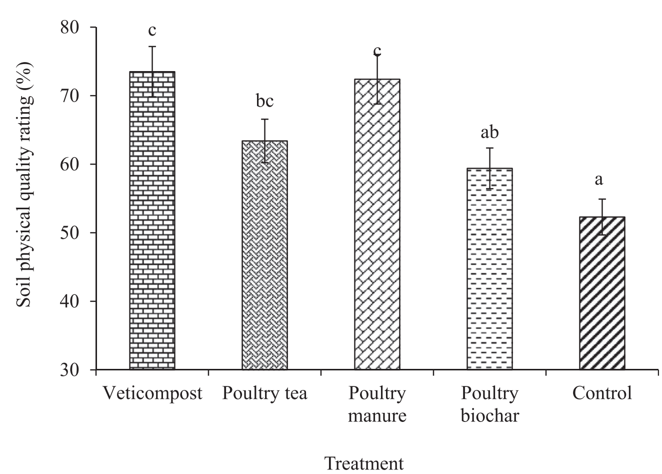

Fig. 3. Soil physical qualities as affected by composted and non-composted poultry manure and biochar. Values are mean SD (n = 4). Bars with a common lowercase letter are not significantly different at $p \le 0.05$. Error bars represent a 95% confidence interval of the mean values.

Table 5
Correlation matrix between soil physical properties and soil physical quality (SPQ).

	SOC	BD	PORt	WSA	MWD	Ksat	AWC	P_T	P_S	P_R
BD	−0.79*									
POR_t	0.78*	−1.00**								
WSA	0.96**	−0.89**	0.88**							
MWD	0.97**	−0.72*	0.71*	0.95**						
K_{sat}	0.70*	−0.33ns[a]	0.31ns	0.67*	0.83**					
AWC	0.73*	−0.63*	0.63*	0.77*	0.61*	0.12ns				
P_T	0.83**	−0.40ns	0.38ns	0.77*	0.92**	0.95**	0.31ns			
P_S	0.65*	−0.97**	0.97**	0.76*	0.54*	0.10ns	0.88**	0.18ns		
P_R	−0.79*	0.30ns	−0.27ns	−0.68*	−0.87**	−0.93**	−0.20	−0.99**	−0.08ns	
SPQ	0.98**	−0.67*	0.66*	0.92**	0.99**	0.79*	0.64*	0.92**	0.50*	−0.88**

BD = bulk density; POR_t = total porosity; WSA = water stable aggregates; MWD = mean weight diameter; K_{sat} = saturated hydraulic conductivity; AWC = available water capacity; P_T = transmission pore; P_S = storage pore; P_R = residual pore.
[a] ns = not significant; *, ** significantly different at 0.05 and 0.01 probability levels.

Table 6
Maize grain yields obtained in the four cropping seasons and pooled grain yields as affected by soil amendments.

Treatment	Maize grain yield (t/ha)				
	Early 2013	Late 2013	Early 2014	Late 2014	Pooled
Veticompost	1.72 ± 0.03[a]	1.84 ± 0.04[a]	1.89 ± 0.03[a]	1.92 ± 0.03[a]	1.84 ± 0.09[a]
Poultry manure	1.73 ± 0.02[a]	1.82 ± 0.02[a]	1.89 ± 0.01[a]	1.88 ± 0.03[a]	1.83 ± 0.07[a]
Poultry tea	1.26 ± 0.03[b]	1.42 ± 0.05[b]	1.45 ± 0.03[b]	1.46 ± 0.03[b]	1.40 ± 0.09[b]
Poultry biochar	0.89 ± 0.04[c]	0.98 ± 0.02[c]	0.99 ± 0.03[c]	1.08 ± 0.02[c]	0.99 ± 0.08[c]
Control	0.68 ± 0.04[cd]	0.48 ± 0.01[d]	0.44 ± 0.04[d]	0.44 ± 0.02[d]	0.51 ± 0.11[d]
$LSD_{(0.05)}$	0.25	0.29	0.30	0.29	0.28

$LSD_{(0.05)}$ = least significant difference at $p \leq 0.05$.
Values followed a common lowercase letter in the same column are not significantly different at $p \leq 0.05$.

(1.73 t/ha), poultry tea (1.26 t/ha) and poultry biochar (0.89 t/ha) plots were higher than those for the unamended control plots by 152.9%, 154.4%, 85.3% and 30.9%, respectively. The gaps between the maize grain yields of the unamended control and the organic amended treatments became wider in subsequent seasons in late 2013 (104.2%–283.3%), early 2014 (125.0%–329.5%) and late 2014 (145.5%–336.4%). The higher grain yields of the organic amendments plots were enhanced by the improvement in the physical quality of the degraded soil and nutrient accumulation in soils (post-field nutrient analysis not reported here). Other studies (Adediran et al., 2003; Mugwe et al., 2007; Are et al., 2012) also found a similar increase in crop yields as a result of nutrient accumulation in the soil following the application of organic manures. The higher carbon-rich lignin and nitrogen contents in veticompost and non-composted poultry manure (Table 1) perhaps increased soil fertility more than those of poultry tea and biochar. However, Tian and Kang (1998) reported that carbon-rich lignin in organic manures might slow down their decomposition and therefore have a long-term effect on nutrient availability.

The results of the present study indicated that the addition of composted and non-composted poultry manure and biochar, to a large extent, had immediate, long-term and direct effects on soil physical parameters. Soil amended with veticompost had the highest physical quality and was closely followed by non-composted poultry manure. Removal of wood wastes from the slurry during poultry tea preparation perhaps reduced its lignin content and subsequently lowered the soil organic carbon content. The application of poultry biochar increased soil water retention more than in the composted and non-composted poultry manures; the benefit was however dwarfed by the potential danger of reducing transmission pores and soil hydraulic conductivity. It was evident from this study that continuous application of composted and non-composted poultry manures resulted in the improvement of some physical properties of degraded soil, and subsequently increased the maize grain yields more than the application of biochar and unamended control. Thus, for maximum benefits, there should be further investigation to evaluate the potential effects of poultry manure and biochar on improving soil physical properties and crop yields on different soil types for different agroecosystems.

Conflict of interest

The authors declare that there is no conflict of interest.

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