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Soil organic carbon and hydraulic properties in response to poultry manure and inorganic fertilizers in two tropical agro-ecologies

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ABSTRACT

The response of soil structure to nutrient management may vary across environments. Poultry manure (PM) and/or inorganic fertilizers (IF) effects on soil pH, organic carbon (SOC), and hydraulic properties were assessed in derived savannah sandy-clay-loam Ultisols and rainforest sandy-loam Alfisols of Nigeria during 2013-2015. The Ultisols were inherently lower in soil pH and SOC than the Alfisols. Three PM rates (0, 5, and 10 t ha^{-1}), each with four NPK/Urea-based IF levels (0, 50, 100, and 150%), were applied in 2013 and 2014 but not in 2015. At crop (maize) maturity, treatment affected the Ultisols more distinctly than the Alfisols. Regardless of IF level, PM_{10} and PM_5 resulted in optimal soil pH (Ultisols) and hydraulic properties (Alfisols), respectively. Treatment $PM_{10}+IF_{50}$ produced overall optimal effects in 2014 and 2015, being among the highest for SOC in the Ultisols (13.30 and 10.23 g kg^{-1}, respectively) and Alfisols (16.10 and 11.60 g kg^{-1}, respectively). Its substitutes for soil pH and hydraulic properties were $PM_{10}+IF_0$ (Ultisols) and PM_5+IF_0 (Alfisols). Unlike most PM-based treatments, sole IFs, especially PM_0+IF_{150}, had pronounced soil-acidifying effects in the Ultisols. The SOC and permeability depended almost entirely on PM across IF levels. Soil pH and SOC were positively correlated with total porosity (Ultisols) and permeability (both soils), with r = 0.60-0.93 (Ultisols) and 0.42-0.66 (Alfisols). Effective PM+IF may not always outperform PM regarding soil pH/SOC, whose influence on soil hydraulic properties can be location-specific. This calls for pre-adoption validation of promising PM+IF options in new tropical agro-environments.

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1. INTRODUCTION

Most tropical soils are deeply weathered, low in soil organic carbon (SOC), and often prone to nutrient leaching. These soils are fragile and characterized by low water holding capacity (Amorim et al., 2022; Igwe, 2011; Klein et al., 2006; Reichert et al., 2009; Reichert et al., 2020; Reichert, Rodrigues, et al., 2016; Vaz et al., 2005), especially those with low clay content (Klein et al., 2006; Obalum & Obi, 2013; Reichert et al., 2020; Reichert et al., 2021; Reichert, Rodrigues, et al., 2016; Reichert et al., 2017). An improvement in soil structure would enhance aeration, water retention, and hydraulic conductivity (Reichert, da Rosa, et al., 2016), while reducing soil erosion and surface sealing (Cassol et al., 2004; Cochrane et al., 2005; Reichert et al., 1992; Reichert & Norton, 1994; Reichert et al., 1994).

Agricultural wastes like poultry manure improve soil structure by enhancing SOC levels in the soil (Adeyemo et al., 2019; Atakora et al., 2013; Baiyeri et al., 2020; Obalum, Ofem, et al., 2024; Obalum, Ugwu, et al., 2024; Onah et al., 2023; Veiga et al., 2010). The increases in SOC lead to increased soil aggregation (Alves et al., 2021; Awe et al., 2021; Batistão et al., 2020; Holthusen et al., 2020; Plaza-Bonilla et al., 2013; Reichert et al., 2022) and improved soil properties such as bulk density and porosity (Obalum & Obi, 2014; Udom & Lale, 2017), pore geometry and functionality (Alves, Roosch, et al.,

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2024), and mechanical properties such as cohesion, compressibility and elasticity (Alves, Holthusen, et al., 2024; Ambus et al., 2018; Braida et al., 2008; Braida et al., 2007; Braida et al., 2006; Reichert et al., 2018). These improvements often result in increased infiltration, aeration, water retention and permeability (Obalum & Obi, 2014; Oguike et al., 2023; Reichert et al., 2022).

Organic fertilizers (manures) are usually bulky, making their sole use cumbersome and unattractive. Additionally, depending on the soil and/or manure type, manures may not always produce desired effects in the soil. For example, manures reduce soil acidity (Onah et al., 2023; Soremi et al., 2017), but occasionally acidify the soil (Ezenne et al., 2019). Inorganic fertilizers (fertilizers) are more convenient to handle, but they often acidify the soil and have no residual effects on the soil pH (Ayeni, 2010; Ndzeshala et al., 2023). They also cause environmental (soil, water, and air) pollution (Agbede et al., 2017; Becker et al., 2009; Kaiser et al., 2010; Onunwa et al., 2021; Reichert et al., 2019).

Because of the widely known links between soil pH, SOC, and aggregation (Obalum et al., 2017; Regelink et al., 2015). The effects of amendments on soil pH could have some ecological implications. The continuous cultivation of acid and fragile tropical soils with inorganic fertilizers may, therefore, further degrade not only the soil pH and SOC, but also the soil structure and the associated aggregates. There has been a renewed effort to integrate organic and inorganic sources of soil amendments judiciously to maximize their benefits.

Integrated soil fertility management (ISFM) is a set of technological soil and water management practices that involves the use of improved germplasm, organic and inorganic amendments, and improved agronomic practices to promote synergies due to combinations of the different components of cropping systems that are designed for these systems, the soil fertility status, and socio-economic profiles (Hörner & Wollni, 2021; Lambrecht et al., 2016; Roobroeck et al., 2016). The complementary application of manures and fertilizers is a key component of ISFM in low-fertility tropical soils. This is particularly true in Nigeria, where this component is often so promoted as if ISFM is all about it in crop production (Ande et al., 2017). This promising component of the ISFM, subsequently referred to as $ISFM_{manure+fertilizer}$ ($ISFM_{mnr+fert}$), can improve and sustain the quality of tropical African soils (Nwite et al., 2012; Nwite et al., 2013; Obalum, Ogumba, et al., 2020; Ogumba et al., 2024); however, its effects often deviate from expectations. Poultry manure is very effective and can decrease soil bulk density (Agbede et al., 2017; Onunwa et al., 2021), but inconsistent results have been reported (Gudadhe et al., 2015; Ortas et al., 2013). A consistent reduction in soil bulk density was observed by Khalid et al. (2014) with $ISFM_{mnr+fert}$ involving different rates of poultry manure in a sandy soil in Ghana.

The inconsistencies in the effects of the $ISFM_{mnr+fert}$ are not limited to the soil bulk density, as they also apply to the related soil porosity. The $ISFM_{mnr+fert}$ has been reported to increase soil porosity (Maltas et al., 2018; Yadav et al., 2019). In southeastern Nigeria, Udom and Lale (2017) reported that soil total porosity was 26%, 24%, and 22% greater with poultry manure-based $ISFM_{mnr+fert}$, poultry manure, and NPK fertilizers, respectively, than with the control. In contrast, (Nweke & Nsoanya, 2013) reported lower soil porosity in poultry manure-amended – but not in NPK-amended – plots than in the control. Improved soil porosity is crucial for water infiltration, permeability, and water storage (Holthusen, Brandt, Reichert, & Horn, 2018; Holthusen, Brandt, Reichert, Horn, et al., 2018; Obalum & Obi, 2014; Reichert et al., 2022; Reichert, Rodrigues, et al., 2016; Suzuki et al., 2022). Saha et al. (2010) reported increases in soil hydraulic conductivity due to manure or $ISFM_{mnr+fert}$ and a decline with inorganic fertilizer. With minimized evaporative losses and raindrop impact, manures can have positive residual effects on the permeability of tropical soils (Ezenne et al., 2019), suggesting that their effects on similar soils vary with climate. Specifically, Udom and Lale (2017) noted that the practice of poultry manure-based $ISFM_{mnr+fert}$ increased the saturated hydraulic conductivity of a sandy-clay-loam soil, whereas the sole application of inorganic fertilizer reduced it.

Although the prospects of the component of ISFM that involves the complementary application of organic and inorganic fertilizers have been explored in Nigeria (Ameh et al., 2025; Bello & Adekunle, 2013; Obalum, Ogumba, et al., 2020; Ogumba et al., 2024; Ojeniyi et al., 2012; Uwah et al., 2011), none of these studies considered the possibility of differing responses across agro-ecological zones, considering the variability of soils formed under different climatic and biophysical environments. Moreover, only a few of these studies viewed the $ISFM_{mnr+fert}$ as a platform to increase soil pH and SOC for a reflection on soil hydraulic properties. We therefore hypothesized that the $ISFM_{mnr+fert}$ would affect the soil pH, SOC, and soil hydraulic properties but differently in different agro-ecological zones. Hence, this study assessed the effects of $ISFM_{mnr+fert}$ alongside the sole application of poultry manure and inorganic fertilizers on the soil pH, SOC and soil hydraulic properties in the derived savannah and rainforest agro-ecological zones of southern Nigeria.

2. MATERIAL AND METHODS

2.1. Description of the study locations

The study was conducted at Nsukka and Ikole in the derived savannah and the rainforest agro-ecological zones, respectively. The site at Nsukka in southeastern Nigeria is located at 06° 52' N and 07° 24' E and is at an elevation of ca. 447 m asl. The climate is humid tropical and characterized by distinct rainy and dry seasons, generally from April to October and November to March, respectively. The mean annual rainfall is approximately 1600 mm (with a bimodal distribution pattern), whereas the mean annual temperature is 28°C, with relative humidity rarely < 60%. The soil, which is formed from false-bedded sandstone, is deeply weathered, coarse-textured and brownish red when moist. It belongs to the order Ultisols and has been sub-classified using the Soil Taxonomy as Typic Kandiustults (Akamigbo & Igbe, 1990). The surface horizon is sandy clay loam in texture (silt and clay contents of 102 and 262 g kg^{-1}, respectively), low in SOC, and ‘porous’. This physico-hydraulic attribute of the soil renders it highly leached of base-forming cations and strongly acidic (Obalum et al., 2012; Obalum, Okpara, et al., 2011).

The site at Ikole in southwestern Nigeria is located at 7°48' N and 5° 31' E and is at an elevation of ca. 571 m. It also has a humid tropical climate, with distinct rainy and dry seasons. Generally, the rainy season lasts from March to mid-November, and the dry season lasts from mid-November to February. The mean annual rainfall is also approximately 1600 mm, while the mean annual temperature and relative humidity are approximately 25°C and 80%, respectively. The soil, which formed from Precambrian Basement complexes of granitic origin, belongs to the order Alfisols (Bolarinwa et al., 2017). Owing to its particle size distribution in the surface horizon with silt and clay contents of 149 and 172 g kg^{-1}, respectively, the soil is a sandy loam.

The Ultisols in Nsukka appear slightly finer in texture than the Alfisols in Ikole, and the former generally presented a lower soil pH and SOC status than did the latter. The crops commonly grown in both locations are maize, cassava, yam, cocoyam and various vegetables.

2.2. Field experimental layout and treatments

The field trials were conducted in Nsukka and Ikole. At each location, a randomized complete block design (RCBD) with four blocks was used. There were 12 treatments arising from a factorial combination of three rates of poultry manure (0, 5 and 10 t ha^{-1}; coded PM_0, PM_5 and PM_{10}, respectively) with four levels of inorganic fertilizers (0, 50, 100 and 150%; coded IF_0, IF_{50}, IF_{100} and IF_{150}, respectively). The 100% level of inorganic fertilizers here refers to the recommended rate for hybrid maize, which is 400 kg NPK 20-10-10 ha^{-1} followed with 150 kg Urea ha^{-1}. The 400 kg NPK 20-10-10 plus 150 kg Urea ha^{-1} translates into 80 kg N, 40 kg P_2O_5, 40 kg K_2O plus 69 kg N ha^{-1}. Of the 12 treatments, six containing both poultry manure and inorganic fertilizers (PM_5+IF_{50}, PM_{10}+IF_{50}, PM_5+IF_{100}, PM_{10}+IF_{100}, PM_5+IF_{150}, and PM_{10}+IF_{150}) represented $ISFM_{mnr+fert}$, five with only poultry manure or inorganic fertilizers (PM_5+IF_0, PM_{10}+IF_0, PM_0+IF_{50}, PM_0+IF_{100}, and PM_0+IF_{150}) represented the sole application of either of them, while the remaining one with neither of them (PM_0+IF_0) represented the native soil as the control.

2.3. Fieldwork, soil sampling and laboratory analyses

The experiment was repeated for three years (2013-2015). The fields were manually cleared and the treatment plots measuring 5.4 m^2 were marked. Poultry manure, at the specified rates, was first applied on the surface. Using an African hoe, the plots were tilled into flatbeds while the manure was incorporated into the topsoil (0-20 cm). One week later, two seeds of hybrid maize (*Zea mays* L. var. M9211 Yellow) were sown per hole at a spacing of 60 cm × 25 cm. The seedlings were thinned to one after two weeks, resulting in 36 plants per 5.4 m^2 plot (66,666 plants ha^{-1}). Full doses of the NPK 20:10:10 component of IF were applied one week after sowing. A half dose of the urea component of IF was applied four weeks after sowing, and the remaining half was applied at maize tasseling. Standard cultural practices were followed, including manual weeding at 4 and 7 weeks after sowing. The treatments were applied in 2013 (early September) and 2014 (late May), but not in 2015 when their residual effects were tested in early June.

At maize maturity, 100-cm^3 soil cores were taken in triplicate from the topsoil (0-20 cm) of each plot. They were trimmed at both ends and, after firmly covering the base with a cheese cloth, used to assess the effects of treatment on some hydraulic properties. The saturated hydraulic conductivity (K_s) was first determined. To do this, the constant head permeameter method was used to measure the steady state volume of water flowing through the undisturbed soil core (Klute & Dirksen, 1986), after which K_s was calculated using the transposed Darcy's equation for vertical flows of liquids as Equation 1.

$$K_s = (Q/At)\,(L/\Delta H) \qquad [1]$$

where K_s is the saturated hydraulic conductivity (cm h^{-1}) of the soil, Q is the steady state volume of water collected from the saturated soil core (cm^3), A is the cross-sectional area (cm^2), t is the time interval (h), L is the length of the soil core (cm), and ΔH is the change in hydraulic head (cm).

Thereafter, the soil cores were re-saturated and subjected to drainage under 60-cm water-tension for 24 h, after which the macroporosity was determined as the volume of water drained, which was taken as hypothetically occupying the macropores and expressed as a ratio of the core's volume (Kunz et al., 2013; Obalum, Nwite, et al., 2011). The microporosity was obtained by subtracting the macroporosity so determined from the total porosity, which was calculated as the proportional volume not occupied by the solid phase of the soil, the ratio of the bulk density in Mg m^{-3} to the assumed particle density (Obalum & Obi, 2014), which here was 2.65 Mg m^{-3}. The core method was used to determine the soil bulk density, whereby the soil core was oven-dried for 48 h at a temperature of 105°C.

Additionally, loose soil samples collected with the soil cores at the time of sampling were air-dried and passed through a 2-mm sieve. Using the <-2-mm portion, the soil pH was determined in suspensions of soil in de-ionized water at a soil-water ratio of 1:2.5 using a glass electrode pH meter (Mclean, 1982), whereas the SOC was determined by the modified Walkley-Black method (Nelson & Sommers, 1996).

2.4. Statistical analysis

Using the software GenStat 7.2 DE, analysis of variance was performed on the data following the procedure for the RCBD experiments. Where significant effects occurred, treatment means were separated based on the Fisher's least significant difference (LSD). Additionally, the SPSS software (IBM SPSS Statistics 21) was used to apply a *t*-test to the data comparing the two agro-ecological zones and to carry out Spearman's simple linear correlations between each of the soil pH and SOC and the soil hydraulic properties of the study. Both the *t*-test and the correlations utilized means across treatments. Differences among means were considered significant at the 5% probability level ($p \le 0.05$).

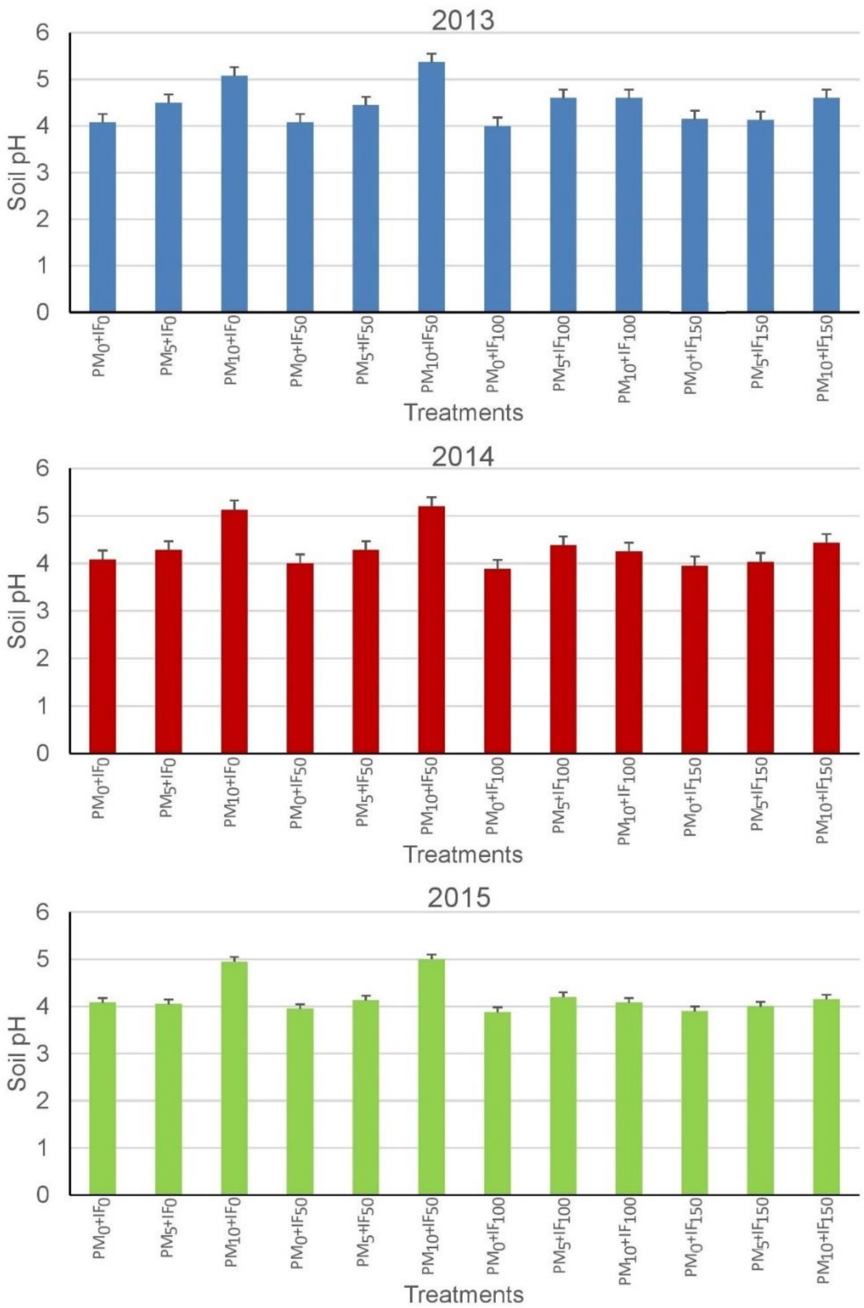

Figure 1: The effects of fertilizer treatments on soil pH at the derived savannah (Ultisols at Nsukka) agro-ecological zones in the 2013, 2014, and 2015 cropping years. Treatment codes bearing PM_0, PM_5, PM_{10} refer to treatments with poultry manure at 0, 5, 10 t ha^{-1}, respectively; those bearing IF_0, IF_{50}, IF_{100}, IF_{150} refer to treatments with inorganic fertilizer at 0%, 50% 100% and 150% recommended fertilizer dose, respectively, being 400 kg ha^{-1} NPK-20:10:10 plus 150 kg ha^{-1} Urea. Error bars represent least significant differences (LSDs) at $p \leq 0.05$.

3. RESULTS

3.1. Soil pH and soil organic carbon

The effects of the combination of poultry manure and inorganic fertilizers at different ratios on the soil pH are shown in Figures 1 and 2. For the Ultisols in Nsukka, the highest values of soil pH occurred in treatments $PM_{10}+IF_{50}$ and $PM_{10}+IF_0$, whereas the lowest values occurred in the control (PM_0+IF_0) and four other treatments (including PM_0+IF_{100} and PM_0+IF_{150}) over all three years of the study (Fig. 1). In 2013, the soil pH was neutral for treatments PM_5+IF_0 (6.68), $PM_{10}+IF_0$ (6.55), $PM_{10}+IF_{50}$ (6.60) and $PM_{10}+IF_{100}$ (6.62), whereas the other treatments, including the control, became slightly acidic. In 2014, all poultry manure and $ISFM_{mnr+fert}$ plots were slightly acidic except for the highest soil pH in $PM_{10}+IF_{50}$ (6.55). The sole application of inorganic fertilizers acidified the soil, with the decreases in soil pH leading to moderately acidic soil in PM_0+IF_{50} (5.93). Greater decreases in soil pH (range, 11.1-11.5% relative to the control) were recorded in PM_0+IF_{150} in 2014 and 2015. For the Alfisols in Ikole, poultry manure and inorganic fertilizers, both as sole applications and as $ISFM_{mnr+fert}$ treatments, also affected the soil pH but to relatively smaller extents (Fig. 2). In 2015, PM_5+IF_0, $PM_{10}+IF_0$, $PM_{10}+IF_{50}$ and $PM_{10}+IF_{150}$ presented slightly acidic soil pH values, whereas PM_5+IF_{50}, PM_5+IF_{100} and PM_5+IF_{150} presented moderately acidic soil pH values.

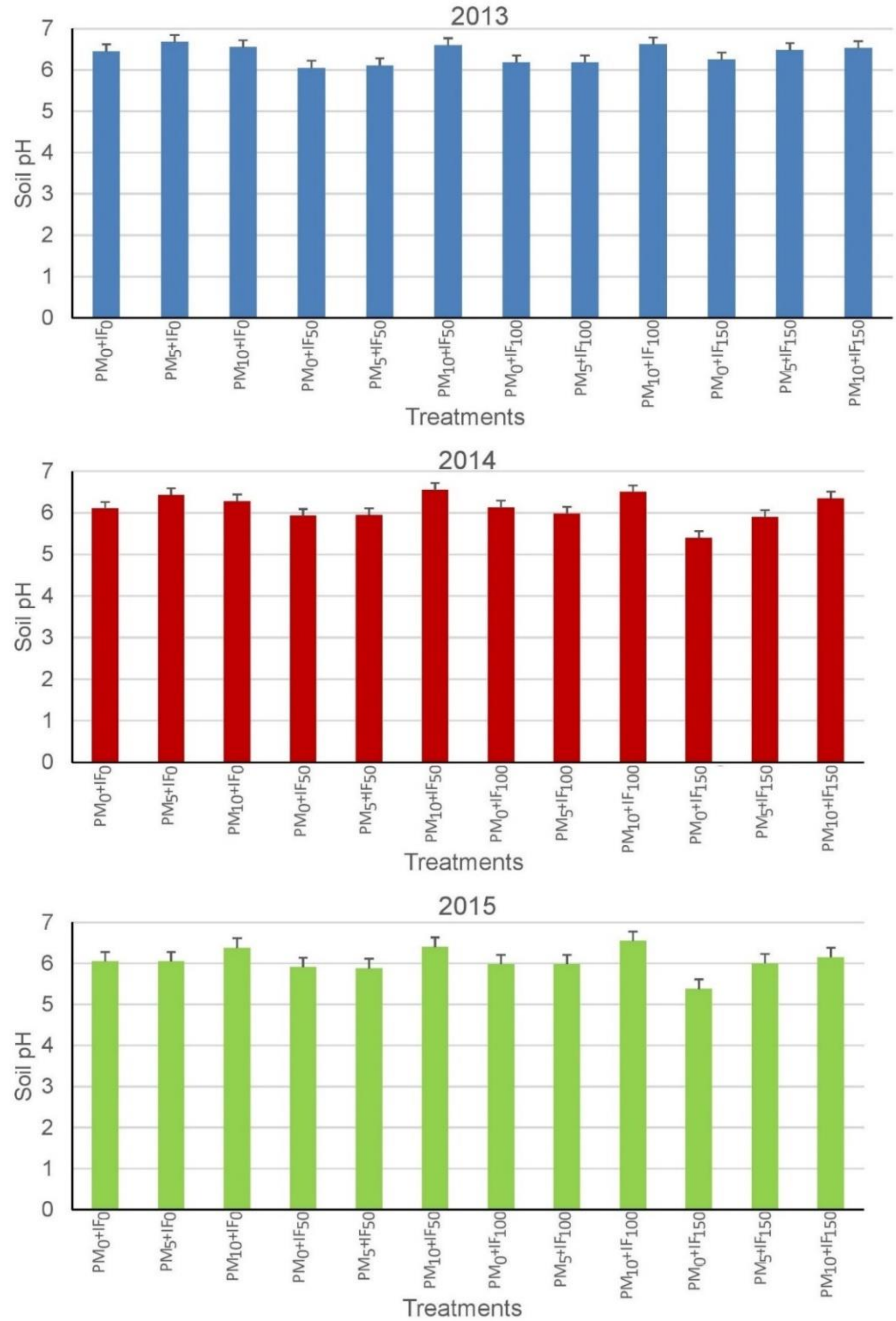

Figure 2: The effects of fertilizer treatments on soil pH at rainforest (Alfisols at Ikole) agro-ecological zones in the 2013, 2014 and 2015 cropping years. Treatment codes bearing PM_0, PM_5, PM_{10} refer to treatments with poultry manure at 0, 5, 10 t ha^{-1}, respectively; those bearing IF_0, IF_{50}, IF_{100}, IF_{150} refer to treatments with inorganic fertilizer at 0%, 50% 100% and 150% recommended fertilizer dose, respectively, being 400 kg ha^{-1} NPK-20:10:10 plus 150 kg ha^{-1} Urea. Error bars represent least significant differences (LSDs) at $p \leq 0.05$.

The SOC concentrations in the soils are presented in Figure 3. The treatment effects were more distinct in the Ultisols than in the Alfisols. For the Ultisols in Nsukka, the SOC values in 2013, 2014 and 2015 were always lowest in the unamended control (8.97, 8.95 and 6.30 g kg^{-1}, respectively), whereas the highest values were observed for treatments PM_{10}+IF_{50} (15.25 g kg^{-1}), PM_{10}+IF_{150} (13.9 g kg^{-1}) and PM_{10}+IF_{100} (10.28 g kg^{-1}), respectively (Fig. 3a).

In 2015, when the residual effects of the treatments were tested, the results for SOC concentrations for the Ultisols in Nsukka were high. The lowest similar SOC values occurred under all four treatments without poultry manure but with increasing levels of inorganic fertilizers. Intermediate similar SOC values were found under all four treatments with poultry manure at 5 t ha^{-1} and increasing levels of inorganic fertilizers starting from the control (i.e., PM_0+IF_0, PM_0+IF_{50}, PM_0+IF_{100}, and PM_0+IF_{150}), whereas the highest similar values were found under treatments with poultry manure at 10 t ha^{-1} and increasing levels of inorganic fertilizers up to the recommended rate of 100% (i.e., PM_{10}+IF_0, PM_{10}+IF_{50}, and PM_{10}+IF_{100}). However, the next treatment in this order, PM_{10}+IF_{150} (which represented the highest rate/levels of both amendments), presented SOC values similar to those categorized as intermediate (Fig. 3a).

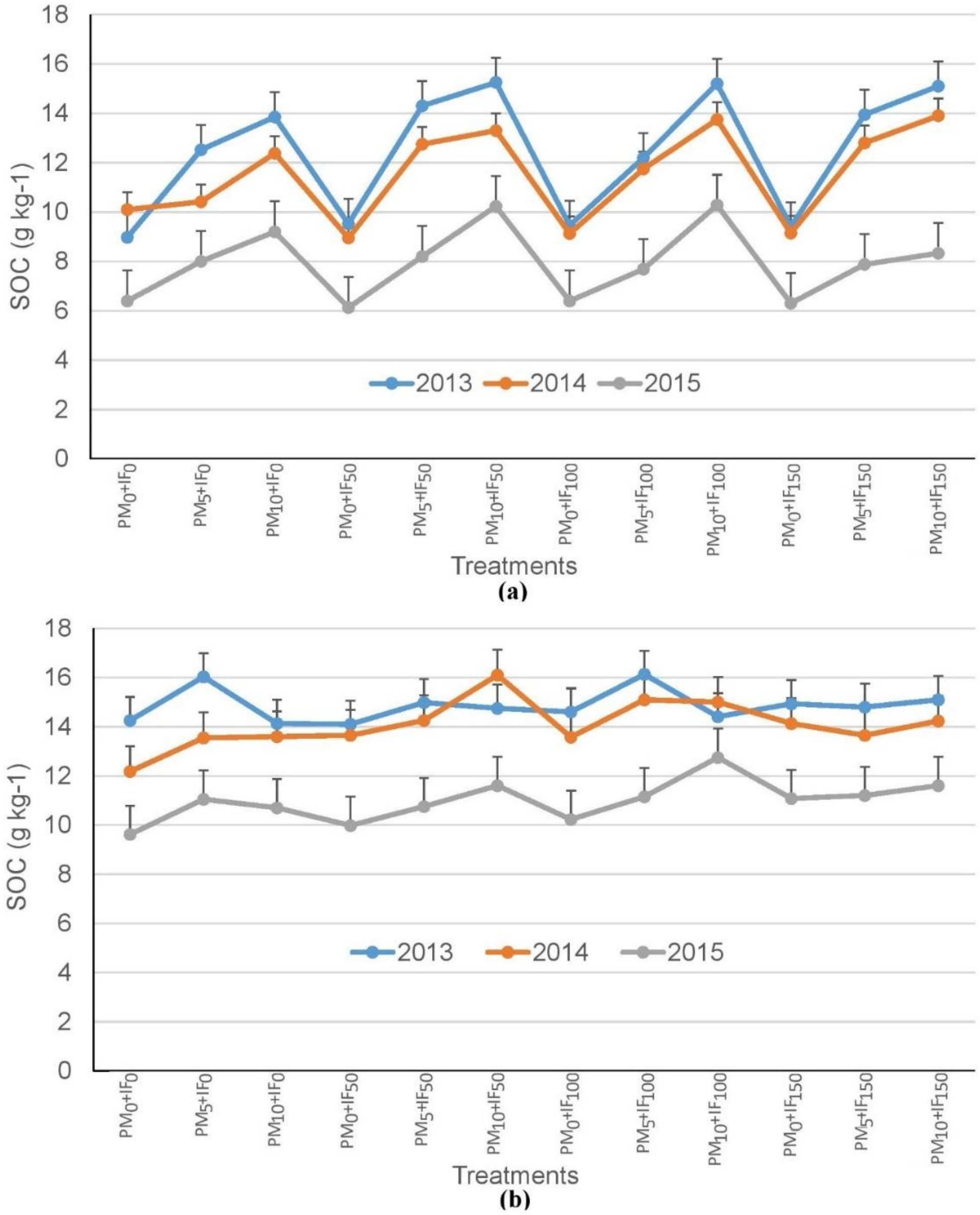

Figure 3: The effects of fertilizer treatments on soil organic carbon (SOC) at **(a)** the derived savannah (Ultisols at Nsukka) and **(b)** rainforest (Alfisols at Ikole) agro-ecological zones in the 2013, 2014 and 2015 cropping years. Treatment codes bearing PM_0, PM_5, PM_{10} refer to treatments with poultry manure at 0, 5, 10 t ha^{-1}, respectively; those bearing IF_0, IF_{50}, IF_{100}, IF_{150} refer to treatments with inorganic fertilizer at 0%, 50% 100% and 150% recommended fertilizer dose, respectively, being 400 kg ha^{-1} NPK-20:10:10 plus 150 kg ha^{-1} Urea. Error bars represent least significant differences (LSDs) at $p \leq 0.05$.

At Ikole, the SOC concentrations in 2013, 2014, and 2015 were also consistently lowest in the non-amended control (14.10, 12.18, and 9.62 g kg^{-1}, respectively); however, the highest values were found in the treatments with the highest rate of poultry manure only in 2014 and 2015 (Fig. 3b). In 2013, treatments PM_5+IF_{100} (16.13 g kg^{-1}) and PM_5+IF_0 (16.03 g kg^{-1}) were similar and exceeded the other treatments (including the control), all of which also presented similar values. In 2014, all amended plots presented increases in the SOC concentration, with the highest values occurring in treatment PM_{10}+IF_{50} (16.10 g kg^{-1}). In 2015, the highest values were found in treatment PM_{10}+IF_{100} (12.75 g kg^{-1}), which were similar to those in treatments PM_{10}+IF_{50} and PM_{10}+IF_{150}, with all amended plots but the PM_0+IF_{50} and PM_0+IF_{100} showing significant increases over the control.

3.2. Soil bulk density, porosity and pore size distribution

The effects of the treatments on the soil bulk density, total porosity, macroporosity and microporosity of the Ultisols in Nsukka are shown in Table 1. In 2013, 2014 and 2015, PM_{10}+IF_0 had the lowest values of soil bulk density (1.35, 1.37, and 1.42 Mg m^{-3}, respectively) and the highest values of both total porosity (0.49, 0.48, and 0.46, respectively) and macroporosity (0.32, 0.29, and 0.24, respectively), and was consistently similar to PM_5+IF_0. Notably, in 2013 and 2014, when the soil received the amendments, the soil bulk density and macroporosity of treatment PM_{10}+IF_0 were similar to those of the $ISFM_{mnr+fert}$ treatments, except for those with the highest level (150%) of inorganic fertilizers.

Table 1. The effects of fertilizer treatments on selected soil hydraulic properties for the Ultisols at Nsukka in the 2013, 2014 and 2015 cropping years

	2013					2014					2015				
Treatments	Soil ρ_b ($Mg\ m^{-3}$)	Total φ	Mac. φ	Mic. φ	K_s ($cm\ h^{-1}$)	ρ_b ($Mg\ m^{-3}$)	Total φ	Mac. φ	Mic. φ	K_s ($cm\ h^{-1}$)	ρ_b ($Mg\ m^{-3}$)	Total φ	Mac. φ	Mic. φ	K_s ($cm\ h^{-1}$)
PM_0+IF_0	1.51	0.43	0.27	0.16	29.25	1.56	0.41	0.22	0.19	31.75	1.67	0.37	0.17	0.20	20.01
PM_5+IF_0	1.40	0.47	0.29	0.19	47.07	1.42	0.46	0.26	0.20	41.25	1.47	0.45	0.23	0.22	39.25
$PM_{10}+IF_0$	1.35	0.49	0.32	0.17	65.18	1.37	0.48	0.29	0.19	54.75	1.42	0.46	0.24	0.22	48.00
PM_0+IF_{50}	1.50	0.43	0.24	0.19	29.76	1.51	0.43	0.21	0.22	28.00	1.57	0.41	0.15	0.26	25.00
PM_5+IF_{50}	1.38	0.48	0.30	0.18	46.08	1.42	0.46	0.26	0.20	45.25	1.48	0.44	0.21	0.23	37.00
$PM_{10}+IF_{50}$	1.39	0.48	0.29	0.19	57.52	1.42	0.46	0.27	0.19	54.00	1.44	0.46	0.23	0.23	53.02
PM_0+IF_{100}	1.49	0.44	0.24	0.20	28.92	1.52	0.43	0.19	0.24	26.00	1.56	0.41	0.18	0.23	24.50
PM_5+IF_{100}	1.38	0.48	0.29	0.19	51.92	1.42	0.46	0.26	0.20	46.25	1.46	0.45	0.21	0.24	43.37
$PM_{10}+IF_{100}$	1.41	0.47	0.28	0.19	66.65	1.41	0.47	0.27	0.20	59.75	1.43	0.46	0.24	0.22	55.00
PM_0+IF_{150}	1.53	0.42	0.22	0.20	28.67	1.56	0.41	0.18	0.23	26.75	1.60	0.40	0.15	0.25	29.00
PM_5+IF_{150}	1.45	0.45	0.25	0.20	31.23	1.46	0.45	0.23	0.22	31.75	1.50	0.43	0.20	0.23	35.25
$PM_{10}+IF_{150}$	1.43	0.46	0.27	0.19	51.23	1.44	0.46	0.24	0.22	46.00	1.48	0.41	0.21	0.22	50.75
$LSD_{(0.05)}$	*0.05*	*0.05*	*0.04*	*ns*	*10.20*	*0.06*	*0.02*	*0.03*	*0.03*	*8.01*	*0.07*	*0.03*	*0.05*	*0.04*	*10.63*

Notes: Treatment codes are poultry manure at any of 0, 5 and 10 t ha^{-1} + inorganic fertilizers at any of 0%, 50%, 100% and 150% of the recommended rates.
ρ_b - bulk density, total φ - total porosity, Mac. φ - macroporosity, Mic. φ – microporosity, K_s - saturated hydraulic conductivity, ns - not significant at $p < 0.05$

Table 2. The effects of fertilizer treatments on selected soil hydraulic properties for the Alfisols at Ikole in the 2013, 2014 and 2015 cropping years

	2013					2014					2015				
Treatments	Soil ρ_b ($Mg\ m^{-3}$)	Total φ	Mac. φ	Mic. φ	K_s ($cm\ h^{-1}$)	ρ_b ($Mg\ m^{-3}$)	Total φ	Mac. φ	Mic. φ	K_s ($cm\ h^{-1}$)	ρ_b ($Mg\ m^{-3}$)	Total φ	Mac. φ	Mic. φ	K_s ($cm\ h^{-1}$)
PM_0+IF_0	1.55	0.41	0.29	0.13	28.91	1.57	0.41	0.25	0.16	29.25	1.57	0.41	0.22	0.19	24.28
PM_5+IF_0	1.41	0.47	0.32	0.15	59.17	1.42	0.46	0.29	0.17	54.25	1.46	0.45	0.22	0.23	48.52
$PM_{10}+IF_0$	1.53	0.42	0.27	0.15	57.62	1.54	0.42	0.27	0.15	49.75	1.52	0.43	0.25	0.18	44.93
PM_0+IF_{50}	1.52	0.43	0.27	0.16	30.31	1.52	0.43	0.23	0.20	31.85	1.50	0.43	0.22	0.22	28.56
PM_5+IF_{50}	1.42	0.46	0.33	0.13	60.44	1.48	0.44	0.28	0.16	53.25	1.53	0.42	0.21	0.21	48.01
$PM_{10}+IF_{50}$	1.41	0.47	0.32	0.15	70.12	1.49	0.44	0.27	0.17	53.00	1.49	0.44	0.24	0.20	51.00
PM_0+IF_{100}	1.51	0.42	0.29	0.13	47.98	1.54	0.42	0.24	0.18	31.18	1.58	0.40	0.18	0.22	32.53
PM_5+IF_{100}	1.52	0.43	0.31	0.12	60.95	1.54	0.42	0.26	0.16	58.75	1.49	0.44	0.22	0.22	45.22
$PM_{10}+IF_{100}$	1.34	0.49	0.35	0.14	67.52	1.52	0.43	0.25	0.18	59.85	1.54	0.42	0.23	0.19	52.29
PM_0+IF_{150}	1.50	0.43	0.28	0.15	42.42	1.54	0.42	0.23	0.19	29.00	1.59	0.40	0.15	0.25	25.96
PM_5+IF_{150}	1.48	0.44	0.27	0.17	52.25	1.52	0.43	0.23	0.20	48.28	1.55	0.42	0.21	0.21	38.47
$PM_{10}+IF_{150}$	1.50	0.43	0.30	0.14	65.59	1.53	0.42	0.23	0.19	57.75	1.50	0.43	0.22	0.21	38.37
$LSD_{(0.05)}$	*0.12*	*0.05*	*0.05*	*ns*	*14.93*	*ns*	*ns*	*ns*	*0.03*	*11.22*	*ns*	*ns*	*0.05*	*ns*	*11.07*

Notes: Treatment codes are poultry manure at any of 0, 5 and 10 t ha^{-1} + inorganic fertilizers at any of 0%, 50%, 100% and 150% of the recommended rates.
ρ_b - bulk density, total φ - total porosity, Mac. φ - macroporosity, Mic. φ – microporosity, K_s - saturated hydraulic conductivity, ns - not significant at $p < 0.05$

The least favourable values of the three soil hydraulic properties (bulk density, total porosity and macroporosity) were always found in treatment PM_0+IF_{150}, and these values were similar to those under PM_0+IF_{100}/PM_0+IF_{50} and, to a smaller extent, the unamended control.

For the Alfisols in Ikole, the soil bulk density, total porosity and macroporosity differed among the treatments in 2013 but not in 2014 (Table 2). The best treatment in 2013 was PM_{10}+IF_{100}, which was generally similar to PM_5+IF_0, PM_5+IF_{50}, and PM_{10}+IF_{50}, which in turn were generally similar to the rest of the treatments except for the control. In 2015, when residual effects were tested, only soil macroporosity was affected, with higher values for PM_{10}+IF_0, PM_{10}+IF_{50}, and PM_{10}+IF_{100} than for PM_0+IF_{100} and PM_0+IF_{150}.

Soil microporosity differed only in 2014 when PM_0+IF_{50}, PM_0+IF_{150}, PM_5+IF_{150}, and PM_{10}+IF_{150} presented the highest values. All four treatments resulted in higher values than did PM_{10}+IF_0 and the control, while PM_0+IF_{50} and PM_5+IF_{150} also resulted in higher values than did PM_5+IF_{50} and PM_5+IF_{100}.

3.3. Soil saturated hydraulic conductivity

Tables 1 and 2 also show the effects of the ISFM treatments on the saturated hydraulic conductivity (K_s) of the studied sandy-clay-loam Ultisols at Nsukka and sandy-loam Alfisols at Ikole, respectively. For the Ultisols in Nsukka, treatment PM_{10}+IF_{100} always resulted in the highest K_s (66.65, 59.75, and 55.00 cm h^{-1} in 2013, 2014, and 2015, respectively), and these values were consistently comparable to those recorded under treatments PM_{10}+IF_{50} and PM_{10}+IF_0. The lowest values were always recorded under treatments PM_0+IF_{150}, PM_0+IF_{100}, and PM_0+IF_{50} which were similar to those of the control. Additionally, PM_0+IF_{150} and PM_5+IF_{150} presented similar K_s values across the three years under consideration.

The results for the Alfisols in Ikole were somewhat similar to those attained for the Ultisols in Nsukka, in that PM_{10}+IF_{100} always gave the highest K_s (67.52, 59.85 and 52.29 cm h^{-1} in 2013, 2014, and 2015, respectively); however, these values were always comparable to those recorded not only under PM_{10}+IF_{50} and PM_{10}+IF_0 but also under PM_5+IF_{100}, PM_5+IF_{50}, and PM_5+IF_0. All these treatments that enhanced K_s presented similar values as treatment PM_{10}+IF_{150} only in 2013 and 2014, when the soil received amendments. Treatments PM_0+IF_{150}, PM_0+IF_{100}, and PM_0+IF_{50}, including the control, generally resulted in the lowest values. Notably, plots that received poultry manure at a rate of 5 t ha^{-1} and those that received poultry manure at 10 t ha^{-1} presented similar K_s values.

Table 3. Soil pH, soil organic carbon and some soil hydraulic properties of the study as compared across treatments for the two agro-ecological zones (derived savannah and rainforest) in 2013, 2014 and 2015 cropping years

Parameter	2013				2014				2015			
	DS	RF	*t*-cal	Sig.	DS	RF	*t*-cal	Sig.	DS	RF	*t*-cal	Sig.
Soil pH	4.47	6.39	−27.17	***	4.32	6.12	−23.06	***	4.20	6.06	−26.17	***
SOC (g kg^{-1})	12.48	14.85	−6.23	***	11.53	14.09	−8.70	***	7.91	10.98	−10.85	***
Soil ρ_b (Mg m^{-3})	1.44	1.47	−2.32	*	1.46	1.52	−4.23	***	1.51	1.53	−1.27	ns
Total ϕ	0.46	0.44	2.42	*	0.45	0.42	4.34	***	0.43	0.42	1.27	ns
Mac. ϕ	0.27	0.30	−3.37	***	0.24	0.25	−1.22	**	0.20	0.21	−1.39	ns
Mic. ϕ	0.19	0.15	7.34	***	0.21	0.17	6.36	***	0.23	0.21	2.90	**
K_s (cm h^{-1})	44.66	53.62	−2.77	**	41.04	47.05	−2.21	*	38.35	40.44	−0.64	ns

Notes: SOC - soil organic carbon, ρ_b - bulk density, total ϕ - total porosity, Mac. ϕ - macroporosity, Mic. ϕ – microporosity, K_s - saturated hydraulic conductivity, DS - derived savannah (Ultisols at Nsukka), RF - rainforest (Alfisols at Ikole), ns - not significant at p < 0 .05, *significant (p < 0 .05), ** highly significant (p < 0 .01), ***very highly significant (p < 0 .001).

Table 4: Correlations of the selected soil hydraulic properties of the study with soil pH and soil organic carbon in the two agro-ecological zones (derived savannah and rainforest) in 2013, 2014 and 2015 cropping years

	Soil pH						Soil organic carbon					
	Derived savannah (Ultisols at Nsukka)			Rainforest (Alfisols at Ikole)			Derived savannah (Ultisols at Nsukka)			Rainforest (Alfisols at Ikole)		
	2013	2014	2015	2013	2014	2015	2013	2014	2015	2013	2014	2015
Soil ρ_b	−0.79**	−0.70**	−0.56*	0.41^{ns}	0.35^{ns}	0.38^{ns}	−0.79**	−0.75**	−0.85***	-0.18^{ns}	−0.25	0.21^{ns}
Total ϕ	0.77**	0.70**	0.58*	0.24^{ns}	0.44^{ns}	0.40^{ns}	0.76**	0.79**	0.79**	0.47^{ns}	0.49^{ns}	0.22^{ns}
Mac.Φ	0.69*	0.75**	0.62*	0.25^{ns}	0.44^{ns}	0.87***	0.61*	0.63*	0.90***	0.37^{ns}	0.19^{ns}	0.26^{ns}
Mic.Φ	-0.15^{ns}	−0.60*	0.20^{ns}	0.04^{ns}	0.26^{ns}	−0.82***	0.03^{ns}	-0.34^{ns}	0.34^{ns}	0.17^{ns}	0.06^{ns}	-0.11^{ns}
K_s	0.85***	0.76**	0.60*	0.48^{ns}	0.57*	0.65*	0.81**	0.80**	0.93***	0.42^{ns}	0.60*	0.66*

Notes: ρ_b - bulk density, total ϕ - total porosity, Mac. ϕ - macroporosity, Mic. ϕ – microporosity, K_s - saturated hydraulic conductivity, ns - not significant at p < 0 .05, *significant (p < 0 .05), ** highly significant (p < 0 .01), ***very highly significant (p < 0 .001)

3.3. Correlations of soil pH and soil organic carbon with soil hydraulic properties

The coefficients of the correlations between the soil pH or SOC and the soil hydraulic properties are shown in Table 4. For the Ultisols in Nsukka, the soil pH was consistently negatively related to the soil bulk density but positively related to the total porosity, macroporosity and K_s. It also showed negative relationships with microporosity but only in 2014. For the Alfisols in Ikole, the relationships were evident only for macroporosity and microporosity in 2015 and for K_s in 2014 and 2015. Notably, soil pH and SOC correlated with hydraulic properties in a rather similar pattern; however, the positive and negative correlations with macroporosity and microporosity, respectively, for the Alfisols in Ikole in 2015 were significant for soil pH but not SOC (Table 4).

4. DISCUSSION

The results presented have shown the effectiveness of complementing poultry manure at 10 t ha^{-1} with NPK and urea-based inorganic fertilizers applied at 50% of the recommended level (PM_{10}+IF_{50}) for coarse-textured loamy tropical soils, regardless of agro-ecological setting. The higher values of soil pH in PM_{10}+IF_{50} than in PM_{10}+IF_{100}/PM_{10}+IF_{150} (Fig. 1 and 2) suggest that sub-optimal levels of inorganic fertilizers, rather than contributing to acidifying the soil, complement poultry manure in increasing the soil pH; however, beyond such sub-optimal levels, this synergy becomes compromised, and the soil-acidifying effect of inorganic fertilizers becomes evident. The values under PM_{10}+IF_{50} and PM_{10}+IF_0 being comparable at Nsukka (Fig. 1) may be linked to the liming effect of poultry manure (Han et al., 2016). Similar increases in soil pH due to poultry manure with or without NPK fertilizer have been reported at this location and elsewhere (Kobierski et al., 2017; Obalum, Ogumba, et al., 2020; Onunwa et al., 2021). The sole application of inorganic fertilizers either caused a decline in soil pH or did not improve the soil pH, as also observed by Obi and Ebo (1995), Obalum, Ogumba, et al. (2020) and Umeugokwe et al. (2021) around the Nsukka location. Increases in soil acidity with the sole application of NPK were reported by Ogundijo et al. (2014). A decline in the pH of tropical soils with inherent extreme acidity is undesirable for increased microbial activity, organic matter mineralization, and nutrient availability and uptake.

In contrast, Ogumba et al. (2024) did not observe any effect of poultry manure applied alone or complemented with NPK fertilizer on soil pH at Nsukka in the Derived Savannah of southern Nigeria. Increases in soil acidity following the addition of only NPK fertilizer were reported by Ayeni (2010). Continuous cultivation with poultry manure at lower rates of 0 and 5 t ha^{-1} involving inorganic fertilizers may thus potentially increase soil acidity in this rainforest zone.

Notably, poultry manure at just 5 t ha^{-1} consistently buffered the soil against acidification due to the application of inorganic fertilizers at the 50% and 100% levels but not at the 150% level for the Ultisols in Nsukka; the reverse was true at Ikole (Fig. 1 & 2). These results imply greater effectiveness of manure in this role in Ultisols than in Alfisols while also highlighting the importance of high soil organic matter in buffering the soil, as was the case for the Alfisols in Ikole.

The results of the SOC concentrations in the soils showed that, in these three years, all treatments with poultry manure (including the $ISFM_{mnr+fert}$ treatments) increased SOC accretion in the soil relative to the control. The differences among the treatments were seemingly driven by the poultry manure constituent of these $ISFM_{mnr+fert}$ treatments. For example, in 2013 and 2014, PM_{10}+IF_{150} with the highest rate/levels of poultry manure and inorganic fertilizers among the $ISFM_{mnr+fert}$ treatments was not different from PM_{10}+IF_{50} with the same rate of poultry manure but with the lowest levels of inorganic fertilizers (Fig. 3a & 3b).

Additionally, PM_0+IF_{50}, PM_0+IF_{100}, and PM_0+IF_{150}, which represent no poultry manure and increasing levels of inorganic fertilizers, presented similar SOC values in 2013 and 2014 (Fig. 3a & 3b). Juxtaposing these data further, however, it appears that inorganic fertilizers are needed at their lowest application level of 50% to enhance the expression of poultry manure effects in the soil. This is buttressed by the higher SOC values in 2013 and 2014 under PM_5+IF_{50} and PM_{10}+IF_{50} than under PM_5+IF_0 and PM_{10}+IF_0, respectively at Nsukka (Fig. 3a). In both years, PM_5+IF_{50} and PM_{10}+IF_0 presented similar SOC concentrations, as also reported by Obi and Ebo (1995) at this study location; however, PM_5+IF_{50} presented lower values than did PM_{10}+IF_{50} in this study, making the latter a better option for enhancing SOC in this derived savannah. Thus, complementing poultry manure applied at 10 t ha^{-1}, being half the recommended rate of 20 t ha^{-1} in this location (Ogunezi et al., 2019), with inorganic fertilizers applied also at half the recommended rates is a promising $ISFM_{mnr+fert}$ strategy as regards SOC management.

In 2015, when the residual effects of the treatments were tested, the results were notable. These results lend support to the (i) afore-mentioned dependence of SOC accretion on poultry manure while showing little or no contribution of inorganic fertilizers to this phenomenon and (ii) the adoption of PM_{10}+IF_{50} as the $ISFM_{mnr+fert}$ strategy for enhancing SOC in the coarse-textured derived savannah soils. Similar SOC values between treatment PM_0+IF_{100} and the control are not unusual in the study area (Obi & Ebo, 1995; Ogumba et al., 2024); the present data only show that increasing the level of inorganic fertilizers in sole application may not cause any difference. Being the residual effects of treatment, the data also suggest that PM_{10}+IF_{50} is a viable choice for stabilizing SOC due to the presence of poultry manure in the soil. Animal manures often do not have residual effects on SOC in sandy-loam Ultisols of the derived savannah due to the prevailing high temperatures and associated rapid decomposition and mineralization rates (Eyibio et al., 2025; Nwite et al., 2014; Obalum, Eyibio, et al., 2020), for which the use of astronomically high rates of poultry manure is now being contemplated (Obalum, Eyibio, et al., 2020).

Treatment PM_5+IF_0 increased SOC in 2013, indicating the effectiveness of poultry manure in increasing SOC in the soil (Soremi et al., 2017). The treatments with the highest rate of poultry manure, which was 10 t ha^{-1}, were not the best in the Alfisols of Ikole in 2013. This could be attributed to the relatively high initial SOC, as was evident in the control (14.25

g kg^{-1}) at this location compared with the Ultisols in Nsukka (8.97 g kg^{-1}) in 2013. In 2014, all amended plots presented increases in SOC, with the highest values in treatment $PM_{10}+IF_{50}$ (Fig. 3b). The same trend was recorded in 2015, although it was non-significant. Increases in SOC even in plots with only inorganic fertilizers relative to the control, as observed in 2014 and for PM_0+IF_{150} in 2015, may be attributed to this inherent medium-to-high SOC status of the soil. Overall, the results again allude to the non-contribution of inorganic fertilizers to SOC accretion, while indicating that $PM_{10}+IF_{50}$ is a suitable $ISFM_{mnr+fert}$ treatment at this location.

When used as complementary soil amendments, animal manures and inorganic fertilizers often have positive effects on the SOC concentration in tropical soils (Ameh et al., 2025; Okojie et al., 2019). The soil can serve as a sink for atmospheric carbon dioxide when rich in SOC (Sandeep et al., 2015; Zhang et al., 2012), which is also a crucial indicator for detecting changes in soil quality (Obalum et al., 2017).

Sole application of inorganic fertilizers tended to favour soil microporosity; however, this may not imply improvements in soil structure. Instead, such increases in microporosity are likely due to clay dispersion and the concurrent collapse of macropores under hydrostatic pressure which may ultimately lead to increases in soil loss due to water erosion (Eyibio et al., 2025). These results suggest that the sole application of poultry manure reduces compaction and promotes aeration in the soil and that $ISFM_{mnr+fert}$ should be implemented without exceeding the recommended level of inorganic fertilizers to achieve similar effects.

With respect to these soil hydraulic properties, the optimum application rate of poultry manure around this location was reported to be 20 t ha^{-1} (Agbede et al., 2017). The present study has shown that $PM_{10}+IF_{100}$ was generally the best in the rainforest zone but that half the application rates of its components (i.e., $PM_{10}+IF_{50}$) could produce similar optimal effects in the soils. The results show that with little or no poultry manure, inorganic fertilizers can lead to increases in the proportion of micropores in the soil, which is attributed to the collapse of soil macropores. Thus, inorganic fertilizers could weaken the stability of macropores in the soils studied, leading to their dilapidation into micropores.

The data for saturated hydraulic conductivity (K_s) of the soils portray this indicator of soil permeability as being controlled by poultry manure alone with inorganic fertilizers at all application levels either having no effect or undermining that of poultry manure where the manure-fertilizer ratio is disproportionately low (Tables 1 & 2). Similar increases in the K_s of soil with poultry manure and decreases in the K_s with inorganic fertilizers have been reported for sandy-clay-loam soil in southeastern Nigeria (Udom & Lale, 2017). The present results reflect the positive effect of SOC on K_s in coarse-textured tropical soils (Oguike et al., 2023).

Poultry manure at rates of 5 and 10 t ha^{-1} resulted in similar K_s values at Ikole (Table 2). This observation was due to the SOC-moderating effect of the prevailing high temperatures in this tropical environment vis-à-vis the initial fairly high SOC content in this Ikole soil, for which the addition of manure beyond 5 t ha^{-1} would not increase SOC further. The K_s data for both soils (locations) suggest that the $ISFM_{mnr+fert}$ treatments are ineffectual for enhancing soil permeability in coarse-textured and loamy tropical soils, as K_s was promoted only by manures even when they were co-applied with inorganic fertilizers at any level.

Since these two locations were under similar management practices, the differences in soil hydraulic properties between them were due more to the differences in their clay contents than to the differences in their SOC contents (Dunjana et al., 2014). Thus, the soil pH, SOC and microporosity, which differed between the two locations even in the year of testing treatment residual effects, represented those which, owing to the differences in biophysical environment including the soil texture between these two locations, would always differ even without soil amendments (see Fig. 1 & 2; Table 1). For example, the lower soil pH at Nsukka than Ikole was expected because the Ultisols of the Nsukka area are highly weathered with low contents of basic cations (Obalum, Okpara, et al., 2011), whereas the Alfisols of Ikole have high to medium contents of basic cations (Shittu, 2014). The lower SOC content for the Ultisols in Nsukka may be traced to the native vegetation (grassland) and greater mineralization of SOC due to the higher environmental temperature than that for the Alfisols in Ikole in the rainforest (Bandyopadhyay et al., 2010). Additionally, the higher soil microporosity for the Ultisols in Nsukka than for the Alfisols in Ikole may be related to the higher clay content in the former than in the latter (Obalum, Nwite, et al., 2011; Obalum & Obi, 2013).

The results of the correlations suggest that the liming effect of manure may increase soil aggregation in humid tropical environments, resulting in reduced soil compaction and increased total porosity, macroporosity and hence water transmission. However, such effects may not be immediately evident in soils with marginal acidity problems, such as the Alfisols in Ikole. In terms of the relationships among soil properties, treatment-induced variations in soil pH, SOC and soil structure rather followed similar trends.

The data for the treatment effects on the soil pH, SOC, and hydraulic properties included in this study showed that the soil and water management practices involving the $ISFM_{mnr+fert}$ generally had more distinct effects in the Ultisols at Nsukka (derived savannah) than in the Alfisols at Ikole (rainforest). Thus, the responsiveness of the soil properties to the treatments of this study, defined here as the ability to discriminate between amended and unamended plots, was generally greater in the Ultisols than in the Alfisols. The higher clay content and hence slower SOC mineralization in Ultisols at Nsukka than in Alfisols at Ikole could partly explain this observation (Dunjana et al., 2014; Mtambanengwe et al., 2004). However, the soil pH and hydraulic properties were less responsive and more readily responsive to poultry manure in the Ultisols (Nsukka site) and Alfisols (Ikole site), respectively. This is exemplified by K_s, whose variations among treatments were due almost entirely to the manure constituent of the $ISFM_{mnr+fert}$, with plots that received poultry manure at 10 t ha^{-1} ($PM_{10}+IF_0$, $PM_{10}+IF_{50}$ and $PM_{10}+IF_{100}$) among those with the highest values for the Ultisols in Nsukka, whereas their counterparts that received this manure at a lower rate of 5 t ha^{-1} produced similar effects for the Alfisols in Ikole (Tables 1 & 2). This aligns with the assertion that more manure is needed to bring Ultisols to the same productivity level as Alfisols (Achieng et al., 2010), represented here by sandy-clay-loam Ultisols (Nsukka location) and sandy-loam Alfisols (Ikole location), respectively. In this study, the favourable soil bulk density, total porosity and K_s of poultry manure-amended plots may be attributed to enhanced macro-aggregation with added organic matter (Gudadhe et al., 2015; Obalum, Ofem, et al., 2024; Obalum, Ugwu, et al., 2024; Ortas et al., 2013). This enhanced soil aggregation increased the proportion of macropores (Muhsin, 2018), leading to increases in K_s. The K_s in humid tropical soils largely depend on soil organic matter-mediated granulation with clay particles to form porous and permeable soil structures (Oguike et al., 2023).

On the other hand, the remaining soil properties, which differed between the studied soils (locations) only in 2013 and 2014, represent soil hydraulic properties whose variations are due more to management than to differences in the biophysical environment. These soil hydraulic properties are responsive to management and thus serve as indices of the relative effectiveness of the treatments at the two locations. For example, the lower soil bulk density for the Ultisols (Nsukka) than for the Alfisols (Ikole) in particularly 2014, when the control plots in these two locations presented similar values (Table 2), suggests that, on average, the treatment more effectively improved this representative soil hydraulic property in the Ultisols than in the Alfisols. This observation supports the insightful comment that the soil properties of this study were more responsive to the organic and/or inorganic soil amendments in the former than in the latter. Considering the role of SOC in lowering soil bulk density (Obalum & Obi, 2014), we attribute this observation to the inherently lower SOC content and hence greater need for organic matter addition via effective animal manures to reduce soil bulk density at both studied sites.

5. CONCLUSIONS

Both $ISFM_{mnr+fert}$ and the sole application of organic and inorganic fertilizers could have more distinct effects in the soil at the derived savannah than the rainforest zone. Poultry manure at a rate of 10 t ha^{-1} complemented with NPK and urea-based inorganic fertilizers applied at 50% of the recommended level (PM_{10}+IF_{50}) was generally the best $ISFM_{mnr+fert}$ in the coarse-textured loamy soils prevailing in these two agro-ecologies. A good substitute for mostly ameliorating soil acidity and improving the hydraulic properties of these soils generally would be the sole application of poultry manure at 10 or 5 t ha^{-1}. This option can also increase SOC concentration in the rainforest. The $ISFM_{mnr+fert}$ strategy may thus not always be necessary to ameliorate soil acidity and increase the hydraulic properties of coarse-textured soils in the humid tropics.

The soil-acidifying effect of inorganic fertilizers can be less pronounced in the derived savannah than in the rainforest zone, with poultry manure being more effective in cushioning this effect in the former than in the latter. Poultry manure promotes SOC accretion and water transmission, with no apparent effect of the inorganic fertilizer level. Though more effective in the derived savannah than the rainforest, PM_{10}+IF_{50} or PM_{10}+IF_0 which improves soil hydraulic properties by modifying the soil pH and SOC status is suggested. The differing responses to treatment in these two contrasting agro-ecologies should serve to discourage unguided adoption of a given combination of organic and inorganic fertilizers in soil and water management outside the zone of original recommendation.

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Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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