RESEARCH ARTICLE

Aggregate stability responses of three derived-savannah soils to poultry-droppings manure at different pulverisation-to-sampling time intervals

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Abstract: Organic inputs to tillage-pulverised soils could, by facilitating soil structure reformation with time, enhance environmental quality. This study examined the aggregate stability responses of three texture-contrasting soils from the derived savannah of southeastern Nigeria to poultry-droppings (PD) manure over time. The soils from Nsukka, Ukehe and Adani with clay contents of 53, 100 and 260 g/kg had antecent organic matter concentrations of 18.77, 29.73 and 16.23 g/kg, respectively, with sandy Nsukka/Ukehe being more stable than loamy Adani. Pulverised soils were amended with PD at rates equivalent to 0, 10, 20, 40 and 70 t/ha, watered and open-incubated under glasshouse conditions. They were augmented to field capacity at three-day intervals and sub-sampled at 2, 4, 8, 12, and 20 weeks after incubation (WAI). Treatment effects were highly soil-dependent. For all three soils, water-stable aggregates, mean-weight diameter (MWD) of aggregates and sand-corrected water-stable aggregates were highest with 70 t/ha at 20 WAI which showed similar MWD of aggregates as 0 t/ha at 20 WAI. Also, 70 and 20 t/ha each at 20 WAI consistently had similar effects (Adani only). Treatment effects on soil bulk density were irregular, with the highest values mostly at 20 WAI across rates. Thus, soil bulk density related inversely with aggregate stability only during 2-12 WAI, owing to their concurrent increases with soil pH beyond 12 WAI. These soil structure indices were not influenced by PD-induced fluctuations in electrical condutivity which always peaked 4 WAI. Heavy and modest PD addition, respectively, to tillage-pulverised sandy and loamy tropical soils promote their re-aggregation after 20 weeks; however, such soils even without manuring could re-structure into aggregates of sizes as though PD-amended over this long interval. Rather than PD-induced salinisation, it is soil pH that influences macro-aggregation up till the 20th week, when soil pH should be ≤ 6.65 to avoid soil densification above 1.71 Mg/m^3.

Keywords: Incubation period, manure rate, organic matter, soil texture, structure reformation

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1 Introduction

Soil structure is characterized by soil aggregation, and results from the rearrangement of primary soil particles, as well as occulation and cementation (Duiker et al., 2003). The associated aggregate stability of soils can have implications for ecological wellbeing, as it defines the extents of root penetration, soil permeability, aeration, microbial activities, and adverse environmental effects of intensive cropping of agricultural lands. The ability of soil aggregates to resist physical stresses determines their ability to sequester and store carbon (Obalum et al., 2012), support germination and rooting of cultivated plants (Angers and Caron, 1998), and responsiveness to surface crusting and erosion (Obalum et al., 2019). Well-managed soil structure could thus check erosion, desertification, and environmental degradation.

Soil texture, Fe and Al oxides, clay minerals, soil organic matter (SOM), base-forming cations, and root exudates are the major soil properties that influence aggregate stability in the tropics (Bronick and Lal, 2005; Igwe et al., 2005; Igwe et al., 2013a). Most tropical soils are deeply weathered, well-drained, acid in reaction and high in Fe and Al oxides but are erosion-prone due to frequent, high-intensity rainfall and low organic-aggregating agents (Igwe et al., 2013a; Ofem et al., 2020). This low structural stability against high-intensity rainfall has long been identified as the most serious soil physical constraint to increased and sustained high-level crop production in the tropical region (Mbagwu et al., 1993). Due to rising pressure on agricultural soils in the region, these soils are often subjected to continuous cropping with various forms of conventional tillage. This practice not only exhausts the soils of their inherent nutrients, but also deteriorates the soil structure. Traditional application of manures (organic fertilizers) and biochars that double as nutrient sources and soil conditioner has the beneficial effects of improving soil pore structure and distribution (Liu et al., 2009; Ebido et al., 2021). Manures are rich in SOM and nutrient elements just as they enhance moisture holding capacity and lateral water movement of sandy soils (Amanullah et al., 2010). Manna et al. (2007) described SOM as a major cause of improvement in soil tilt and structural quality.

The richness and superiority of poultry droppings (PD) over such other manures as pig, goat and cattle dungs in improving soil properties has been reported (Chandrashekara et al., 2000; Chukwuma et al., 2024). The PD is a highly sought-after manure among farmers because of its role in increasing crop productivity (Nwite et al., 2013; Ogunezi et al., 2019; Nnadi et al., 2020). Its being a difficult-to-substitute nutrient source in nusery media (Adubasim et al., 2018), its efficacy in remediation of crude oil-polluted soils (Jidere et al., 2012; Ezenne et al., 2014), and its potential for use in biofuel production (Woldesenbet et al., 2013) all place additional demand on it. Considering the effectiveness of PD when used for agronomic production, ecological restoration or energy production and hence competing demand for it, there is a need to intensify on PD-related soil research to maximise its benefits amongst its various users.

Research on judicious use of PD has traditionally focussed on establishing the optimum agronomic cum ecological rates (Ogunezi et al., 2019; Azuka and Idu, 2021); with only few studies focussing solely on optimum ecological rates (Ezeaku et al., 2020; Udom et al., 2022). The inference from these available data (Ogunezi et al., 2019; Azuka and Idu, 2021) is that PD needs to be applied at the rate of 20 t/ha for optimal effects on crop productivity in coarse-textured tropical soils, but between 30 and 40 t/ha for optimal effects on aggregate stability of these soils 8 and 14 weeks later, respectively. Indications are that under conditions of slowed decomposition and mineralization, PD manure applied at the rate of 40 t/ha may produce optimal effects on soil aggregate stability in shorter times, say 2-4 weeks after application (Chukwuma et al., 2024). Generally, the effects of animal biowaste manures on soil properties that influence aggregate stability in tropical soils have been found to relate to the time since its addition to the soil (Azeez and Averbeke, 2012). These literature data not only suggest that time since manure application is also an important factor in aggregate stability of these soils, but also that there could be interesting interactions between PD rate and duration on their aggregate stability. Wuddivira et al. (2009) reported increased aggregate stability of some tropical soils using 12% farmyard manure at 8 weeks of incubation; however, they did not find any interactions between manure rate and duration in the soils.

In an attempt to satisfy food security demands, the soils are regularly tilled and pulverised leading to disruption of soil structure and dislodging of soil aggregates, without due attention to its reformation and aggregate stability. Viable soil and water management practices including PD addition are often used to surmount the challenges posed by this frequent soil pulverisation. In the best scenario, the soils are manure-amended under field conditions to stabilize the structure overtime and check nutrient loss. Because the effects of PD on soil aggregate stability varies with soil characteristics (Igwe et al., 2013b), it is necessary to assses such effects in some pulverised soils across soil types. Preparing the soil for pot trials involves sun-drying and crushing the soil clods, translating into loss of soil moisture, soil structure deformation, and a decrease in SOM content. This situation often results in lower microbial and fungal activities that invariably contribute to soil aggregation (Plante and McGill, 2002). Soils so prepared thus offer the opportunity to study PD effects on soil structure reformation and associated stabilization of tillage-disturbed and pulverised soils with time.

The current study utilized some three texture-contrasting agricultural soils from Nsukka agroecological zone in the derived savannah of southeastern Nigeria whose structures have been destroyed by pulverisation and hence requiring a structure reformation and stabilization for optimal soil functions. The study set out to determine the influence of application rate of PD and time interval since its application on the structure-related properties of such hitherto tilled and pulverised soils in the derived savannah of the tropics. The aim was to determine the optimum application rate and time interval after application for the much-needed post-tillage improvements in the structure stability of these tropical soils.

2 Materials and Methods

2.1 Study locations, climate and geology of the study area, and sample collection

The study was carried out with three representative soils belonging to three textural classes viz. sand, loamy sand and loam collected from Nsukka (6°51’24”N, 7°23’45”E), Ukehe (6°39’0”N, 7°25’0”E) and Adani (6°44’0”N, 7°01’0”E), respectively, ca. 60, 49 and 63 km, respectively, away from Enugu, southeastern Nigeria. The climate is humid tropical. Mean annual rainfall is in the range of 1600-2000 mm, and is bimodally distributed with peaks in June/July and September/October, often with high intensity. The dry season usually lasts from November to March. Mean monthly temperatures vary between 25 and 28°C. The dominant underlying geological materials in the study area are Sandstone and Shale of varying formations. However, the low-lying and poorly-drained areas are mainly of alluvial formations. The vegetation of the area typifies that of derived savannah, with some patchy relicts of rainforest (Igwe et al., 2013a).

Soil samples were collected from upland soils at Nsukka and Ukehe but from a lowland soil at Adani at 0-20 cm depth using an auger. The study was conducted in the glasshouse at the Faculty of Agriculture, University of Nigeria, Nsukka, between 15 January and 5 June, 2014.

2.2 Glasshouse study and experimental design

The experiment was set up as a factorial study of the effects of application rate of PD manure and duration of incubation of the soil-manure mixture (i.e., time interval since PD application) on soil aggregate stability. To have a better understanding of such effects which may be defined by the inherent texture of the soil, the study was executed using topsoils from 0-20 cm depths with contrasting contents of clay and silt from the selected three locations. These sandy and loamy soils of varying clay and silt contents are the dominant soils found in the Derived Savannah of southeastern Nigeria and hence typify the soil resources of the area.

The soils together with PD manure were air-dried in the glasshouse and crushed to pass via 2 mm sieve to remove any $>$-2-mm non-soil material and debris before preparation and potting of the soil-manure mixture. The crushing was done to simulate soil pulverisation as applicable to the use of conventional tillage to incorporate surface-applied manure into the topsoil. However, doing so and preparing the soil-manure mixture using not the soils in their moist but their air-dry forms was not just to ensure a thorough mix of soil and manure with ease, but more importantly to avoid puddling the soil while striving to achieve this thorough mix.

The manure-amended soils were incubated using 18-cm deep cylindrical plastic pots with surface area of 284 cm^2. The pots were perforated at the bottom to allow for gradual drainage of water. Because of texture-related differences in loose-form densities of the soil aggregates, 5.5, 5.1 and 4.4 kg of the air-dry and sieved soils from Nsukka, Ukehe and Adani, respectively were required to maintain a uniform volume of ca. 5,100 cm^3 in the plastic pots. The PD manure was added at the rates of 0, 28.40, 56.80, 113.60 and 198.80 g per potted soil, aimed at getting equivalents of 0, 10, 20, 40 and 70 t/ha, respectively on surface area basis. Treatments were replicated thrice in a completely randomized design (CRD) for each of the three soils giving 15 potted soils per soil and 45 potted soils in all. Since treatment effects were to be tested separately for each soil, and thus presented in relative terms, randomization was done soil by soil.

Soil and manure were mixed homogenously and potted before watering the mixture to field capacity to initiate open incubation and hence the process of re-structuring and aggregation. The soils were subsequently watered to field capacity at three-day intervals till 20 weeks after incubation (WAI). Potted soils were maintained weed-free all through the glasshouse study. Sub-samples of potted soils were taken for analyses at 2, 4, 8, 12 and 20 WAI.

2.3 Laboratory analyses

The soils as sampled from the three locations were analyzed before the study. Particle size distribution was determined by the Bouyoucous hydrometer method. Soil bulk density was determined by the core method using the 100-cm^3 capacity cores. Before oven-drying the soil cores for 24 h as required for the bulk density, they were first saturated and weighed to enable determination of total porosity, computed as the percentage ratio of volume of water at saturation (taken as numerically equal to its mass since the density of water is 1 Mg/m^3) and the volume of its sampler (Obalum et al., 2011a). Then, saturated hydraulic conductivity was determined by the constant head permeameter method, and the values in cm/h computed using the transposed Darcy's equation, being the ratio of the product of steady state volume of outflow (cm^3) and length of the soil column (cm) to the product of its cross-sectional area (cm^2), change in hydraulic head (cm), and time interval (h). Soil aggregates were subjected to wet sieving using the procedure described by Kemper and Rosenau (1986), described shortly for the analyses done after treatment. Soil pH was determined electrometrically using a pH meter with a soil-water ratio of 1:2.5. Soil organic matter (SOM) concentration was obtained by the modied Walkley-Black wet digestion and combustion method, while total nitrogen was determined by semi-macro Kjeldahl method. Basic cations (K^+, Ca^{2+}, Mg^{2+}, Na^+) were determined by the titrimetric method, while cation exchange capacity (CEC) was determined by the ammonium acetate displacement method and available phosphorus by using the Bray-2 method. The parameters were determined as described by Soil Survey Staff (2014).

After treatment and intervallic sampling, soil bulk density was determined using improvised smaller cores (internal diameter of 2.2 cm and height of 2.7 cm) at every sampling interval to reduce soil structure disruption, considering the small size of the plastic pots. Using Kemper and Rosenau (1986) procedure, the aggregates were separated. Twenty-five grams of air-dried soil aggregates less than 4.75 mm in diameter were separated using a nest of sieves of 2.0, 1.00, 0.50, and 0.25 mm. Water-stable aggregates (WSA) were those that resisted dispersion in water and hence were retained on the sieves after 5 minutes of vertical oscillation. After wet sieving, these dispersion-resistant WSA on each of the four sieves were oven-dried at 40°C for 48 h, merged together, and weighed. The weight was reported as a percentage of the initial mass of soil aggregates, and this was termed %WSA. Thereafter, the sample of merged soil aggregates was washed using 0.1N NaOH to obtain the mass of sand it contained. Then, the trio of %WSA, MWD of soil aggregates and %WSA corrected for sand (WSA_{cfs}) were used as measures of macro-aggregation and aggregate stability of the soils, with the last two represented as:

$$\%WSA_{cfs} = \frac{WSAs - mass\ of\ sand}{initial\ mass\ of\ aggregates - mass\ of\ sand} x\ 100\%$$

$$\text{MWD} = \sum_{i=1}^{n} XiWi$$

where WSA is the sum of the weights of dispersion-resistant soil aggregates on the four sieves used for the wet sieving, *Xi* is mean diameter of size fraction (mm), *Wi* is proportion by weight of the total aggregates for a given size fraction (g/g), and *n* is number of sieves used.

2.4 Data analysis

The soil data were subjected to a two-way analysis of variance for a factorial experiment in a CRD using the software GenStat Discovery Release 7.2 DE (3rd edn.), to test for the interaction effects of application rate of PD and time interval since its application to the soil as well as their main effects. Where the analysis detected significant treatment effects, means were separated by the software-generated least significant difference at $p \leq 0.05$ (LSD$_{(0.05)}$).

3 Results and Discussion

3.1 Selected properties of the three soils and the poultry droppings (PD) before use

Selected physical and chemical properties of the studied soils (Nsukka, Ukehe and Adani) at 0-20 cm of soil depth before the application of PD are presented in Table 1. The soil textures show dominance of sand-sized particles in Nsukka and Ukehe but not Adani, with the soil textural classes being sand, loamy sand and loam, respectively. The dominance of sand-sized particles in Nsukka and Ukehe reflects the influence of the false-bedded sandstone lithology of these soils. The high rainfall regime in the area and sand dominance of the soils facilitate leaching of basic cations leading to low CEC and hence fertility of the soils. Compared to Nsukka and Ukehe, Adani soil has a substantial proportion of silt (320 g/kg), owing to its alluvial lithology.

Bulk density was less than 1.40 Mg/m^3 in the studied soils (range, 1.24-1.37 Mg/m^3), while microporosity ranged from 46.00% to 54.50% (Table 1). The mean values of soil bulk density (1.40-1.51 Mg/m^3) reported by Obalum and Obi (2010) from a tillage experiment in the Nsukka area are slightly higher than those in the current study, thus corroborrating the posited adverse effects of conventional tillage on soil structure in the derived savannah of the tropics.

The indices of aggregate stability of the soils viz percent water-stable aggregates (%WSA), mean-weight diameter (MWD) of soil aggregates, and %WSA corrected for sand (%WSA$_{cfs}$) differed thus Ukehe > Nsukka > Adani. This is understandably due to the dominance of kaolinite in Nsukka and Ukehe soils and the presence of smectite in Adani soil (Igwe et al., 1999), and the tendency for higher macro-aggregate stability of sandier than clayey soils (Mbagwu et al., 1991; Lomeling et al., 2016). The stability of Ukehe soil may also be attributed to its fairly high SOM content (Igwe et al., 2005; Igwe et al., 2013a). The value of MWD of aggregates at Nsukka (1.75 mm) is intermediate compared to the range of 1.1-2.9 mm reported by Obalum and Obi (2010), while Opara et al. (2007) reported, as with the present study, higher values in Nsukka than Adani.

The lowest stability of Adani soil has implications. Aggregate stability of the topsoil correlates with soil erodibility (Le Bissonnais et al., 2007; Obalum et al., 2019). Because of the impact of heavy raindrops and their splashes on soil aggregates in the humid tropics, low stability of soil aggregates could lead to their quick deformation and dispersion in water, leading to the loss of finer aggregates in runoff and associated rill erosion (Igwe et al., 2005; Ihem et al., 2017). This phenomenon is despite the positive influence of the several climate-associated wetting and drying cycles on aggregate stability of tropical soils (Igwe and Obalum, 2013).

Soil pH values of Nsukka, Ukehe and Adani soils were < 5.5 (Table 1), rating them in the strongly acid range (Holland et al., 1989). These low soil pH values reflect the high rainfall regime and the unstable and erodible nature of the soils (Ihem et al., 2017). Nsukka soil showing the lowest value reflects its false-bedded sandstone lithology giving deeply weathered and porous, excessively leached soils, often with appreciable presence of exchangeable acidity (Obalum et al., 2011b). Such low pH values adversely affect soil microbial activity. Similar low values of soil pH (4.4-5.4) were obtained by Opara et al. (2007) in Adani and Nsukka.

Soil organic matter (SOM) and total N showed maximum values in Ukehe, while available P showed maximum value

Table 1. Selected physicochemical properties of the soils before treatment

Location	Clay (g/kg)	Silt (g/kg)	Sand (g/kg)	Textural class	BD (Mg/m^3)	%Micro-porosity	Ks (cm/h)	% WSA	MWD (mm)	% WSA$_{cfs}$	pH-H$_2$O	pH-KCl	SOM (g/kg)	Total N (g/kg)	AvP (mg/kg)	CEC (cmol/kg)
Nsukka	53	67	880	Sand	1.37	46.00	58.77	69.3	1.75	57.16	4.8	4.0	18.8	0.73	9.64	5.73
Ukehe	100	93	807	Loamy sand	1.26	54.50	42.69	78.9	1.82	69.94	5.3	4.4	29.7	1.27	3.11	9.47
Adani	260	320	420	Loam	1.24	51.00	26.12	21.3	0.51	18.34	5.0	4.0	16.2	1.23	6.22	13.00

Note: Ks - saturated hydraulic conductivity, BD - bulk density, MWD - mean-weight diameter, WSA - water stable aggregate, WSA - water-stable aggregates, WSA$_{cfs}$ - water-stable aggregates corrected for sand, SOM - soil organic matter, AvP - available P, CEC - cation exchange capacity.

in Nsukka (Table 1). Irrespective of locations, SOM content could be rated medium to high (Holland et al., 1989). Opara et al. (2007) reported low to medium values of SOM for Adani and Nsukka soils, and attributed same to drying and wetting cycles that stimulated microbial decomposition of SOM. Low SOM, coupled with silt and clay contents, leads to low aggregate stability against degradative forces (Obalum et al., 2011c). By contrast, a considerable amount of SOM ensures good aggregate and soil structure formation, which tends to facilitate water movement through the soil (Ofem et al., 2021; Oguike et al., 2023). The CEC of soils differed thus Nsukka $<$ Ukehe $<$ Adani (Table 1).

Soil available P and CEC are in the low range for tropical soils (Holland et al., 1989). The low capacity of the soils to hold cations in their exchange complex may have resulted from the low surface area and chemical inertness of the dominating sand particles, as well as their contents of SOM (Obalum et al., 2013). Overall, total N, available P, exchangeable K and CEC of the soils depict them as being of low to very low fertility status, necessitating the use PD as an exogenous amendment to improve soil fertility.

Some chemical properties of the PD used are shown (Table 2). The pH as well as organic matter and N contents of the PD were quite high relative to the studied soils.

Table 2. Selected properties of the poultry droppings used for the study

pH	%					
	OM	N	K	Ca	Mg	Na
8.1	64.05	2.31	6.34	4.8	1.6	6.01

Note: OM - organic matter.

3.2 Interaction effects of poultry droppings (PD) rate and time interval since application on macro-aggregate stability of the three soils

The interaction effects of PD rate and time interval on macro-aggregate stability indices (%WSA, MWD and %WSA$_{cfs}$) of the soils studied are shown (Table 3). In all three soils, %WSA was highest with 70 t/ha at 20 WAI. For all application rates, %WSA increased mostly with time resulting in peak values at 20 WAI. This shows that the aggregation function of organic materials is related to the decomposition of SOM (Adesodun et al., 2001). However, for Ukehe and Adani soils, the optimum effects were obtained with 40 t/ha at 8 WAI and with 20 t/ha at 2-4 WAI, respectively. High values of %WSA indicate that soil aggregates would resist disintegration when hit by large raindrops during high-intensity rainfall events that characterize the tropics.

The MWD of aggrgeates had a similar trend as the %WSA with over 80% of the peak values occurring for all PD rates at 20 WAI, the exceptions being Ukehe soil where the maximum values for 10 and 20 t/ha occurred at 12 WAI (Table 3). Notably, MWD of aggregates was either higher in 0 t/ha (control) than 70 t/ha (Nsukka soil) or similar in these two rates (Ukehe and Adani soils) at 20 WAI. This observation, which was probably due to an increase in cohesion development that occurs with time (Kemper and Rosenau, 1986), implies enhanced aggregation of hitherto tillage-disturbed and pulverised soil without PD but over a longer time interval. The organic amendment of the soils would explain the similarity in the trends of MWD of aggregates and %WSA (Are et al., 2017). The PD manure used in the present study has been reported to improve the structure stability of sandy-loam Nsukka soil (Ogunezi et al., 2019; Onah et al., 2023).

The %WSA$_{cfs}$ in all three soils also generally increased with both PD rate and time interval, such that the maximum values occurred with the highest rate (70 t/ha) at the longest time interval between soil-manure incubation and sampling (20 WAI). Similar to the observation for %WSA, 0 t/ha at 20 WAI and 70 t/ha at 12 WAI consistently had similar effects on %WSA$_{cfs}$. Also, for Adani soil, the best generally treatment of 70 t/ha at 20 WAI was similar to 20 t/ha at 20 WAI for all three indices of macro-aggregate stability of this study.

Overall, the upland Nsukka and Ukehe soils showed to be more stable than the lowland Adani soil. This gradient in aggregate stability was to the extent that PD amendment of Adani soil could not close the gap. For instance, the highest MWD of aggregates of 1.27 mm in this study obtained in Nsukka soil with 0 t/ha at 20 WAI more than doubled the value obtained in Adani soil with 70 t/ha at 20 WAI. These observations suggests that inherent soil factors such as texture and, perhaps, mineralogy are more important than organic amendment and time interval in aggregate stability of the soils under investigation. Aggregate stability is relatively high for coarse and medium-textured soils like sandy loams with low SOM contents (Lomeling et al., 2016).

The similarity in the trends of %WSA, MWD and %WSA$_{cfs}$ among the PD treatments and soils of the current study aligns with the study of Obalum et al. (2011a). The macro-aggregate stability indices generally increased with PD rate, suggesting that a good association existed between these indices and SOM (Manna et al., 2007; Li et al., 2011; Ouyang et al., 2013; Onah et al., 2023). This may be explained by the binding action of organic molecules in the soil and SOM-mediated increases in the hydrophobicity of soil aggregates confering on them the ability to resist slaking in water (Abiven et al., 2009). This way, the soil aggregates are preserved from collapse.

3.3 Interaction effects of poultry droppings (PD) rate and time interval since application on soil bulk density of the three soils

The interaction effects of PD rate and time interval on bulk density of the soils are presented in Table 4. These interaction effects were significant, but characterized by an irregular

Table 3. Interaction effects of poultry droppings rate and time interval on water-stable aggre-gates, mean-weight diameter and water-stable aggregate corrected for sand of the three soils

Rates (t/ha)	Interval (weeks)	% WSA	MWD (mm)	% WSA_{cfs}	% WSA	MWD (mm)	% WSA_{cfs}	% WSA	MWD (mm)	% WSA_{cfs}
			Nsukka			Ukehe			Adani	
0	2	24.00	0.49	9.45	34.88	0.55	15.01	7.76	0.22	6.68
	4	30.24	0.52	12.14	26.52	0.45	8.33	10.32	0.28	8.91
	8	31.76	0.66	16.44	32.80	0.63	16.07	12.04	0.34	10.40
	12	34.92	0.79	17.93	33.36	0.70	18.30	13.80	0.41	10.48
	20	49.04	1.27	34.87	49.04	0.86	34.87	16.44	0.51	14.37
10	2	28.60	0.46	17.41	38.28	0.57	17.31	7.64	0.38	6.53
	4	30.60	0.52	12.58	36.48	0.60	20.87	8.80	0.27	8.05
	8	29.72	0.58	14.23	45.92	0.83	29.23	8.88	0.29	12.15
	12	35.48	0.73	20.49	48.92	1.50	29.88	9.92	0.31	7.97
	20	45.16	0.93	31.25	45.16	1.18	31.25	15.72	0.47	13.23
20	2	37.12	0.75	21.58	40.28	0.68	22.91	19.64	0.59	16.37
	4	33.88	0.60	18.71	49.04	0.70	30.83	20.72	0.58	18.06
	8	32.00	0.63	20.02	48.64	0.78	37.85	14.72	0.34	12.70
	12	38.48	0.84	24.87	43.76	0.90	27.41	21.36	0.46	19.32
	20	45.80	0.99	33.70	45.80	0.84	33.70	25.64	0.63	23.16
40	2	35.40	0.60	17.33	46.64	0.72	29.41	16.52	0.45	8.96
	4	35.04	0.63	17.46	44.48	0.63	20.03	15.60	0.37	12.56
	8	39.88	0.62	25.48	51.52	0.83	35.56	15.16	0.40	12.17
	12	44.40	0.71	29.28	51.88	0.86	34.45	18.60	0.44	15.15
	20	49.36	0.83	36.47	49.36	1.02	36.47	18.36	0.44	14.77
70	2	38.08	0.64	17.10	49.44	0.79	33.34	14.84	0.36	10.63
	4	47.16	0.70	24.52	52.60	0.68	31.89	15.92	0.38	13.50
	8	44.68	0.70	28.39	48.64	0.82	31.85	13.92	0.38	11.15
	12	53.20	0.94	39.01	53.76	0.88	39.03	22.72	0.49	19.93
	20	61.56	1.10	50.51	61.96	0.96	50.51	26.72	0.60	24.12
	$LSD_{(0.05)}$	*7.92*	*0.16*	*7.28*	*11.36*	*0.35*	*10.67*	*8.28*	*0.23*	*7.86*

Note: MWD - Mean-weight diameter, WSA - water stable aggregate, WSA_{cfs} - Water stable aggregate corrected for sand, $\text{LSD}_{(0.05)}$ - Least significant difference at $p \leq 0.05$.

Table 4. Interaction effects of poultry droppings rate and time interval since application on bulk density (Mg/m^3) of the three soils

Rates (t/ha)	Interval (weeks)	Nsukka	Ukehe	Adani
0	2	1.56	1.44	1.42
	4	1.76	1.45	1.46
	8	1.61	1.45	1.43
	12	1.56	1.42	1.39
	20	1.94	1.43	1.62
10	2	1.56	1.40	1.42
	4	1.58	1.38	1.39
	8	1.64	1.32	1.40
	12	1.56	1.41	1.35
	20	2.00	2.05	1.61
20	2	1.46	1.30	1.39
	4	1.47	1.35	1.30
	8	1.57	1.29	1.40
	12	1.51	1.32	1.39
	20	1.81	1.85	2.12
40	2	1.52	1.33	1.39
	4	1.57	1.32	1.41
	8	1.56	1.33	1.39
	12	1.52	1.32	1.39
	20	2.04	1.87	1.71
70	2	1.48	1.33	1.37
	4	1.57	1.34	1.39
	8	1.58	1.31	1.41
	12	1.52	1.29	1.37
	20	2.08	1.75	1.25
	$LSD_{(0.05)}$	*0.15*	*0.11*	*0.19*

Note: $\text{LSD}_{(0.05)}$ - Least significant difference at $p \leq 0.05$.

trend among the three soils. The effects were such that, with the exceptions of 0 t/ha for Ukehe soil and 70 t/ha for Adani soil, bulk density values for all the PD rates investigated always peaked at 20 WAI for all three soils (Nsukka, Ukehe and Adani). For Ukehe soil, lowest and similar bulk densities were attained with 20 t/ha at 2 WAI, 20 t/ha at 8 WAI and 70 t/ha at 12 WAI. The interactions between rate of PD and time interval imply that neither of them could serve as a stand-alone factor to index bulk density of the soils; differences among application rates apparently depend on the time lapse before assessing soil bulk density, and vice versa. One other remarkable observation, however, was that PD at 20 t/ha and sampling 2 WAI was among treatments showing the lowest bulk density values across all three soils.

3.4 Main effects of application rate of poultry droppings (PD) on macro-aggregate stability and soil bulk density of the three soils

Aggregate stability indices (%WSA, MWD and $\%\text{WSA}_{cfs}$) generally increased with PD rate from 10 to 70 t/ha for Nsukka and Ukehe soils, and from 10 to 20 t/ha for Adani soil (Table 5). The data also show that 10 t/ha was superior to 0 t/ha (no-amendment control) only for Ukehe soil, but that 20 t/ha produced similar or better results than 40 and 70 t/ha

Table 5. Main effects of application rate of poultry droppings on aggregate stability indices and soil bulk density of the three soils

Location	Rate (t/ha)	DTST (^{o}C)	% WSA	MWD (mm)	% WSA$_{cfs}$	BD (Mg/m^3)
Nsukka	0	33	34.00	0.74	18.71	1.69
	10	34	33.92	0.73	19.19	1.67
	20	33	37.64	0.79	23.77	1.56
	40	33	40.80	0.68	25.20	1.59
	70	32	48.96	0.81	31.91	1.59
	LSD $_{(0.05)}$		*3.52*	*0.07*	*3.26*	*NS*
Ukehe	0	33	35.32	0.64	18.51	1.44
	10	35	42.96	0.94	25.71	1.51
	20	33	45.52	0.78	30.54	1.41
	40	33	48.76	0.81	31.19	1.43
	70	32	53.20	0.82	37.32	1.40
	LSD $_{(0.05)}$		*5.08*	*0.17*	*4.77*	*0.05*
Adani	0	33	12.08	0.35	10.17	1.46
	10	34	10.28	0.34	9.59	1.43
	20	36	20.40	0.52	17.93	1.52
	40	33	16.84	0.42	12.72	1.46
	70	32	18.80	0.44	15.86	1.36
	LSD $_{(0.05)}$		*3.72*	*0.10*	*0.51*	*0.08*

Note: DTST - Day-time soil temperature, WSA - Water-stable aggregates, MWD - mean-weight diameter of soil aggregates, WSA$_{cfs}$ - Water-stable aggregates corrected for sand, BD - Bulk density, LSD$_{(0.05)}$ - Least significant difference at $p \leq 0.05$.

in Adani soil, implying that PD was most effective in this soil. To buttress this point, relative to 10 t/ha, the optimal 70 t/ha for Nsukka and Ukehe soils increased %WSA, respectively by about 44% and 24%; the corresponding increase due to the lower-rate optimal 20 t/ha for Adani soil was 98%. These results reflect the higher sand content of Nsukka and Ukehe soils compared to the least stable Adani soil (Mbagwu et al., 1991), and the fact that PD effects of soil aggregate stability could be location-specific. Obalum et al. (2011c), stressing the relevance of soil structural stability for soil water management, identified low SOM content as a reason for the poorly aggregated and structurally unstable soils in Nsukka agroecological zone. Li et al. (2010) showed that manure application promoted the formation of macro-aggregates. The increases in soil aggregate stability in the present study may be attributed to amendment-induced increases in SOM, as has been reported for organic materials (Opara et al., 2007; Wuddivira et al., 2009) including PD (Adesodun et al., 2001; Ogunezi et al., 2019). The stability against deformation of soil aggregates relates directly with the MWD of aggregates and portends that soils with higher SOM or manure are more aggregated and resistant to structural deformation.

By the aggregate stability indices of this study (%WSA, MWD and %WSA$_{cfs}$), Adani soil was the least stable of the three soils. This has been linked to its mineralogical and textural dissimilarity with Nsukka and Ukehe soils (Mbagwu et al., 1991; Igwe et al., 1999; Lomeling et al., 2016), but the lowest SOM in this Adani soil before treatment (Table 1) could also be a factor. Despite its lowest pre-amendment aggregate stability, this Adani soil recorded the highest proportional increases in aggregate stability at the highest PD rate relative to the control, and this could be due to its highest clay content and hence relative abundance of clay to complex with SOM. The SOM often contributes to macro-aggregation in tropical soils both under natural field conditions (Idowu, 2003; Igwe et al., 2013a) or following organic amendment (Mbah et al., 2007), as also evident in the present study, with the greatest response to PD by the least stable Adani soil compared to the other two soils. This observation highlights the greater influence of intrinsic factors on aggregate stability response of humid tropical soils to organic input.

Generally, increasing PD application rate led to decreases in bulk density for the studied soils, the differences being significant for Ukehe and Adani soils. The implication of these decreases in soil bulk density with increasing SOM decomposition is progressive enhancement of water retention of especially the clay-rich Adani soil (Obalum et al., 2011d). Obi and Ebo (1995), Boateng et al. (2006) and Obalum et al. (2020) reported decreases in soil bulk density following application of PD. In a study of responses of soil aggregate stability to long-term manure application, Whalen and Chang (2002) observed increases in bulk density due to the manurial treatment. Increases in soil aggregate stability associated with enhanced SOM status often manifest in reduction of bulk density of tropical soils (Obalum and Obi, 2014). Treatment of PD that generally increased aggregate stability of the soils also causing decreases in soil bulk density was, therefore, expected. The SOM usually reduces soil compactibility thereby providing a higher soil porosity and lower bulk density (Oguike et al., 2023).

3.5 Main effects of time lapse since application of poultry droppings (PD) on macro-aggregate stability and soil bulk density of the three soils

The main effects of time lapse after the application of PD on some soil properties are presented in Table 6. There were significant increases in %WSA, MWD and %WSA$_{cfs}$ and soil pH. Best results at 20 weeks indicate the essentiality of time after PD application in effective soil structure management. Also, the similar humid tropical environment among the soils may have exerted a similar impact on the soils, resulting in similar effects on the soil properties.

Soil bulk density indicated similar values at 2, 4, 8 and 12 weeks after PD application but was higher 20 weeks after PD application compared to these shorter time intervals ($\leq$ 12 weeks) for all three soils. These results may appear to portary time lapse as a more important factor in soil pore system development than PD application, mainly for Nsukka soil where bulk density indicated similar values among the PD rates. Inverse relationships are often observed between bulk density and aggregate stability of tropical soils (Idowu, 2003; Igwe et al., 2005; Obalum and Obi, 2014). Again, the

Table 6. Main effects of time lapse since application of poultry droppings on aggregate stability indices and soil bulk density of the three soils

Location	Interval (weeks)	DTST (^{o}C)	% WSA	MWD (mm)	% WSA$_{cfs}$	BD (Mg/m^3)
Nsukka	2	33	32.64	0.59	16.57	1.57
	4	34	34.56	0.59	17.08	1.59
	8	33	32.64	0.63	20.19	1.59
	12	33	41.28	0.80	26.32	1.53
	20	32	50.20	1.02	37.36	1.97
	LSD $_{(0.05)}$		*3.52*	*0.07*	*2.26*	*0.07*
Ukehe	2	33	41.92	0.66	23.60	1.36
	4	35	41.84	0.61	22.39	1.37
	8	33	50.20	0.78	30.11	1.34
	12	33	45.52	0.97	29.81	1.35
	20	32	50.20	0.97	37.36	1.79
	LSD $_{(0.05)}$		*5.08*	*0.16*	*4.77*	*0.05*
Adani	2	33	13.28	0.39	9.83	1.39
	4	34	14.36	0.37	12.21	1.39
	8	36	12.96	0.35	11.71	1.41
	12	33	17.28	0.42	14.57	1.39
	20	32	20.56	0.53	17.93	1.66
	LSD $_{(0.05)}$		*3.72*	*0.10*	*3.51*	*0.08*

Note: DTST - Day-time soil temperature, WSA - Water-stable aggregates, MWD - mean-weight diameter of soil aggregates, WSA$_{cfs}$ - Water-stable aggregates corrected for sand, LSD$_{(0.05)}$ - Least significant difference at $p \leq 0.05$.

present data suggest that such relationships manifest within a specified time interval between last disturbance of the soil and the aggregation process, beyond which soil bulk density and aggregate stability assume a positive relationship.

3.6 Treatment effects on soil pH and electrical conductivity of the soils

The interaction effects of application rate of PD and time lapse since application on soil pH and electrical conductivity (EC) are presented in Table 7, while the main effects of these two factors are presented in Table 8. The interaction effects were evident for both soil pH and EC across the three soils (Table 7). Soil pH showed was lowest in 0 t/ha during 8-12 WAI and generally highest in 70 t/ha treatments. Notably, soil pH showed different patterns in 0 t/ha where it decreased from 2 to 12 WAI but increased at 20 WAI and in 10 t/ha where it increased steadily with time. In 20, 40 and 70 t/ha, however, soil pH exhibited no definite pattern over 2-20 WAI for Nsukka and Ukehe soils, whereas the tendency to increase with incubation time persisted in 20 t/ha and vice versa in 40 and 70 t/ha for Adani soil. The main effects showed that soil pH increased with PD and also with time, the percentage increases in 70 t/ha relative to the control (0 t/ha) being 39.66%, 24.56% and 42.59%, and increases at 20 relative to 2 WAI being of 4.17%, 5.80% and 45.28% for Nsukka, Ukehe and Adani soils, respectively (Table 8). Thus, PD application rate is a weightier factor than time lapse in ameliorating acidity of Nsukka and Ukehe soils following pulverisation, unlike Adani soil where these two factors contribute fairly

Table 7. Interaction effects of poultry droppings rate and time interval since application on soil pH and electrical conductivity of the three soils

Rates (t/ha)	Interval (weeks)	Soil pH-H$_2$O			EC (mS/m)		
		Nsukka	Ukehe	Adani	Nsukka	Ukehe	Adani
0	2	5.8	5.6	5.5	1.3	0.7	1.3
	4	5.5	5.7	5.3	2.0	7.0	8.3
	8	5.4	5.3	5.1	3.7	0.7	2.7
	12	5.3	5.6	5.1	1.3	1.0	1.0
	20	6.9	6.5	5.8	0.7	1.0	1.0
10	2	7.0	6.5	5.8	0.7	1.7	1.0
	4	7.1	6.8	6.7	14.3	12.3	30.3
	8	7.2	7.5	6.8	5.0	0.7	0.7
	12	7.2	6.5	6.7	1.0	1.3	0.7
	20	7.4	7.4	6.8	0.7	0.7	1.0
20	2	7.6	6.5	5.8	6.3	4.0	3.7
	4	6.9	6.8	6.7	51.3	42.3	60.7
	8	7.5	7.6	7.1	0.7	0.3	1.0
	12	6.8	6.8	7.0	1.0	1.0	1.3
	20	7.3	7.4	7.3	1.3	0.3	1.0
40	2	7.7	7.5	7.7	2.7	4.0	3.7
	4	7.7	7.5	7.5	33.0	41.3	66.3
	8	7.5	7.8	7.6	0.7	0.3	1.7
	12	7.8	7.7	7.4	1.3	1.3	1.7
	20	8.0	7.6	7.2	0.0	0.7	1.3
70	2	7.9	7.9	8.0	2.0	3.0	4.0
	4	8.1	7.9	7.7	40.3	48.3	75.0
	8	8.2	8.2	7.8	1.0	1.0	1.0
	12	8.3	8.1	7.6	0.7	1.3	0.7
	20	8.0	7.8	7.4	0.0	0.1	0.7
	LSD $_{(0.05)}$	*0.51*	*0.42*	*0.50*	*7.81*	*3.44*	*7.95*

Note: EC - Electrical conductivity, LSD$_{(0.05)}$ - Least significant difference at $p \leq 0.05$.

Table 8. Main effects of each of application rate of poultry droppings and time lapse since application on soil pH and electircal conductivity of the three soils

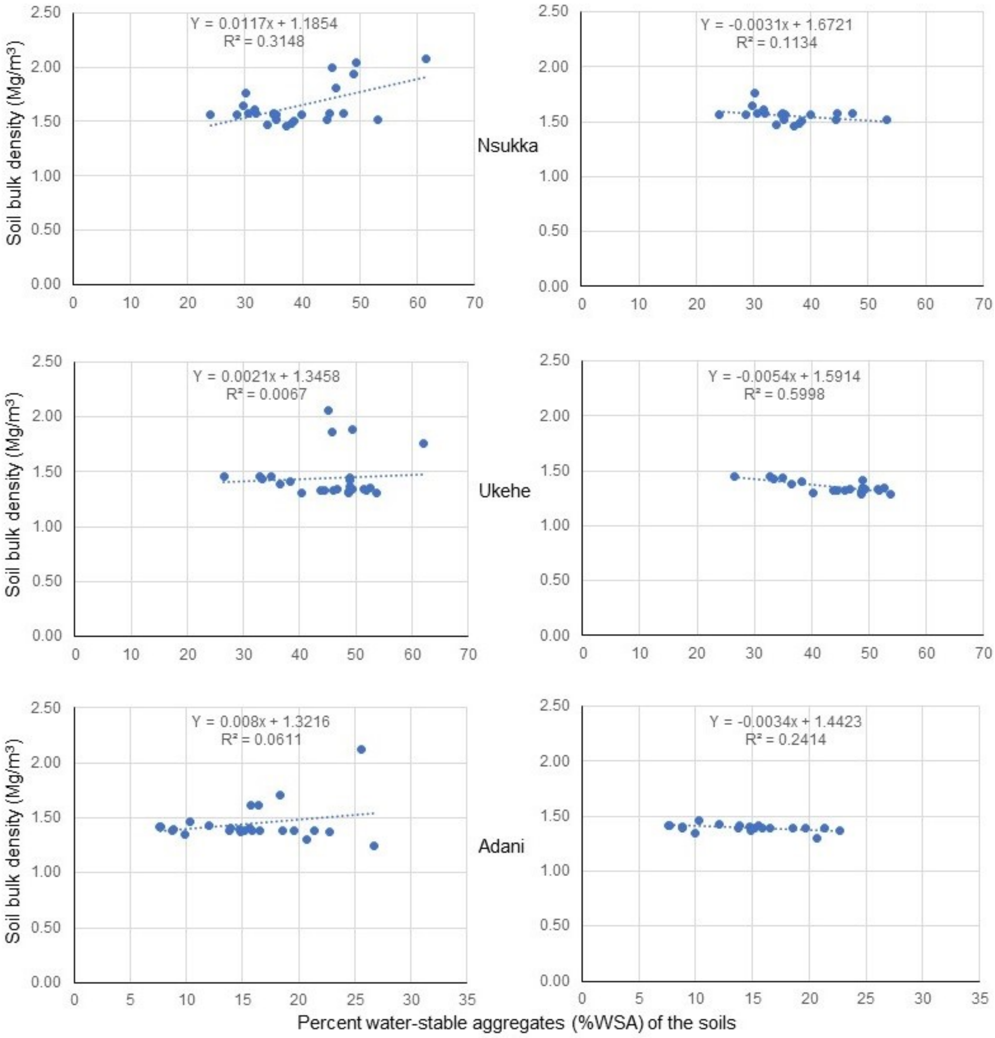
Location	Rate (t/ha)	Soil pH-H$_2$O	EC (mS/m)	Interval (weeks)	Soil pH-H$_2$O	EC (mS/m)
Nsukka	0	5.8	1.8	2	7.2	2.6
	10	7.2	4.3	4	7.0	28.2
	20	7.2	12.1	8	7.1	2.2
	40	7.7	7.5	12	7.1	1.1
	70	8.1	8.8	20	7.5	0.5
	LSD $_{(0.05)}$	*0.23*	*3.49*	*LSD* $_{(0.05)}$	*0.19*	*1.54*
Ukehe	0	5.7	2.1	2	6.9	2.7
	10	6.5	3.3	4	7.0	30.2
	20	7.0	9.6	8	7.1	0.6
	40	7.0	9.5	12	7.0	1.2
	70	7.1	10.7	20	7.3	0.6
	LSD $_{(0.05)}$	*0.18*	*1.54*	*LSD* $_{(0.05)}$	*0.19*	*1.54*
Adani	0	5.4	2.9	2	5.3	2.7
	10	6.6	6.7	4	6.7	48.1
	20	7.0	13.5	8	7.0	1.4
	40	7.5	14.9	12	7.5	1.1
	70	7.7	16.3	20	7.7	1.0
	LSD $_{(0.05)}$	*0.23*	*3.56*	*LSD* $_{(0.05)}$	*0.25*	*3.55*

Note: EC - Electrical conductivity, LSD$_{(0.05)}$ - Least significant difference at $p \leq 0.05$.

equally. The results further showed the optimal application rate to be soil-specific, and that, beyond 20 t/ha, Nsukka and Ukehe soils were the least and most buffered, respectively.

Overall, the results show that PD could be an effective liming material for acid tropical soils (Ogunezi et al., 2019; 2020; Umeugokwe et al., 2021). This liming effect of PD in these soils may be atributed to its appreciable content of base-forming elements. It could also be due to the replacement of OH- in Al or Fe hydroxyl oxides by organic anions released during PD decomposition (Van et al., 1996; Pocknee and Summer, 1997), the increases in negative charge of which facilitate the retention of the otherwise leached basic cations in the soil system (Wuddivira et al., 2009). The PD-mediated preponderance of negative charges manifesting as increases in soil pH would also explain the direct relationship often observed between PD-associated SOM and aggregate stability of the soils (Ogunezi et al., 2019). As observed here, soil pH often shows a positive relationship with PD application rate (Duruigbo et al., 2007; Ogunezi et al., 2019) and time interval since application (Onah et al., 2022). Soil pH also controls the solubility, availability (Hue et al., 1992; Hue and Licudine, 1999), and toxicity or deficiency of most soil nutrients (Azeez and Averbeke, 2012). Considering the high-intensity rainfall as well as coarse texture and low SOM status of most agricultural soils for which soil erosion and leaching of base-forming cations are related serious problems in the study region, these PD effects on soil pH have important agroecological implications.

The EC of the soils was quite erratic, fluctuating without a definite trend as influenced by the rate and time interval of PD application (Table 7). However, a striking point is the consistent peak values at 4 WAI for all application rates, whereas over 70% of minimum values occurred at 20 WAI. Minimum values of 0.0 in Nsukka (40 t/ha), 0.10 in Ukehe and 0.70 mS/m in Adani at 70 t/ha were obtained at 20 WAI. The main effects showed that, for Nsukka soil, 20 t/ha gave



(a)

(b)

Figure 1. Regression of soil bulk density on percent water-stable aggregates of the pulverised and poultry droppings-amended soils before (a) and after (b) excluding data for 20 weeks after incubation for structure reformation when soil bulk density was higher compared to the shorter time intervals (2-12 weeks).

higher EC than all other rates but 70 t/ha, while for Ukehe and Adani soils 20, 40, and 70 t/ha were similar and higher than 10 t/ha and the control, while showing that the soils are most prone to salinity effects around four weeks after pulverisation and PD application (Table 8).

Soil EC indicates SOM mineralization of SOM and serves as a measure of soluble nutrients for both cations and anions (De Neve et al., 2000), making it to often toe the pattern of SOM in the soil (Tyopine et al., 2022). Animal feed additives contain appreciable amounts of salts (Dong et al., 2001; Goff, 2006). Increases in EC are thus attributed to the salt released during microbial decarboxylation and mineralization of PD (Davies et al., 2006; Wuddivira et al., 2009). Similar increases in EC with increasing PD rate have been reported by Watanabe et al. (2016). Also, Azeez and Averbeke (2012) reported an increase in EC with increasing duration of incubation, a situation with high potential for inducing salinisation in the soil. For the three soils studied, no meaningful relationships were found between the indices of soil structure and EC, suggesting that PD-induced salinisation of the soils do not influence macro-aggregation.

3.7 On the anomalous pattern of changes in bulk density of the PD-amended soils with time

The most plausible reason for the observed increases in soil bulk density of the pulverised and PD-amended soils beyond 12 WAI and soil structure reformation (Table 6) is the difference in the pattern of PD effects on soil bulk density and macro-aggregate stability. In this study, these two indices of soil structure exhibited similar response patterns up till 12 WAI but not at 20 WAI. Thus, no inverse relationships existed between soil bulk density and macro-aggregate stability of the PD-amended and restructuring soils, until the data for 20 WAI were excluded. Using %WSA to represent all three macro-aggregate stability indices of this study, these seemingly time-dependent relationships are illustrated (Figure 1). These density-stability relationships were most pronounced for Ukehe soil followed by Adani soil, the two soils where PD caused significant decreases in soil bulk density.

On examining the situation further, soil bulk density and aggregate stability were found to exhibit differential responses to treatment-induced changes in soil pH. Soil bulk density of the pulverised, PD-amended soils was apparently not influenced by the changes in soil pH during 2-12 WAI but increased with soil pH at 20 WAI, while their aggregate stability increased with increases in soil pH up till the last sampling at 20 WAI and soil structure reformation. Thus, there were differences in the shape and strength of the relationships between soil bulk density and soil pH as examined for up till 20 WAI and for the shorter time intervals. The reverse was true for aggregate stability. Using Ukehe soil where the seemingly time-dependent density-stability relationship was most pronounced, these differential responses of soil bulk density and macro-aggregate stability to changes in soil pH are exemplified (Figure 2 and 3, respectively).

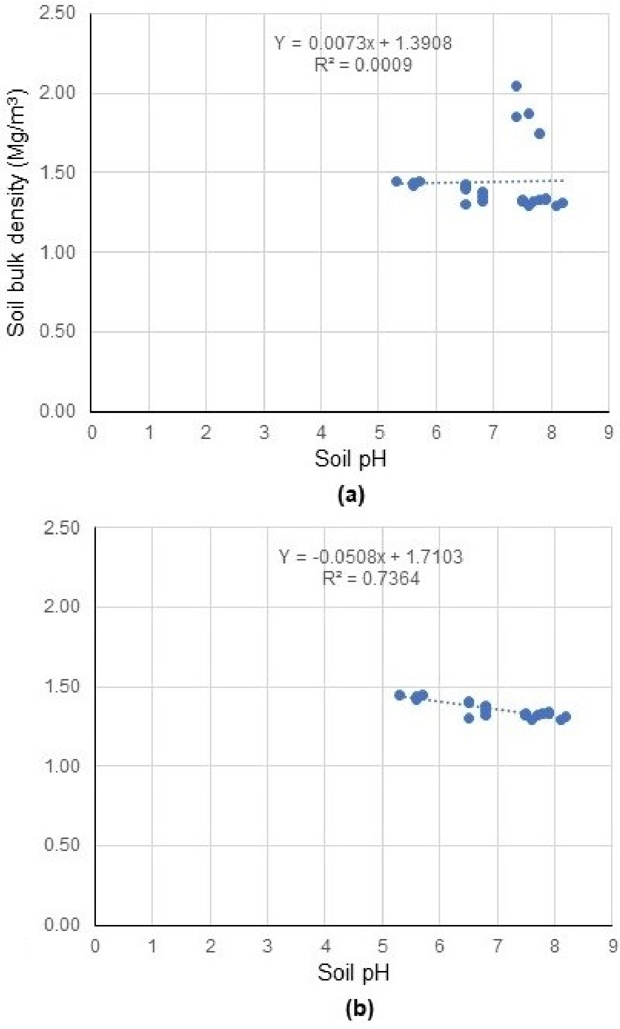


Figure 2. Regression of bulk density on soil pH for the pulverised and poultry droppings-amended Ukehe soil before (a) and after (b) excluding data for 20 weeks after incubation for soil structure reformation when soil bulk density was higher compared to the shorter time intervals (2-12 weeks).

The observation for soil bulk density suggests that, around 20 WAI, further release of negative charges due to the added manure advances repulsion between clay particles leading to clay dispersion and plugging of soil pores (Wuddivira et al., 2009), which translates into higher soil bulk density. But 2-12 WAI is the time limit when the progressive increases in the release of such negative charges remain below or equal to the corresponding release of positively charged base-forming cations in the soil, translating into greater retention of the latter. This manifests not just as progressive increases in soil pH but also as progressive improvements in aggregation and hence decreases in soil bulk density. By the relationship shown, soil bulk density decreases from 1.71 Mg/m^3 by about 0.05 Mg/m^3 for every unit change in soil pH (Figure 2a). By contrast, at and even beyond this stage

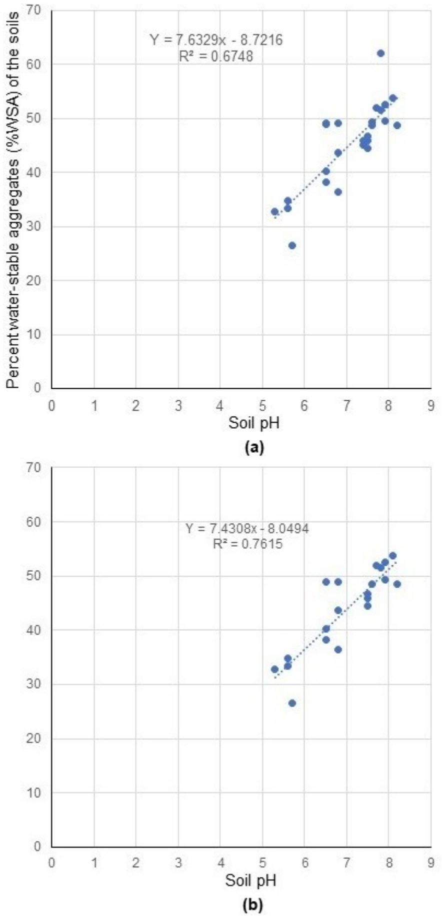


Figure 3. Regression of percent water-stable aggregates on soil pH for the pulverised and poultry droppings-amended Ukehe soil before (a) and after (b) excluding data for 20 weeks after incubation for soil structure reformation when soil bulk density was higher compared to the shorter time intervals (2-12 weeks).

of structure reformation of tillage-pulverised and manure-amended soil, SOM-mediated progressive improvements in micro-aggregate stability of the soils are expected to still prevail (Adesodun et al., 2001; Wortmann and Shapiro, 2007), because the excess negative charges induced in these soils usually promote the binding of positively charged Fe and Al oxides (Wuddivira et al., 2009; Igwe et al., 2013a).

The relationship between soil bulk density and soil pH at 20 WAI, obtained with the three soils combined, is shown (Figure 4). The data show that, regardless of soil type, the probability of bulk density exceeding the aforementioned upper limit during 2-12 WAI (1.71 Mg/m^3) once soil pH exceeds 6.65 around 20 WAI is about 44%. Considering that this critical value is already high particularly for the loamy Adani soil, the use of PD manure as a source of SOM to facilitate structure reformation in tillage-disturbed soils of the humid tropics should be done with caution. Such a soil and water management practice should aim at adopting soil-specific modest application rates of PD that would, instead of producing excessive liming effect in the soil that becomes increasingly evident with time, always maintain the soil pH at a near-neutral value below 7.

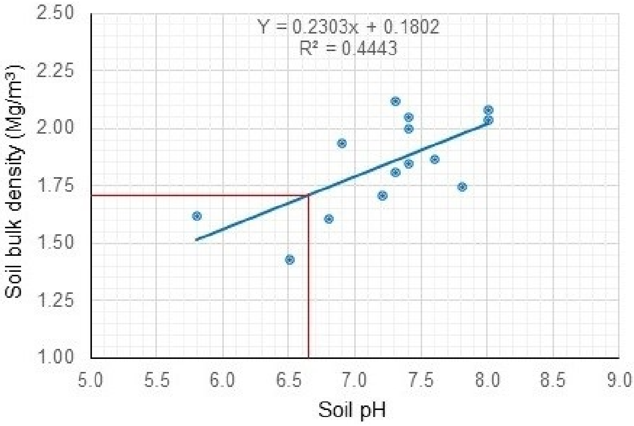


Figure 4. Regression of soil bulk density on soil pH for the pulverised and poultry droppings-amended soils at 20 weeks after incubation for soil structure reformation, using data for the three soils (Nsukka, Ukehe and Adani) combined.

On the other hand, the time-insensitive positive relationship between macroaggregate stability and soil pH in this study of PD manure's ability to promote re-aggregation of tillage-disturbed acid tropical soils seems desirable. Contrary to this observation, Idowu (2003) found a negative relationship between aggregate stability and soil pH (range, 4.5-7.0) in southwestern Nigeria, attributing the observation to the presence of Fe^{2+} and Al^{3+} in soil solution. Maintaining the soil pH below 7 in order not to induce increases in soil bulk density (as suggested by the data in Figure 4) may thus change the direction of the relationship between macroaggregate stability and soil pH. The present results would also be explained by the said presence of Fe^{2+} and Al^{3+}. The influence of these acid-formimg cations would depend on whether they are occuring freely in soil solution as key agents of flocculation but also decreasing soil pH (Idowu, 2003), or flocculating with negatively charged SOM radicals steadily released from the mineralizing manure into the soil system (Wuddivira et al., 2009). In humid tropical soils, therefore, there is a need for a balance in these seemingly double-edge roles of the cations, achievable by application of PD at rates that raise the soil pH to near-neutral values below 7. By our data, these acidity-ameliorating rates would appear to lie between 10 and 20 t/ha (Table 5). Somewhat similar to this observation, Duruigbo et al. (2007) reported increases in soil pH from 4.1 in the control to 5.8 due to a maximum PD rate of 15 t/ha in southeastern Nigeria.

4 Conclusions and Recommendation

Application of PD manure to somewhat degraded soils of the humid tropics that are frequently subjected to structure-disrupting tillage and allowing the amended soils ample time to mineralise is a promising soil and water management option for promoting the much-needed re-aggregation while ameliorating soil acidity. The highest improvements in soil macro-aggregate stability seem to be achieved with increasing application rate and time interval. However, these PD and time effects can be soil-dependent, as such improvements could be achieved less easily as regards quantity of PD manure to apply generally in sandy, loose and hence highly leached soils compared to their loamy counterparts. Interestingly, this study found soil structure reformation following tillage and associated loosening or structure deformation to not only proceed in these soils without manuring, but also to attain the extent of giving similar sizes of soil aggregates as though PD-amended after a long time interval of about 20 weeks. Leaving the soils so disturbed unamended for a considerable length of time but without further disturbance could thus be a good soil structure reformation strategy.

In this study, we found that the expected decreases in soil bulk density with increasing macro-aggregation of PD-amended soils might cease to be realised at a certain critical stage of their mineralisation when the progressive increases in soil pH start causing increases in these two indices of soil structure alike. Such increases in soil pH of PD-amended tropical soils could, therefore, ultimately lead to soil compaction even with increased macro-aggregate stability. To avoid this situation, PD manuring should aim at initial slow decreases in soil bulk density achievable with gradual increases in soil pH up to a maximum of 6.65. It is also important to exercise caution in the use of PD manure in improving re-aggregation of tillage-pulverised tropical soils, for indications are that soils so amended may become saline around four weeks later, even when such salinisation may not influence soil macro-aggregation.

Overall, soil texture and, perhaps, mineralogy appear to be the underlying factors in structure reformation responses of humid tropical soils to PD manure but not passage of time. The agronomic implications of the findings of this study is that, if structure-disrupting conventional tillage must be practised in arable crop production, no two short-season crops with a growth cycle of less than 20 weeks should consecutively follow each other.

Author Contributions

Obalum S.E. conceptualized and designed the study, participated in field collection of soil samples, supervised the study, conducted the data analyses, and improved on the writing of the edited draft of the manuscript. Ofem K.I. carried out the data screening and also edited the first draft of the manuscript. Nwamba D.C. participated in field collection of soil samples and also carried out the glasshouse study and the laboratory soil analyses. Joseph P.O. participated in setting up the glasshouse study and was also involved in managing the literature. Edeh G.I. was involved in designing the study and writing of the first draft of the manuscript. Amalu U.C. examined and approved the data for publication and also edited the first draft of the manuscript. Charles A. Igwe provided the logistics and assisted with the overall advisory and administrative management of the project. All authors read and approved the final draft of the paper.

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Conflict of Interest

The authors declare no competing interests.

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