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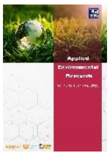

Research Article

Seasonal Variations in CO_2 Emission from Poultry Manure-amended Soils in Two Contrasting Tropical Agroecosystems

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Abstract

The soil remains the largest carbon sink, the capacity of which varies spatiotemporally and with anthropogenic activities, with implications for carbon dioxide (CO_2) emissions and associated global warming. Despite the increasing popularity of organic amendments in the ecologically and anthropoculturally diverse farming systems of tropical Africa, manure-induced CO_2 emissions in this region with high soil-carbon-sequestration potential are poorly documented. This study assessed seasonal CO_2 emissions from poultry manure-amended sandy-clay-loam and sandy-loam soils in the Rainforest-Savannah and Southern Guinea Savannah zones, respectively, of Nigeria. Following manure application at 3 rates (0, 10, and 15 t ha^{-1}), soil samples were collected during 5 periods (onset, peak and cessation of the rainy season and onset and peak of the dry season). Soil CO_2 emissions were monitored after 7-, 14- and 21-day incubations. The emissions varied across manure rates, sampling periods and locations. Compared with 0 t ha^{-1} treatment, 15 and 10 t ha^{-1} treatments consistently resulted in higher emissions. These emissions were generally highest at the peaks of the rainy/dry season and lowest at the end of the rainy season, while higher at the southern Guinea Savannah than the Rainforest-Savannah zone. Overall, all three factors studied together described the emissions, which were lower for 7-day than for 14/21-day incubation. To reduce CO_2 emissions, poultry manure application at rates ≥ 10 t ha^{-1} should be discouraged in the humid tropics, particularly locations with fairly warm climates and sandy soils. This study highlights the global warming implications of the increasing adoption of animal manures as organofertilizers and, by extension, the nonconfined rearing of poultry/livestock in tropical African agro-ecosystems. Studies involving different organic soil amendments at varying application rates and agronomic management practices are suggested, especially for coarse-textured soils of the widespread savannah, to deepen the understanding of the mechanisms regulating CO_2 emissions.

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Introduction

A high amount of greenhouse gas (GHG) emissions originate from anthropogenic activities (Yue and Gao, 2018), in which 22% of total GHG emissions are the result of agricultural activities (Platis et al., 2019). Among all known GHGs, carbon dioxide (CO_2) is perhaps the most devastating. Increases in the atmospheric concentration of CO_2 affect ozone levels in several ways, including by moderating the levels of nitrogen oxides (through the stratosphere cooling effect of such increases) that attack and deplete the ozone layer (Stolarski et al., 2015). The net effects of this dynamic balance of CO_2 and nitrogen oxides are global warming (greenhouse effects) and climate change (Igwe and Obalum, 2023). The soil is the largest carbon sink in our terrestrial ecosystems, and its capacity in this regard can be compromised by anthropogenic—mostly agricultural—activities, with impli-cations for CO_2 emissions and associated global warming.

The sequestration of organic carbon in agricultural soils remains a climate change mitigation tool that deserves the attention of scientists (Lassaletta et al., 2015). Agricultural activities influence both carbon sequestration and CO_2 emissions via several processes, the topmost of which is the soil application of manures. There have been reports of significant and marginal increases in CO_2 fluxes in agricultural soils after manuring (Liu et al., 2024; Ryals and Silver, 2013; Cai et al, 2012). The application of crop residues and animal waste to soil usually increases soil microbial biomass and CO_2 emissions (Rahman, 2013). Manuring thus leads to microbial-enhanced decomposition of the substrate and the release of CO_2 as a byproduct (Nawaz et al., 2017). Animal manures are a source of carbon for microbial activity (Uzoh et al., 2015), but they also strongly increase CO_2 emissions (Oraegbunam et al., 2023). Soil respiration, a measure of soil biological activity, is a major flux within the global carbon cycle and results in the emission of approximately 10 times more CO_2 to the atmosphere annually than fossil fuel combustion does (Lassaletta et al., 2015; Bond-Lamberty and Thomson, 2010). Agricultural intensification through the use of agrochemicals, mostly mineral fertilizers, but their abuse causes soil nutritional imbalances and environmental pollution (Penuelas et al., 2023). This situation has paved the way for increased use of different animal manures (sometimes with nitrogen-rich mineral fertilizers), which, however, concurrently increase agronomic production and GHG emissions. Poultry-dropping manure is, to date, the richest and most readily mineralized of all animal manures (Chukwuma et al., 2024; Chandrashekara et al., 2000) and hence the most widely used in agronomic production. Gerber et al. (Gerber et al., 2013) predicted that poultry production, mostly chicken meat and eggs, would increase by 61% and 39%, respectively, by 2030. The poultry industry is thus rapidly growing globally, resulting in high production of poultry manure (Bolu et al., 2014). The use of poultry manure as an organic amendment enhances soil quality and productivity (Obalum et al, 2024a; 2024b; Onah et al., 2023; Umeugokwe et al., 2021; Nnadi et al., 2020; Ogumba et al., 2020; Ogunezi et al., 2019); however, as a good source of nutrients and energy for its microbiome and soil microbes, poultry manure often causes substantial increases in CO_2 emissions (Shakoor et al., 2021).

While poultry manure has gained attention over the years for its use in improving soil conditions, its mineralization might be affected by external factors. This is because both poultry manure nutrients and environmental conditions, such as temperature variations, can affect GHG emissions (Brouček and Čermák, 2015). Such emissions could thus vary not only among locations (Iboko et al., 2023) but also across seasons of the year in a location. For proper isolation of the environmental conditions under which organo-based soil fertility management is most suitable with respect to GHG emissions, there is a need to integrate environmental factors in the investigations involved (Olaleye et al., 2020). Such an approach would enrich our knowledge of the dynamics of mineralization, especially fast-mineralizing organic amendments such as poultry manure, in soils and, therefore, provide a better understanding of their CO_2 emission rates from such soils.

Tropical regions are characterized by diverse ecological settings. This is especially true in tropical Africa, where the agro-environment exhibits ecological and anthropo-cultural diversities, represented by distinct rainy and dry seasons, diverse soil resources and many indigenous/exotic agricultural production systems. Considering that tropical Africa is potentially the world's soil carbon sequestration center for offsetting GHG emissions (Obalum et al., 2012a), understanding carbon dynamics across its diverse agro-ecologies is crucial. Despite this situation and the increasing popularity of organic amendments in this region, studies on variations in CO_2 emissions due to agricultural management practices in the region's rainforest and vast savannah agro-ecosystems are rare (Iboko et al., 2023), and virtually none exists specifically for the continued use of the most popular poultry manure.

In the derived savannah of Nigeria, which epitomizes the warm climates of tropical Africa, soil organic carbon is susceptible to changes in the short to medium term due to alterations in land use and management practices (Obalum et al., 2012a; Anikwe, 2010), implying that soil CO_2 emissions are similarly affected. The relatively short timeframe required to acquire data on the carbon dynamics of tropical African agroecosystems is considered an advantage in the much-needed research efforts. To address the problem of limited attention given to carbon dynamics in the savannah zone of the tropical region

(Boakye-Danquah et al., 2014), we monitored the seasonal variations in soil CO_2 emissions in response to poultry manure application in the Rainforest–Savannah transition and Southern Guinea Savannah zones of Nigeria. We hypothesized that CO_2 emissions would vary with the application rate of poultry manure during different sampling seasons in contrasting agroecological zones (locations), regardless of the soil incubation interval for the emissions.

Materials and methods

1) Description of the study locations/sites

This study was conducted in two agroecological zones in Nigeria during the 2021 and 2022 annual cycles. The agroecosystems included the Rainforest–Savannah transition zone, represented by Akure in Ondo State, and the Southern Guinea Savannah Zone, represented by Anyigba in Kogi State, both of which are in Nigeria. Akure is located in the southwest region (7.18° N and 5.84° E), with a mean annual rainfall between 1300 and 1600 mm, which usually occurs from March to November, with a peak in July. The dry season lasts for three months, from December to February. It has a mean annual temperature of 32°C and a relative humidity of 85% to 100% during the rainy season and < 60% during the dry season and is at an elevation ranging from 255 m to 381 m above sea level (Fasinmirin and Oguntuase, 2006; Onyekwelu et al., 2006). Anyigba is located in North Central China (7.30° N and 6.42° E). The mean annual rainfall is 1408 mm, with a bimodal distribution pattern that usually peaks between July and September. The dry season lasts for approximately five months, from November through March. The temperature varies from 17 to 36.2°C. The relative humidity is moderately high and varies from an average of 65% to 85% throughout the year. The topography of the area consists of undulating plains or land slopes (Amhakhian and Osemwota, 2012).

2) Experimental design

The two agroecological zones (rainforest–Savannah transition and southern Guinea savannah) were the major factors. The sampling period (5) was the subfactor, and the poultry manure rates (3) were the subfactors. The 5 sampling periods consisting of the subfactors were the onset of the rainy season (ORS), peak of the rainy season (PRS), cessation of the rainy season (CRS), onset of the dry season (ODS), and peak of the dry season (PDS) (the classification is presented in Tables 2 and 3). The 3 application rates of poultry manure consisting of the subfactors were 0, 10, and 15 t ha^{-1}. At each location, the 3 poultry manure rates were applied to 4-m^2 (2 m × 2 m) plots, which were replicated 3 times in a randomized complete block design (RCBD), resulting in 9 plots. The plots were fenced using earthen bunds that were raised 30 cm high to prevent overland flow among the plots, with the replicates and the plots therein demarcated with 1-m wide walkways. The 9 plots were sampled at the designated 5 sampling periods, resulting in 45 observations per location and 90 observations for the 2 locations. The experiment lasted from March 2021 to February 2022.

3) Experimental procedures and sample collection

The key physicochemical properties of the soils present at the two study locations are summarized in Table 1. These soil properties, including the cation exchange parameters, help in comparing the two locations in terms of preamendment soil fertility status. The sites have loamy soil in the rainforest–Savannah zone and coarse-textured sandy loam soil in the southern Guinea savannah zone. The poultry manures used as organic soil amendments in this study were collected from the animal section of the respective Teaching & Research Farms of the Federal University of Technology, Akure, and Prince Abubakar Audu University, Anyigba, which are the two locations of the study. Following the procedure of Carter and Gregorich (2007), the poultry manures were analyzed for their nutrient compositions (Table 2). Poultry manures used as soil amendments in southern Nigeria often have low CN ratios of 6.4–7.9 (Nnadi et al., 2021; Ogumba et al., 2020; Igwe et al., 2013; Nwite et al., 2012a; b) or intermediate values of 10.4–14.9 (Ugwu et al., 2024; Ndzeshala et al., 2023; Adubasim et al., 2018). The CN ratios of the poultry manures in the present study are thus low (range, 7.8–8.4), implying their rapid decomposition and mineralization in the soil.

The experimental field was adequately prepared before the surface of the poultry manure was broadcast. Equivalent amounts of 10 and 15 t ha^{-1} poultry manure for the 4-m^2 plots were applied to the plots to receive them at the two locations before the onset of the rains in March 2021. The application was by broadcasting, after which the manure was incorporated into the soil with a hoe. Soil samples were collected during the sampling periods from each plot at the 0–15 cm depth via a soil auger. The five sampling periods of ORS, PRS, CRS, ODS and PDS corresponded to March–April 2021, May–August 2021, September–October 2021, November– December 2021 and January–February 2022, respectively, following the meteorological data recorded throughout the sampling periods. Large pieces of plant material were removed. The soil samples were immediately transferred into zip-lock bags in the field to prevent them from drying, and they were taken to the laboratory for CO_2 emission determination.

Data on monthly variations in weather parameters during the entire sampling months were collected from the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL) and the collaborating Federal University of Technology, Akure, for the rainforest-Savannah zone location and also from the Department of Geography of Prince Abubakar Audu University, Anyigba, for the Southern Guinea Savannah Zone location (Tables 3 and 4).

4) Determination of CO_2 emissions

The CO_2 emissions were determined following the laboratory procedure of Herath et al. (2015). In this method, approximately 50 g of each soil sample was placed in preweighed Agee jars. The weights of each soil sample and Agee jar were weighted to obtain the wet weight of each soil slice. Then, 25 mL of 0.5 M sodium hydroxide (NaOH) solution was dispensed into a 125-mL conical flask and placed on the soil surface inside the Agee jar to absorb CO_2. A control consisting of three blank Agee jars containing 25 mL of 0.5 M NaOH in a 125-mL conical flask with no soil was set up. The lids of all the jars were screwed tightly and incubated at 25°C for 7, 14, and 21 days. On the day of expiration of each incubation interval, the conical flasks were removed, and the amount of CO_2–C evolved was analyzed via volumetric titration. To do this, 4 mL of 0.5 M NaOH trapping solution from the control jar was pipetted into a 50-mL conical flask. This was followed by the addition of 10 mL of 0.4 M barium chloride. Four drops of the phenolphthalein indicator were subsequently added to the flask, resulting in a flak yellow color. The content was titrated with a 0.2 M HCl acid solution to obtain a colorless solution (end point). Reading was performed on the burette, and the volume of HCl acid used in the titration process was noted. This procedure was repeated for the other two blanks and for the trapping solution used in the other jars. The mass of CO_2 (mg) emitted per gram of wet soil slice was computed following Rahman (2013), as briefly described below.

First, the number of moles of CO_2 reacted with NaOH was obtained as the difference in volume (mL) of the HCl acid used to titrate NaOH in the conical flask removed from the control jars and that used to titrate the NaOH in the conical flask removed from the soil-containing jars (i.e., the volume of the acid saved for a given treatment relative to the control) multiplied by the normality of the acid. The number of moles of CO_2 that reacted with NaOH was then multiplied by the equivalent weight of CO_2, which was 22 g, to obtain the mass of CO_2 (mg) emitted per gram of wet soil slice. The CO_2 emission was expressed as mg CO_2 50 g^{-1} soil.

5) Statistical analysis

As a factorial study of the effects of poultry manure, sampling period and location, two-way analysis of variance was used to examine the CO_2 emissions for significant differences among the poultry manure rate, sampling period and location treatments separately for the three soil incubation intervals (7, 14 and 21 days). To do this, we used the MINITAB Analytical System (Minitab® 19), and the means were separated by Tukey's test at the 5% probability level ($P < 0.05$).

Table 1 Soil physicochemical properties at the two study locations before poultry manure application

Parameters	Locations	
	Rainforest-Savannah	Southern Guinea Savannah
Soil pH in H_2O	6.2	4.8
Soil organic carbon (g kg^{-1})	24.70	7.90
Soil total nitrogen (g kg-1)	3.00	0.40
Available phosphorus (mg kg^{-1})	1.88	5.87
Exchangeable sodium (cmol kg^{-1})	0.08	0.37
Exchangeable potassium (cmol kg^{-1})	2.14	1.56
Exchangeable magnesium (cmol kg^{-1})	2.35	1.54
Exchangeable calcium (cmol kg^{-1})	4.46	3.38
Total exchangeable bases (cmol kg^{-1})	9.03	6.85
Exchangeable acidity (cmol kg^{-1})	0.82	1.49
Cation exchange capacity (cmol kg^{-1})	10.13	8.5
Clay (g kg^{-1})	252	141
Silt (g kg^{-1})	162	79
Sand (g kg^{-1})	586	782
Texture class	Sandy clay loam	Sandy loam

Table 2 Nutrient composition (g kg^{-1}) of the poultry manures as collected and used for each location

Locations	Organic carbon	Nitrogen	Phosphorus	Potassium	Calcium	C/N
Rainforest-Savannah	254.00	32.40	30.00	15.60	12.40	7.84
Southern Guinea Savannah	245.60	29.30	25.20	14.00	10.00	8.38

Table 3 Monthly weather variables at the Rainforest-Savannah transition zone during the study

Sampling periods	Months of the year	Soil temperature (°C)		Rainfall (mm)	Relative humidity (%)
		Maximum	Minimum		
ORS	March 2021	32.5	24.8	84.5	96.12
	April 2021	31.7	24.5	139.5	95.98
PRS	May 2021	29.8	24.0	132.6	96.34
	June 2021	28.7	23.1	233.7	97.29
	July 2021	27.3	23.0	115.6	97.73
	August 2021	27.2	23.1	251.8	96.24
CRS	September 2021	28.7	23.3	269.7	98.68
	October 2021	29.6	23.9	158.9	98.29
ODS	November 2021	31.0	24.3	50.8	97.11
	December 2021	33.4	22.7	5.5	94.63
PDS	January 2022	33.6	20.6	0.0	95.20
	February 2022	35.6	25.3	8.6	84.57
	Mean	*30.8*	*23.6*	*120.9*	*95.7*

Source: West African Science Service Center on Climate Change and Adapted Land Use (WASCAL), Federal University of Technology, Akure, Nigeria.

ORS – onset of rainy season, PRS – peak of rainy season, CRS – cessation of rainy season, ODS – onset of dry season, PDS – peak of dry season

Table 4 Monthly weather variables at the Southern Guinea Savannah zone during the study

Sampling periods	Months of the year	Soil temperature (°C)		Rainfall (mm)	Relative humidity (%)
		Maximum	Minimum		
ORS	March 2021	33.7	21.7	0.6	84.00
	April 2021	33.3	21.0	45.0	83.20
PRS	May 2021	32.6	20.3	51.0	83.10
	June 2021	30.5	19.4	94.0	83.30
	July 2021	29.0	18.4	63.0	88.00
	August 2021	28.3	18.0	131.0	84.00
CRS	September 2021	28.9	17.8	87.0	83.60
	October 2021	30.9	25.3	44.0	84.20
ODS	November 2021	33.0	26.4	2.0	83.10
	December 2021	33.3	25.9	0.0	84.50
PDS	January 2022	33.3	21.6	0.0	86.90
	February 2022	34.2	21.7	38.0	83.50
	Mean	*31.7*	*21.5*	*46.3*	*84.3*

Source: Department of Geography, Prince Abubakar Audu University, Kogi State, Nigeria.

ORS – onset of rainy season, PRS – peak of rainy season, CRS – cessation of rainy season, ODS – onset of dry season, PDS – peak of dry season

Results and discussion

1) Variations in CO_2 emissions according to poultry manure rate, sampling period and location

Figure 1 shows the variations in CO_2 emissions due to the different rates of poultry manure as pooled across the sampling periods and locations and presents all three incubation intervals of 7, 14 and 21 days. Among the manure application rates, significant increases in CO_2 emissions were consistently found at 15 t ha^{-1}, which, however, was similar to the increase of 10 t ha^{-1}. These two treatments showed higher emissions than 0 t ha^{-1}. Under glasshouse conditions, the application of poultry manure at a rate equivalent to approximately 30 t ha^{-1} to loamy sand in southwestern Nigeria was reported to increase CO_2 emissions by approximately three times 14 days after incubation (Oladipo et al., 2011). Measurements under field conditions following poultry manure application at a rate of 3 t ha^{-1} to a silty-clay soil elsewhere in the tropics also revealed higher CO_2 emissions in amended plots than in their unamended counterparts (Abbas et al., 2012). A comparison of the quantities of CO_2 emissions in the present study with those of other tropical studies just cited (Abbas et al., 2012; Oladipo et al., 2011) is, however, difficult due to environmental and methodological differences.

The intent of soil application of poultry manure is often to increase soil organic carbon and nutrient stocks. In southern Guinea savannah, which was one of the locations of the present study, such an increase in soil organic carbon in response to poultry manure was recently reported (Joseph et al., 2025). In the derived savannah of southeastern Nigeria, which lies between the two locations of this study, the application of poultry manure has been reported to increase the soil organic carbon content (Chukwuma et al., 2024; Ndzeshala et al., 2023; Adekiya et al., 2020; Adeyemo et al., 2019; Ogunezi et al., 2019; Nwite et al., 2012b), even beyond the season of its application (Osakwe et al., 2025a; 2025b; Onah et al., 2023). With respect to environ-mental quality, therefore, poultry manure could have two seemingly opposing effects: increases in CO_2 emissions and increases in soil organic carbon.

For agronomic production in the derived savannah of southeastern Nigeria, poultry manure has been suggested to be applied at a minimum rate of 10 t ha^{-1} (Obi and Ebo, 1995), but the optimum rate is generally 20 t ha^{-1} (Azuka and Idu, 2021; Nnadi et al., 2020; Ogunezi et al., 2019). In the present study, this minimum 'agronomic' rate of 10 t ha^{-1} always caused higher CO_2 emissions than did 0 t ha^{-1}. As the incubation interval increased, CO_2 emission increased. These observations demonstrated that poultry manure application to the studied soils at 15 t ha^{-1} would increase CO_2 emissions and that reducing the rate to 10 t ha^{-1} would not make any difference. Therefore, a tradeoff is involved in adopting 10 t ha^{-1} poultry manure, which may have positive effects on soil organic carbon and agronomic productivity with a reduced negative impact on the environment.

The CO_2 emissions varied among the sampling periods but were not consistent across the three incubation intervals of the study (Figure 2(a)). The highest CO_2 emissions were during the PRS, ODS and PDS for the 14-day incubation, but during ODS and PDS for the 7-day incubation and PRS and PDS for the 21-day incubation, whereas the lowest was always during the CRS. Averaged across the three incubation intervals, however, the CO_2 emissions showed an overall pattern of initially rising from the ORS to the PRS and later falling as the rainy season advanced until the cessation of rains (i.e., the CRS), from when it started rising steadily with increasing environmental drought until and during the PDS (Figure 2(b)). The increase in CO_2 emissions from the ORS to PRS might be due to increasing activation of soil microbes to enhance decomposition after an intense period of soil dryness (Adebola et al., 2017). The ORS/PRS and ODS/PDS, which are the onset and peak of the rainy and dry seasons, respectively, are used to compare these two distinct seasons in terms of CO_2 emissions, and it is clear that the former recorded lower emissions than the latter. Seasonal variations in CO_2 emissions are due to differences in climatic conditions (including rainfall and temperature) and soil types (Liebig et al., 2013). However, since we keep the location (climate and soil) constant, as shown in Figure 2(b), the lower emissions in the rainy season than in the dry season were due to the generally cooler weather in the rainy season than in the dry season (Oladipo et al., 2011) and the associated lower soil temperatures and higher soil thermal capacity in the former than in the latter (Okorie et al., 2024).

Notably, for all the sampling periods/seasons, there were steady increases in CO_2 emissions with increasing intervals of incubation (Figure 2(a)). With this observation, we decided to show the pattern of emissions for the three incubation intervals regardless of the poultry manure treatment, sampling period and location (Figure 3). The emissions were generally lower at 7 days than at 14 days, which, in turn, was lower than those at 21 days of soil incubation. Soil microorganisms are usually more active at the early stages than at the later stages of soil incubation (Oraegbunam et al., 2023). Although soil microbial activity was not determined in the present study, the data shown suggest that there were decreases in soil microbial activity with increasing duration of incubation of the various treatments. The data shown further suggest that more but not double the amount of CO_2 emissions would be expected with doubling the monitoring intervals, and even more but not triple the amount of emissions would be expected with tripling the monitoring intervals.

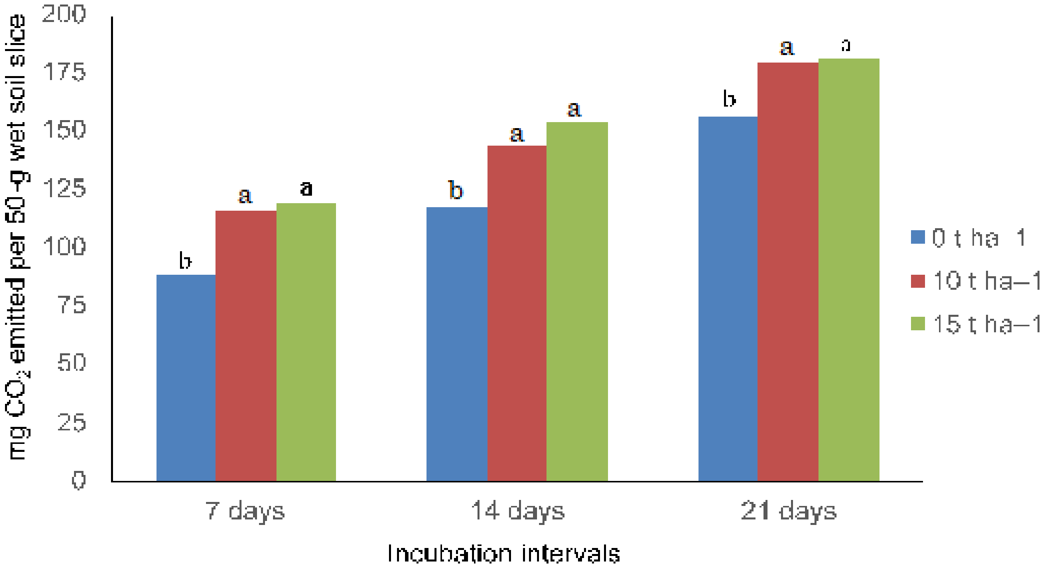

Figure 1 Poultry manure application rates as they influence soil CO_2 emissions across sampling periods and study locations at the three soil incubation intervals. Bars with the same letters for a given incubation interval are not significantly different ($P > 0.05$).

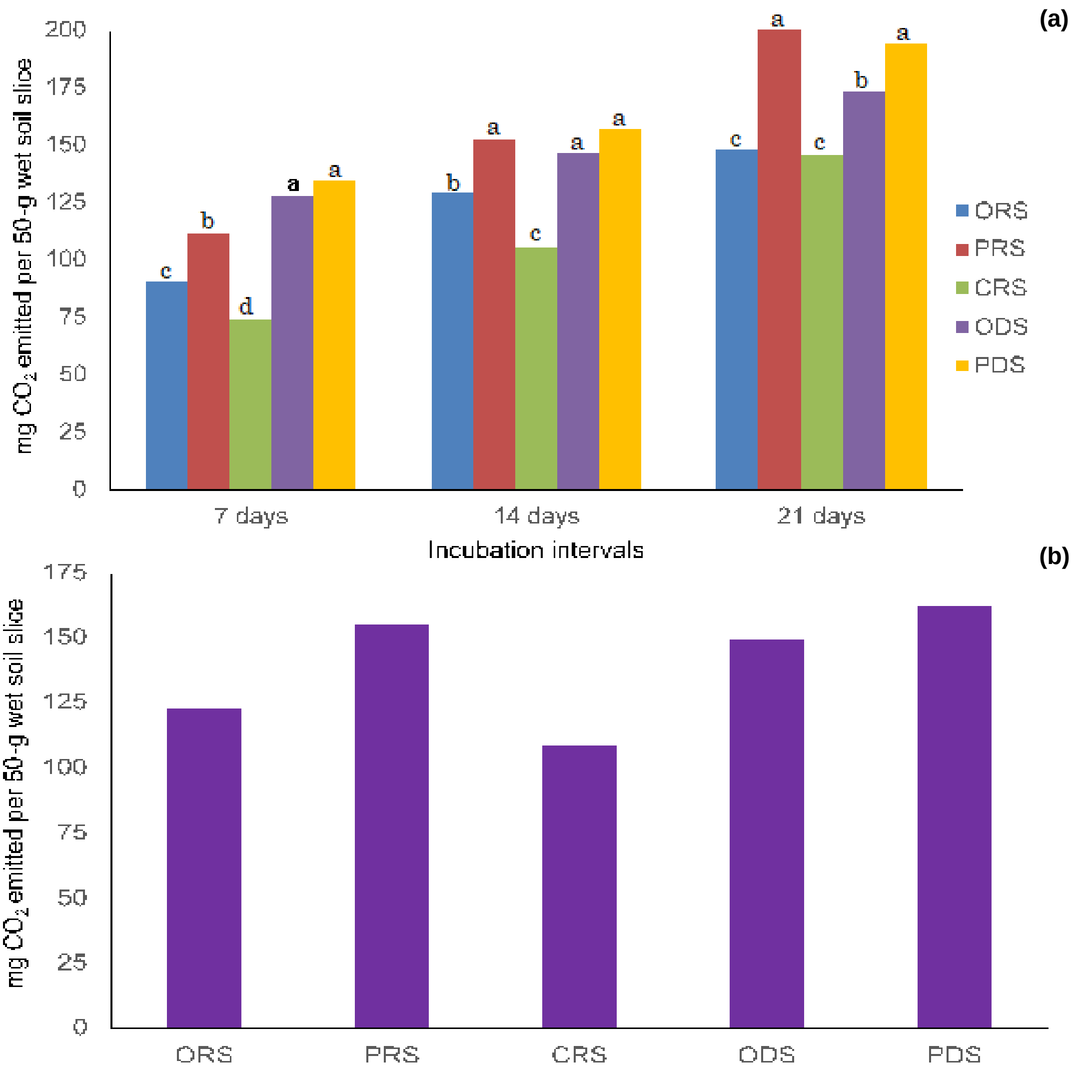

Figure 2 (a) Sampling period influence on soil CO_2 emissions across poultry manure rates and study locations at the three soil incubation intervals and (b) Pattern of differences in soil CO_2 emissions among the five sampling periods regardless of poultry manure rate and study location, as averaged across the three soil incubation intervals. ORS, rainy season onset; PRS, rainy season peak; CRS, rainy season cessation; ODS, dry season onset; PDS, dry season peak. Bars with different letters for a given incubation interval are significantly different ($P < 0.05$).

Compared with the Rainforest-Savannah zone, the southern Guinea savannah zone presented significant ($P < 0.05$) increases in soil CO_2 emissions (Figure 4). This could be attributed to the differences in local climate between the two agroecological zones. Considering the meteorological phenomenon of the isohyperthermal soil temperature regime in most tropical locations, the relatively warm southern Guinea savannah generally records higher soil temperatures than the rainforest-Savannah. Compared with those in the rainforest-Savannah zone, there were extreme temperatures and lower amounts of rainfall in the southern Guinea savannah zone during the study (Tables 3 and 4). This translates into greater soil drought in southern Guinea savannah than in the rainforest-Savannah zone, which implies greater decomposition of organic materials in the soil and loss to the atmosphere as CO_2 in the former than in the latter. Efe et al. (2016) reported similar increases in CO_2 emissions due to high temperatures within the Guinea savanna areas of Nigeria.

Additionally, soil texture plays a critical role in CO_2 emissions (Vinhal-Freitas et al., 2017). The sandier soil texture at southern Guinea Savannah than at rainforest-Savannah, with a higher clay content (Table 1), would provoke lower clay complexation and protection of organic carbon, implying faster release of carbon from its microbial biomass. The contributions of clay to CO_2 emissions were reported by Jäger et al. (2011), who monitored CO_2 emissions following the application of animal manure. They reported that soils with high clay contents presented decreased CO_2 emissions due to a decrease in the manure mineralization process. Such a decrease is a result of clay-mediated reductions in the bioavailability of nutrients in the soil (Shakoor et al., 2021), and this must have been the case with rainforest-Savannah, which has a relatively high clay content. There have been similar reports of a tendency for increased carbon accumulation and sequestration in the soils of the rainforest, derived savannah, and core savannah zones with higher clay contents than in those with lower clay contents (Oguike et al., 2023; Ahukaemere et al., 2016; 2015; Obalum et al., 2013; 2012b). However, Igwe et al. (2013), who worked with flooded rice soils, reported otherwise. Additionally, the data presented by Obalum et al. (2014), who also worked with flooded rice soils in two agroecologies of Nigeria, revealed the underlying influence of location on the clay content effect on organic carbon accumulation.

Furthermore, according to the soil organic carbon and total nitrogen contents of the two soils in this study (Table 1), as well as the C/N ratios of the poultry manures applied to them (Table 2), greater decomposition of organic carbon and hence the release of CO_2 to the atmosphere would be expected at the rainforest-Savannah than at the Southern Guinea Savannah. However, this was not the case for CO_2 emissions. The higher soil pH in the rainforest-Savannah than in the southern Guinea savannah (Table 1) might have contributed to the lower CO_2 emissions in the former than in the latter. In addition to the soil environment (swine wastewater), Dai et al. (2013) reported higher CO_2 emissions at a pH of 5.5 than at a pH of 6.0. For acidic soils of the derived savannah, animal manures increase both the soil pH and organic carbon content (Chukwuma et al., 2024), and these two soil properties may not have meaningful relationships in unamended soils (Ifeanyi-Onyishi et al., 2024).

2) Treatment effects on CO_2 emissions

The interaction effects of poultry manure rate and study location on CO_2 emissions are shown for the three soil incubation intervals of this study (Table 5). The application rates of 10 and 15 t ha^{-1} were generally higher than 0 t ha^{-1} for the two study locations. These results suggest that CO_2 emissions depend more on the poultry manure rate than on location, implying that the intensity of application of organic soil amendments rather than the prevailing climate and soil type is the key factor driving CO_2 emissions in tropical agroecosystems. The similarity of poultry manure's effects on CO_2 emissions in the two contrasting agro-ecologies was most likely because of its sole application in this study without involving its combination or comparison with mineral fertilizers (Iboko et al., 2023).

Table 6 shows the effects of poultry manure rates and sampling periods on CO_2 emissions for the three soil incubation intervals. For all three incubation intervals, the highest emissions were always due to 15 t ha^{-1} during the PDS. This was understandably due to the combination of this high manure rate and extreme soil temperatures during PDS, which resulted in greater microbial decomposition. Among the treatments with the highest CO_2 values were 10 t ha^{-1} during the PDS and 15 t ha^{-1} during the ODS, for the 7-day incubation; 15 t ha^{-1} during the ODS and 10 t ha^{-1} during the PRS, for the 14-day incubation; and 10 t ha^{-1} during the PDS and all three manure rates during the PRS, for the 21-day incubation. The lowest emissions were due to all three manure rates during the CRS and 0 and 15 t ha^{-1} during the ORS for the 7-day incubation; 0 and 10 t ha^{-1} during the CRS and 0 t ha^{-1} during the ORS for the 14-day incubation; and 0 t ha^{-1} during the CRS and PRS for the 21-day incubation. The CO_2 emissions thus depended on both the manure rate and sampling period, with the latter as the larger driver, as the emissions were generally lowest during the CRS, especially at the 14- and 21-day incubation intervals.

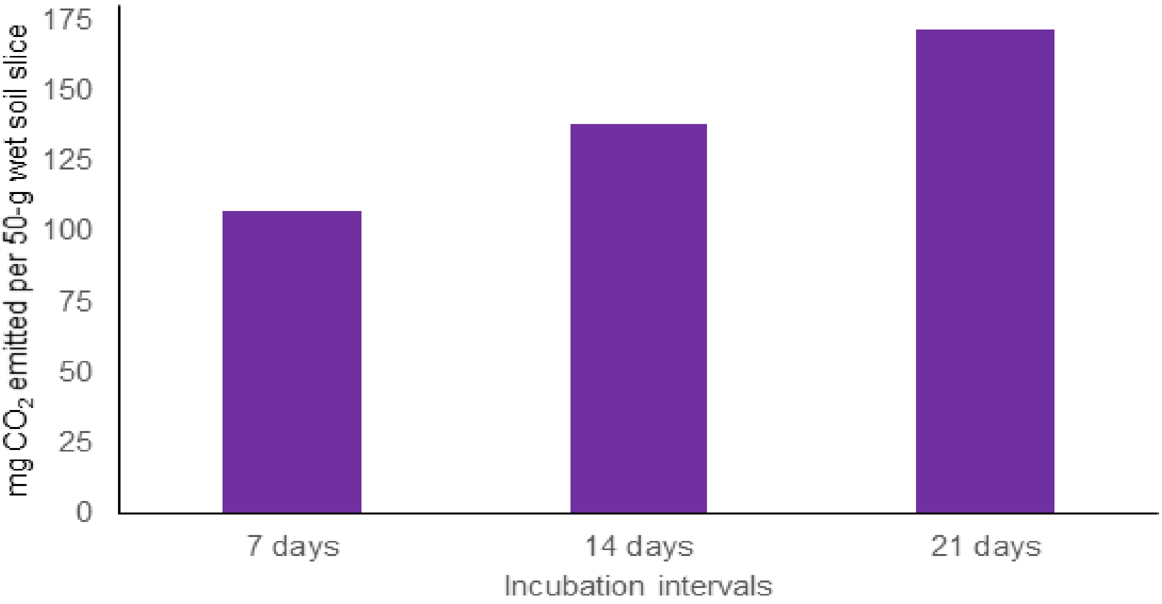

Figure 3 The mean values of soil CO_2 emissions for the three incubation intervals regardless of poultry manure rate, sampling period and location.

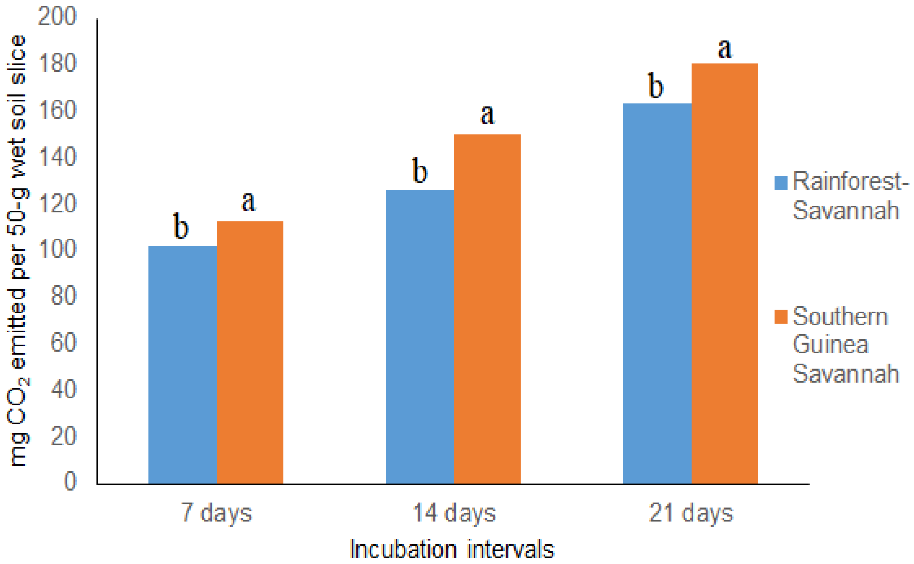

Figure 4 Influence of location on soil CO_2 emissions across sampling periods and poultry manure rates at the three soil incubation intervals. Bars with different letters for a given incubation interval are significantly different ($P < 0.05$).

Table 5 Interaction effects of poultry manure application rates and study locations on CO_2 emissions (mg CO_2 emitted 50-g^{-1} wet soil slice) at the three soil incubation intervals

Locations	Application rates (t ha^{-1})	Incubation intervals		
		7 days	14 days	21 days
Rainforest-Savannah	0	82.84^c	106.87^c	148.26^c
	10	113.73^b	132.92^b	170.62^b
	15	110.49^b	137.99^b	171.69^b
Southern Guinea Savannah	0	93.59^c	127.79^b	163.67^{bc}
	10	117.57^{ab}	153.95^a	188.27^a
	15	126.55^a	168.27^a	190.07^a

Remark: The means with same letters in the columns separated using Tukey's test are not significantly different ($P > 0.05$).

Furthermore, the interaction effects of poultry manure rate, sampling period and study location on CO_2 emissions are shown for the three soil incubation intervals (Table 7). The 10 and 15 t ha^{-1} during the PDS and 15 t ha^{-1} during the PRS in southern Guinea Savannah consistently resulted in the highest emissions, among those of some other treatments. Surprisingly, treatments of 0 t ha^{-1} during the PRS and the PDS of the southern Guinea savannah and the rainforest-savannah, respectively, for 21 days of incubation were among those resulting in the highest emissions in this study. This shows that the coarse-textured soils of tropical Africa, despite their low organic matter status, can be significant sources of CO_2 (Iboko et al., 2023). The lowest CO_2 emissions were due to some treatments occurring in both the rainforest-Savannah and the southern Guinea savannah. Overall, soil CO_2 emissions depend on all three factors (manure rate, sampling period and location), with increasing manure rates not necessarily equating to increased emissions. The emissions generally decreased during the CRS, especially in the rainforest-Savannah.

Conclusions

This study highlights significant spatial and temporal variations in CO_2 emissions from tropical African agroecosystems following soil amendment with poultry manure. Regardless of climate and soil type, applying poultry manure at a rate of ≥ 10 t ha^{-1} leads to increased CO_2 emissions. With or without poultry manure, soils emit CO_2 in a sinusoidal pattern throughout the year, typically with higher amplitudes during the peaks of the rainy and dry seasons and lower amplitudes during the cessation of rains. Such emissions tend to be higher in drier regions than in more humid zones of the tropics. Additionally, CO_2 emission rates can be elevated within short intervals of approximately 7 days and then gradually decrease over time if soil and environmental conditions do not favor emissions. To deepen our understanding of the mechanisms regulating CO_2 emissions and develop effective strategies for enhancing the soil carbon sink capacity in the humid tropics, further studies of poultry manure application rates ≤ 10 t ha^{-1} and other organic amendments at varying rates are suggested for the prevailing agronomic management practices of the region. Such studies are needed, especially for the coarse-textured soils of the widespread savannah.

Table 6 Interaction effects of poultry manure application rates and sampling period on CO_2 emissions (mg CO_2 emitted 50-g^{-1} wet soil slice) at the three soil incubation intervals

Sampling periods	Application rates (t ha^{-1})	Incubation intervals		
		7 days	14 days	21 days
ORS	0	74.37^{h}	110.89^{ef}	126.77^{h}
	10	100.06^{fg}	136.37^{cd}	162.13^{efg}
	15	96.80^{gh}	142.27^{b}	151.43^{fg}
PRS	0	82.98^{gh}	132.28^{cd}	196.53^{abc}
	10	123.37^{bcde}	163.90^{ab}	201.35^{ab}
	15	127.23^{bcde}	160.97^{b}	202.53^{ab}
CRS	0	61.83^{h}	95.73^{f}	128.30^{h}
	10	85.25^{fgh}	104.53^{ef}	146.50^{gh}
	15	73.45^{h}	117.47^{de}	161.27^{efg}
ODS	0	115.55^{cde}	126.93^{d}	150.80^{fgh}
	10	129.47^{bcde}	153.83^{b}	190.67^{bcd}
	15	138.92^{abc}	165.37^{ab}	176.73^{cde}
PDS	0	106.33^{efg}	125.05^{de}	173.13^{cdef}
	10	140.08^{abc}	160.63^{b}	194.67^{abcd}
	15	156.20^{a}	183.78^{a}	215.23^{a}

Remark: ORS – onset of rainy season, PRS – peak of rainy season, CRS – cessation of rainy season, ODS – onset of dry season, PDS – peak of dry season. The means with same letters in the columns separated using Tukey's test are not significantly different (*P* > 0.05).

Table 7 Interaction effects of poultry manure rates, sampling periods and study locations on CO_2 emissions (mg CO_2 emitted 50-g^{-1} wet soil slice) at the three soil incubation intervals

Locations	Sampling periods	Application rate (t ha^{-1})	Incubation intervals		
			7 days	14 days	21 days
Rainforest-Savannah	ORS	0	60.75^{hi}	91.83^{klmn}	100.41^{jkl}
		10	97.46^{fgh}	113.79^{ijk}	118.00^{hijk}
		15	83.60^{efghi}	115.87^{hijklm}	109.27^{ijk}
	PRS	0	54.50^{i}	106.97^{jklm}	181.87^{bcde}
		10	112.20^{de}	161.33^{cdef}	197.44^{abc}
		15	86.53^{fghi}	140.07^{fghij}	196.90^{abc}
	CRS	0	57.67^{i}	72.89^{n}	118.00^{hijk}
		10	63.43^{ghi}	82.200^{mn}	133.33^{ghij}
		15	61.13^{hi}	96.33^{klmn}	145.00^{fgh}
	ODS	0	138.60^{abcd}	153.27^{defg}	156.93^{efg}
		10	155.47^{abc}	168.67^{bcdef}	206.07^{ab}
		15	163.53^{a}	168.83^{bcdef}	196.07^{abcd}
	PDS	0	102.67^{def}	109.37^{ijklm}	184.07^{abcde}
		10	140.07^{abcd}	138.60^{fghj}	198.27^{abc}
		15	157.67^{ab}	168.84^{bcdef}	211.20^{ab}
Southern Guinea Savannah	ORS	0	88.00^{efghi}	121.37^{ijkl}	161.70^{cdef}
		10	102.67^{def}	154.73^{defg}	210.47^{a}
		15	110.00^{de}	175.27^{cde}	187.00^{abc}
	PRS	0	111.47^{de}	157.67^{cdefg}	211.20^{ab}
		10	134.53^{abcd}	166.47^{bcdef}	205.27^{abc}
		15	167.93^{a}	181.87^{abcde}	208.17^{ab}
	CRS	0	66.00^{fghi}	118.57^{hijk}	138.60^{ghi}
		10	107.07^{def}	126.87^{ghijk}	159.67^{defg}
		15	85.77^{efghi}	136.60^{fghil}	177.53^{bcdef}
	ODS	0	92.50^{efghi}	100.60^{klmn}	144.67^{fgh}
		10	103.47^{def}	139.00^{fghij}	175.27^{bcdef}
		15	114.30^{cde}	148.87^{efgh}	158.40^{efg}
	PDS	0	110.00^{de}	140.73^{fghi}	162.20^{cdefg}
		10	140.10^{abcd}	182.67^{abcd}	190.67^{abcde}

Remark: ORS – onset of rainy season, PRS – peak of rainy season, CRS – cessation of rainy season, ODS – onset of dry season, PDS – peak of dry season. The means with same letters in the columns separated using Tukey's test are not significantly different (P ≥ 0.05).

Overall, soil CO_2 emissions largely depend on the presence or absence of animal manure in soils and on environmental factors, including season-dependent meteorological conditions, the local climate, and soil characteristics in humid tropical agroecosystems. None of these factors—animal manure, application timing, season, or location—alone can adequately describe emissions in tropical African agroecosystems. To better understand the mechanisms regulating CO_2 emissions, further studies involving various organic-based soil amendments and agronomic management practices are necessary in savannah agro-ecologies, which are widespread in tropical Africa, especially those focused on the dominant coarse-textured soils. Such studies will help create a robust database for developing strategies to increase the carbon sink capacity of these soils.

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Data availability statement

Information and data used in the study will be disclosed upon request.

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Conflicts of interest

The authors declare that there are no conflicts of interest in competing financial or personal relationships that could have appeared to influence the work reported in this work.

Dedication

The lead author (Gladys M. Akande), a lecturer at Prince Abubakar Audu University, Anyigba Kogi State, Nigeria passed away while this paper was still under peer review, and this occurred some four and a half months after a successful oral defense of her PhD thesis at the Federal University of Technology, Akure, Ondo State, Nigeria. We posthumously dedicate this publication (which is emanating from this PhD thesis) to her and her immediate family, specifically her hard-sought and only child (baby boy) who was just a day old at her demise and her ever supportive husband, while praying for the repose of her amiable soul.

References

Ahukaemere, C. M. (2016). Sub-soil carbon and nitrogen sequestration: Soil profile measurement approach. *Malaysian Journal of Soil Science*, *20*, 37–48.

Ahukaemere, C. M., Akamigbo, F. O. R., Onweremadu, E. U., Ndukwu, B. N., & Osisi, F.A. (2015). Carbon and nitrogen forms and sequestration in relation to agricultural land use types in humid ecosystem. *Journal of Global Biosciences, 4*(3), 1655–1665.

Abbas, F., Fares, A., Valenzuela, H. R., & Fares, S. (2012). Carbon dioxide emissions from an organically amended tropical soil. *Journal of Sustainable Agriculture*, *36* (1), 3–17.

Adebola, A. E., Ewulo, B. S., & Arije, D. N. (2017). Effects of different animal manures on soil physical and microbial properties. *Applied Tropical Agriculture*, *22*(1), 128–133.

Adekiya, O. A., Ogunboye, O. I., Ewulo, B. S., & Olayanju, A. (2020). Effects of different rates of poultry manure and split applications of urea fertilizer on soil chemical properties, growth, and yield of maize. *The Scientific World Journal,* 4610515.

Adeyemo, A. J., Akingbola, O. O., & Ojeniyi, S. O. (2019). Effects of poultry manure on soil infiltration, organic matter contents and maize performance on two contrasting degraded Alfisols in southwestern Nigeria. *International Journal of Recycling of Organic Waste in Agriculture*, *8*(Suppl. 1), S73–S80.

Adubasim, C. V., Igwenagu, C. M., Josiah, G. O., Obalum, S. E., Okonkwo, U. M., Uzoh, I. M., & Sato, S. (2018). Substitution of manure source and aerator in nursery media on sandy-loam topsoil and their fertility indices 4 months after formulation. *International Journal of Recycling of Organic Waste in Agriculture*, *7*(4), 305–312.

Amhakhian, S. O., & Osemwota, I. O. (2012). Physical and chemical properties of soil in Kogi State, Guinea Savanna zone of Nigeria. *Nigeria Journal of Soil Science*, *22*(1), 44–52.

Anikwe, M. A. (2010). Carbon storage in soils of Southeastern Nigeria under different management practices. *Carbon Balance and Management*, 5, 5.

Azuka, C. V., & Idu, M. C. (2021). Effect of organic manures application on soil physicochemical properties of coarse-textured Ultisol and okra productivity in Nsukka, southeastern Nigeria. *Agricultural Science Digest*, *42*(2), 145–151.

Boakye-Danquah, J., Antwi, E. K., Saito, O., Abekoe, M. K., & Takeuchi, K. (2014). Impact of farm management practices and agricultural land use on soil organic carbon storage potential in the savannah ecological zone of Northern Ghana. *Journal of Disaster Research*, *9*(4), 484–500.

Bolu, S., Aderibigbe, S., & Oyelayo, L. (2014). Effects of treated poultry litter on potential greenhouse gas emission and field agronomic performance. *Ethiopian Journal of Environmental Studies and Management*, *7*(6), 677–684.

Bond-Lamberty, B., & Thomson, A. (2015). Temperature-associated increases in the global soil respiration record. *Nature*, *464*(7288), 579–582.

Brouček, J., & Čermák, B. (2015). Emission of harmful gases from poultry farms and possibilities of their reduction. *Ekologia*, *34*(1), 89–100.

Cai, Y., Ding, W., & Luo, J. (2012). Spatial variation of nitrous oxide emission between interrow soil and interrow plus row soil in a long-term maize cultivated sandy loam soil. *Geoderma*, *181–182*, 2–10.

Carter, M. R., & Gregorich, E. G. (2007). *Soil Sampling and Methods of Analysis* (2nd edition). CRC Press.

Chandrashekara, S. I., Harlapur, S., Muralikrishan, & Girijesh, G. K. (2000). Response of maize to organic manures with inorganic fertilizers. *Karnataka Journal of Agricultural Science*, *13*, 144–146.

Chukwuma, C. C., Oraegbunam, C. J., Ndzeshala, S. D., Uchida, Y., Ugwu, V. U., Obalum, S. E., & Igwe, C.A. (2024). Phosphorus mineralization in two lithologically dissimilar tropical soils as influenced by animal manure type and amendment-to-sampling time interval. *Communications in Soil Science and Plant Analysis*, *55*(5), 707–722.

Dai, X. R., & Blanes-Vidal, V. (2013). Emissions of ammonia, carbon dioxide, and hydrogen sulfide from swine wastewater during and after acidification treatment: Effect of pH, mixing and aeration. *Journal of Environmental Management*, *115*, 147–154.

Efe, S. (2016). Evaluation of carbon dioxide emissions and temperature variation in Nigerian cities. *Journal of Geography, Environment and Earth Science International*, *6*(2), 1–9.

Fasinmirin, J. T., & Oguntuase, A. M. (2006). Soil moisture distribution pattern in *Amaranthus cruentus* field under drip irrigation system. *African Journal of Agricultural Research*, *3*, 486–493

Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., & Tempio, G. (2013). *Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities*. Food and Agriculture Organization (FAO). United Nations.

Herath, H. M. S. K., Camps-Arbestain, M., Hedley, M. J., Kirschbaum, M. U. F., Wang, T., & Van Hale, R. (2015). Experimental evidence for sequestering C with biochar by avoidance of CO_2 emissions from original feedstock and protection of native soil organic matter. *GCB Bioenergy*, *7*(3), 512–526.

Iboko, M. P., Dossou-Yovo, E. R., Obalum, S. E., Oraegbunam, C. J., Diedhiou, S., Brümmer, C., & Témé, N. (2023). Paddy rice yield and greenhouse gas emissions: Any trade-off due to co-application of biochar and nitrogen fertilizer? A systematic review. *Heliyon*, *9*, e22132.

Ifeanyi-Onyishi, I. F., Ezeaku, V. I., Umeugokwe, C. P., Ezeaku, P. I., & Obalum, S. E. (2024). Distribution of soil fertility indices in aggregate size fractions under different land-use types for coarse-textured soils of the derived savannah. *Journal of Degraded and Mining Lands Management*, *12*(1), 6695–6704.

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

Igwe, C. A., & Obalum, S.E. (2023). Sustainable agriculture in fragile ecosystems. In Nnabude, P. C., Onunwa, A. O., Uko, I., Okolie, C. U., Okpata, P. N. (Eds.), *Soil: The Indispensable Link. Anambra State, Nigeria* (pp. 32–51). Cadventures Press.

Jäger, N., Stange, C. F., Ludwig, B., Flessa, H. (2011). Emission rates of N_2O and CO_2 from soils with different organic matter content from three long-term fertilization experiments – A laboratory study. *Biology and Fertility of Soils*, *47*(5), 483–494.

Joseph, P. O., Ojomah, F. O., & Abioye, J. B. (2025). Poultry manure-induced influence on soil properties of coarse-textured tropical soil. *Journal of Wastes and Biomass Management*, *7*(1), 1–5.

Lassaletta, L., & Aguilera, E. (2015). Soil carbon sequestration is a climate stabilization wedge: Comments on Sommer and Bossio (2014). *Journal of Environmental Management*, *153*, 48–49.

Liebig, M. A., Kronberg, S. L., Hendrickson, J. R., Dong, X., & Gross, J. R. (2013). Carbon dioxide efflux from long-term grazing management systems in a semiarid region. *Agriculture, Ecosystems and Environment*, *164*, 137–144.

Liu, L., Ouyang, Z., Hu, C., & Li, J. (2024). Quantifying direct CO_2 emissions from organic manure fertilizer and maize residual roots using 13C labeling technique: A field study. *Science of the Total Environment*, *906*, 167603.

Nawaz, A., Lal, R., Shrestha, R. K., & Farooq, M. (2017). Mulching affects soil properties and greenhouse gas emissions under long-term no-till and plough-till systems in Alfisol of central Ohio. *Land Degradation and Development*, *28*(2), 673–681.

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

Nnadi, A. L., Nnanna, P. I., Onyia, V. N., Obalum, S. E., & Igwe, C. A. (2020). Growth and yield responses of high-density coverage sweet potato to liming and fertilizer combinations for sandy-loam Ultisols at Nsukka, southeastern Nigeria. *Proceedings of the 44th Annual Conference of Soil Science Society of Nigeria (SSSN) (16-20 March 2020), Nigeria*, 263–269.

Nnadi, A. L., Ugwu, V. U., Nwite, J. C., Obalum, S. E., Igwe, C. A., & Wakatsuki, T. (2021). Manurial amendments and source of water for supplemental irrigation of sawah-rice system influenced soil quality and rice yield. *Agro-Science*, *20*(1), 95–102.

Nwite, J. C., Obalum, S. E., Igwe, C. A., Ogbodo, E. N., Keke, C. I., Essien, B. A., & Wakatsuki, T. (2012a). Sawah rice system, a technology for sustainable rice production and soil chemical properties improvement in Ebonyi State of Southeastern Nigeria. *World Journal of Agricultural Sciences*, *8*(4), 351–358.

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

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

Obalum, S. E., Ofem, K. I., Nwamba, D. C., Joseph, P. O., Edeh, I. G., Amalu, U. C., & Igwe, C. A. (2024a). Aggregate stability responses of three derived-savannah soils to poultry-droppings manure at different pulverisation-to-sampling time intervals. *Applied Environmental Biotechnology*, *9*(1), 38–51.

Obalum, S. E., Ugwu, V. U., Etukudo, N. E., Joseph, P. O., Onah, C. J., Eyibio, N. U., & Igwe, C. A. (2024b). Residual effects of heavy application of poultry-droppings manure on aggregation, P-fertility and hydraulic properties of well-drained tropical soils. *Applied Environmental Biotechnology*, *9*(2), 58–65.

Obalum, S. E., Watanabe, Y., Igwe, C. A., Obi, M. E., & Wakatsuki, T. (2014). Puddling intensity for late-season sawah systems based on soil hydrophysical conditions and rice performance. *International Agrophysics*, *28*(3), 331–340.

Obalum, S. E., Oppong, J., Igwe, C. A., Watanabe, Y., & Obi, M. E. (2013). Spatial variability of uncultivated soils in derived savanna. *International Agrophysics*, *27*(1), 57–67.

Obalum, S. E., Watanabe, Y., Igwe, C. A., Obi, M. E., & Wakatsuki, T. (2012a). Carbon stock in the solum of some coarse-textured soils under secondary forest, grassland fallow and bare footpath in the derived savanna of southeastern Nigeria. *Soil Research*, *50*(2), 157–166.

Obalum, S. E., Nwite, J. C., Watanabe, Y., Igwe, C. A., & Wakatsuki, T. (2012b). Comparative topsoil characterization of sawah rice fields in selected inland valleys around Bida, north-central Nigeria: Physicochemical properties and fertility status. *Tropical Agriculture and Development*, *56*(2), 39–48.

Obi, M. E., & Ebo, P. O. (1995). The effect of organic and inorganic amendments on soil physical properties and maize production in a severely degraded sandy soil in southern Nigeria*. Bioresource Technology*, *51*, 117–123.

Oguike, P. C., Onwuka, B. M., & Obalum, S. E. (2023). Soil organic matter control of water transmission properties of coarse-textured soils under contrasting land-use types in tropical rainforest. *International Journal of Hydrology Science and Technology*, *16*(1), 93–106.

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

Ogunezi, K. C., Okebalama, C. B., & Obalum, S. E. (2019). Optimum poultry droppings rate for coarse-loamy Ultisols based on soil macro-aggregation and fertility indices and evaluation using cucumber (*Cucumis sativus*). *Proceedings of the 43rd Annual Conference of Soil Science Society of Nigeria (SSSN) (15-19 July 2019), Nigeria*.

Ogumba, P. O., Okorie, B. O., Eleke, P. N., Anyanwu, L. O., Ebido, N. E., Onwuka, M. I., & Obalum, S. E. (2024a). Prospects of enhancing cattle-dung manure's effectiveness by partial substitution with poultry droppings-compost mix for slash-and-burn managed tropical soils. *West African Journal of Applied Ecology*, *32*(2), 10–22

Ogumba, P. O., Orah, A. I., Ndzeshala, S. T., Ebido, N. E., Nnadi, A. L., Law-Ogbomo, K. E., Obalum, S. E., & Igwe, C. A. (2024b). Synthetic lime and manure-NPK effects in sandy-loam Ultisols after growing sweet potato in successive rainy and dry seasons. *Agriculturae Conspectus Scientificus*, *89*(4), 361–371

Okorie, B. O., Obi, J. O., Chioke, G. U., Obalum, S. E., Onah, C. J., Nnadi, A. L., Igwe, C. A., & Obi, M.E. (2024). The concept of bio-economic mulching in droughty tropical agroecosystems and its trans-season effects on soil hydro-thermal regime and okra performance. SAINS TANAH – Journal of Soil Science and Agroclimatology, *21*(2), 165–178.

Oladipo, O. G., Olayinka, A., Aladesanmi, O. T., Sanni, M., Famurewa, A. J., & Siyanbola, W. O. (2011). Risk mitigation strategies and policy implications for carbon dioxide (CO_2) emission in organically-amended soils in Nigeria. *African Journal of Environmental Science and Technology*, *4*(11), 801–806.

Olaleye, A., Peak, D., Shorunke, A., Dhillon, G., Oyedele, D., Adebooye, O., & Akponikpe, P. B. I. (2020). Effect of manure and urea fertilization on yield, carbon speciation and greenhouse gas emissions from vegetable production systems of Nigeria and Republic of Benin: A phytotron study. *Agronomy*, *10*, 400.

Onah, C. J., Nnadi, A. L., Eyibio, N. U., Obi, J. O., Orah, A. I., Amuji, C. F., & Obalum, S. E. (2023). Off-season heavy application of poultry manure to droughty-acid soils under heavily protective organic mulch later burnt to ash improves their productivity. *West African Journal of Applied Ecology*, *31*(1), 23–36.

Onyekwelu, J. C., Mosandl, R., & Stimm, B. (2006). Productivity, site evaluation and state of nutrition of *Gmelina arborea* plantations in Oluwa and Omo Forest Reserves, Nigeria. *Forest Ecology and Management*, *229*(1-3), 214–227.

Oraegbunam, C. J., Kimura, A., Yamamoto, T., Madegwa, Y. M., Obalum, S. E., Tatsumi, C., Watanabe, T., & Uchida, Y. (2023). Bacterial communities and soil properties influencing dung decomposition and gas emissions among Japanese dairy farms. *Journal of Soil Science and Plant Nutrition*, *23*(3), 3343–3348.

Osakwe, U. C., Ogunleye, K. S. Obalum, S. E., Babalola, T. S., & Igwe, C. A. (2025a). Aggregate stability in relation to hydrolysable organic carbon in humid tropical ultisol under manure-fertilizer amendments. *Indian Journal of Ecology*, *54*(4), 715–722.

Osakwe, U. C., Obalum, S. E., Buri, M. M., Babalola, T. S., Igwe, C. A. & Reichert, J. M. (2025b). Soil organic carbon and hydraulic properties in response to poultry manure and inorganic fertilizers in two tropical agro-ecologies. *SAINS TANAH - Journal of Soil Science and Agroclimatology*, *22*(2), 300–316.

Penuelas, J., Coello, F., & Sardans, J. (2023). A better use of fertilizers is needed for global food security and environmental sustainability. *Agriculture and Food Security*, *12*, 5.

Platis, D. P., Anagnostopoulos, C. D., Tsaboula, A. D., Menexes, G. C., Kalburtji, K. L., & Mamolos, A. P. (2019). Energy analysis, and carbon and water footprint for environmentally friendly farming practices in agroecosystems and agroforestry. *Sustainability*, 11, 6.

Rahman, M. M. (2013). Carbon dioxide emission from soil. *Agricultural Research*, *2*(2), 132–139.

Ryals, R., & Silver, W. L. (2013). Effects of organic matter amendments on net primary productivity and greenhouse gas emissions in annual grasslands. *Ecological Applications*, *23*(1), 46–59.

Shakoor, A., Shakoor, S., Rehman, A., Ashraf, F., Abdullah, M., Shahzad, S.M., Farooq, T.H., Ashraf, M., Manzoor, M. A., Altaf, M. M., & Altaf, M. A. (2021). Effect of animal manure, crop type, climate zone, and soil attributes on greenhouse gas emissions from agricultural soils—A global meta-analysis. *Journal of Cleaner Production*, *278*, 124019.

Stolarski, R. S., Douglass, A. R., Oman, L. D., & Waugh, D. W. (2015). Impact of future nitrous oxide and carbon dioxide emissions on the stratospheric ozone layer. *Environmental Research Letters*, *10*, 034011.

Ugwu, V. U., Orah, A. I., Osuji, C. I., Akubue, J. C., Obalum, S. E., Onuze, B. A., & Igwe, C. A. (2024). Lime and manure application to low-fertility tropical soils enhances phosphorus bioavailability for increased agronomic productivity. *Agroindustrial Science*, *14*(3), 225–235.

Umeugokwe, C. P., Ugwu, V. U., Umeugochukwu, O. P., Uzoh, I. M., Obalum, S. E., Ddamulira, G., Karwani, G. M., & Alenoma, G. (2021). Soil fertility indices of tropical loamy sand as influenced by Bambara groundnut variety, plant spacing and fertilizer type. *Agro-Science*, *20*(1), 65–71.

Uzoh, I. M., Obalum, S. E., & Ene, J. (2015). Mineralization rate constants, half-lives and effects of two organic amendments on maize yield and carbon-nitrogen status of loamy Ultisol in southeastern Nigeria. *Agro-Science*, *14*(3), 35–40.

Vinhal-Freitas, I. C., Corrêa, G. F., Wendling, B., Bobuľská, L., & Ferreira, A. S. (2017). Soil textural class plays a major role in evaluating the effects of land use on soil quality indicators. *Ecological Indicators*, 74, 182–190.

Yue, X. L., & Gao, Q. X. (2018). Contributions of natural systems and human activity to greenhouse gas emissions. *Advances in Climate Change Research*, *9*(4), 243–252.