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Determination of Land-use-specific Greenhouse Gas Emissions Contribution in Nigeria

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Abstract
Background: Climate change (CC) is a threat to humanity due to the rise in global warming as a result of increased concentrations of emitted greenhouse gases (GHGs). Proper GHG emission accounting has been either lacking or grossly uncertain in Nigeria and Africa. **Aim:** This work addresses this gap by identifying four dominant land uses (LUs) in the agricultural sector to quantify fluxes of carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) gases using the static chamber technique. **Methods:** The research was carried out in Northern Guinea Savannah (NGS) during the wet and cold dry seasons of 2025/2026. Cropland (maize/cowpea), plantation (mango), grasscover (*Digitaria smutsii*) and animal paddock (cattle pen) were selected as treatments and four static chambers were installed in each as observation points. Gas sample collection was performed weekly across wet and dry seasons (WS and DS), using a 10-mL syringe and gas-free pressurized vials. The design involved a Randomized Complete Design using four replications and the collection of four gas samples at 0, 15, 30 and 45 minutes intervals per measurement event. The GHGs were determined using SKY-2000-M infrared gas sensors. Flux calculation was performed in excel where only values with rsq above 0.85 were considered. Q-Q and residual plots were used as data normality checkers before proceeding with statistical analyses. Soil moisture and weather parameters were monitored in-situ to the completion of the experiment. Soil samples were appropriately collected at 0 – 15 cm, processed and analysed following standard protocols to compare the LUs. Datasets were analysed by Analysis of Variance and Least Significant Difference by *Agricole* function using R 4.4.2. **Results:** Results indicate that animal paddock and cropland emitted significantly higher CO_2-C relative to plantation and grasscover in WS. During the DS, the animal paddock and plantation showed higher CO_2-C. Animal paddock consistently emitted the highest N_2O-N in both seasons, while grasscover served as a net sink during the DS. Similarly, CH_4-C flux varied significantly among the land uses in both seasons, with animal paddock and plantation being the greatest and lowest CH_4-C emitters, respectively. Soil characteristics measured were significantly at variance among the LUs. Notably, the soil reaction of all the LUs falls within the slightly acidic (6.53) to near neutral (6.72) pH, except the animal paddock, which was strongly alkaline (8.47). For organic carbon (OC), and total nitrogen (TN) nutrients, the animal paddock recorded the highest: 56.12 and 4.11 g kg^{-1}, while cropland recorded the lowest: 4.01 and 0.711 g kg^{-1}, respectively. Results of the available P, K^+ and Ca^{2+} were 12.3, 33.5 and 7.12 folds greater in the animal paddock compared with the cropland, respectively. **Conclusion:** In NGS Nigeria, the animal paddock is the most prominent emission hotspot with the greatest global warming potential implication compared to other agricultural LUs. The animal paddock has demonstrated excessive nutrient accumulations. Integration of cow dung into organo-mineral fertilizer and research on soil biochemistry are highly recommended.

Keywords: climate change; global warming; greenhouse gases; land use; mitigation

1. Introduction

Within the agricultural context, different land uses (LUs), such as cultivated land, managed grassland, plantation cropping and animal paddocking, are managed differently in terms of tillage operation, fertilizer treatment, water application, manure deposition, and cultivation intensity (Berça et al., 2022; Kamara et al., 2020; Wang et al., 2025). These variations are largely responsible for the differences in physicochemical and biological dynamics, and fluid fluxes among different LUs (Bashir et al., 2021; Tefera et al., 2025). In this sense, lands have to vary in their production capacity, resilience and greenhouse gas (GHG) emissions potential when submitted to different uses (Antonio et al., 2014; Ernst et al., 2024; Mir et al., 2021; Yahaya et al., 2024). This was confirmed by Ramadhan et al. (2022), who reported 45.3% higher methane (CH_4) emission in rice fields compared to land under animal rearing. Similarly, Aliyu (2025) observed higher CO_2 and N_2O emissions in maize plots treated with combined poultry manure and nitrogen-based fertilizer relative to sole applications. According to Aitova et al. (2023), frequent rewetting of grassland escalated CH_4 flux by 87%, but reduced CO_2 by 50%. Generally, releases of GHGs from agricultural LUs are unwanted because they are inimical to crop production sustainability and environmental stability.

Greenhouse gases contribute to global temperature, which triggers climate change (CC) to dwindle crop and animal production, monumentally (Kim, 2010; Tongwane et al., 2021). According to the Greenhouse gas Working Group, IPCC (2013), global temperature is projected to increase by 4 °C in the 21st century. In Nigeria, the Nigerian Meteorological Agency (NiMet, 2026) data shows the warmest temperature trend (+0.9 – + 4.0 °C) between around 2015 and 2024. This climate scenario indicates a troubling trend as per agricultural activities and sustainable food production are concerned (Nisbet et al., 2019; Salhi et al., 2023). It is worth noting that Africa is the most susceptible continent to CC extreme events – dry spells, droughts and devastating flooding, which frequently overstretch smallholder farming systems by subjecting them to an unbearable shock (Idris, 2020; International Organization for Migration [IOM], 2024; Kimathi et al., 2020). Yet, CC adaptation and mitigation commitment is snail-paced in the region due to GHG emission data paucity, uncertainty and non-specification, affecting GHG inventory quality, globally and locally (Kuunifaa et al., 2026; Nisbet et al., 2019). These challenges appear prominent and more complex in Nigeria, where the farming system is classically non-commercial and smallholder-based, typified by multiple and heterogeneous cropping patterns (Food and Agriculture Organization [FAO], 2025; Idris, 2020). This is suggestive that intensified measurement and reporting of land-use-specific GHG emissions is pertinent in both local and global CC mitigation and adaptation efforts.

Furthermore, previous studies in Nigeria depicted a skewed focus by concentrating on assessing GHG emissions from specific imposed treatments/practices, largely fertilizer types, forms and rates. For instance, Aliyu (2025) assessed the effect of biochar, poultry manure and nitrogen fertilizer applied at different rates on GHG emission, while Abdulkadir et al. (2018) measured emissions from cattle manure added at 7.5, 15, 22.5 and 30 ton ha $^{-1}$ rates applied through broadcasting, spot and banding methods. Also, Girei (2021) considered different urea and NPK fertilizer forms applied through banding, broadcasting and deep placement methods as well as two water application methods: alternate wetting and drying and continuous flooding. This suggests that the studies fall short in capturing numerous other emission hot moments triggered particularly by tillage, weeding practices, and rainfall and temperature fluctuations. Also, the studies were only able to compare the within-system practices, thus did not delve beyond a single land use. Another shortcoming of the said studies is that their experimental plots may not be a true replica of the typical common farmer practice, hence may not represent the Business as Usual (BaU) emission scenario. Consequently, this research was justifiably designed to provide land-use-specific GHG emissions data for major land uses under the BaU scenario to help scientists, government agents and climate change actors in developing short, medium and long–term mitigation measures for impact-based sustainable agricultural production. Additionally, robust GHG data generated in this study could serve as a resource base for modelling and GIS-RS technologies that are now being widely explored to estimate GHG emission as highlighted by Nickless et al. (2020) and Rosenstock et al. (2016). Study site selection was not arbitrary. The Northern Guinea Savanna agroecology has been documented as one of most suitable zones for maize, legume, mango and livestock productions in Nigeria (Foli, 2012; Mohammed et al., 2020; Ogunbode et al., 2024; Shehu et al., 2019), hence selected for this research. The main objective of this research work is to measure emissions of principal GHGs from soils subjected to different agricultural LUs in the Northern Guinea Savannah zones of Nigeria.

2. Methods

2.1 Descriptions of the Study Site

The study was executed in the Northern Guinea Savannah of Nigeria, specifically in the research farms of the Institute for Agricultural Research (IAR) and National Animal Production Research Institute (NAPRI), Ahmadu Bello University, Zaria, Nigeria. Cropland (maize/cowpea) and plantation (Mango) were in the IAR situated on Long. 7° 36' 30'' E and Lat.11° 10' 37''N whereas grasscover (*Digitaria smutsii*), and animal paddock (cattle pen) were in NAPRI situated on Long. 7° 34' 1' E and Lat. 11° 12' 34'' N (Fig. 1). Meteorologically, the mean annual rainfall in the zone is 996.5 mm and is received largely between April and September, with peak rainfall experienced in August; however, with some observed anomalies (Yamusa, 2020). The mean daily temperature of the area is 24– 34 °C with an altitude of 686m above sea level.

2.2 Greenhouse Gas Measurement

2.2.1 Chamber fabrication

A polyvinyl chloride (PVC) cylinder was used as the chamber material because it is nonreactive, sturdy and does not require insulation, as recommended by Collier et al. (2014). The closed end of the PVC cylinder was sliced up to make it two-opened-ended. The two-opened-end cylinder was re-sized to 23 cm height. Fifteen (15) cm was measured and marked from its base, and small round perforations (0.5 cm diameter) were made around its wall using an electric drill. The purpose of the perforation was to allow for free lateral water drainage into the soil to subdue water ponding. The upper 8 cm was left unperforated to trap gases emitted from the soil. The cover of the PVC cylinder (polystyrene bucket) was vented at 3 different points at 5 cm intervals. Two of the vents were tightly plugged by fitting-in Butyl rubber stoppers for gas sampling and in-chamber temperature measurement, while the other served as a vent tube for pressure equalization between the chamber head space and ambient air, as outlined by Xu et al. (2006) and Collier et al.

(2014). Figure 2 shows the schematic representation of the fabricated chamber with detailed dimensions.

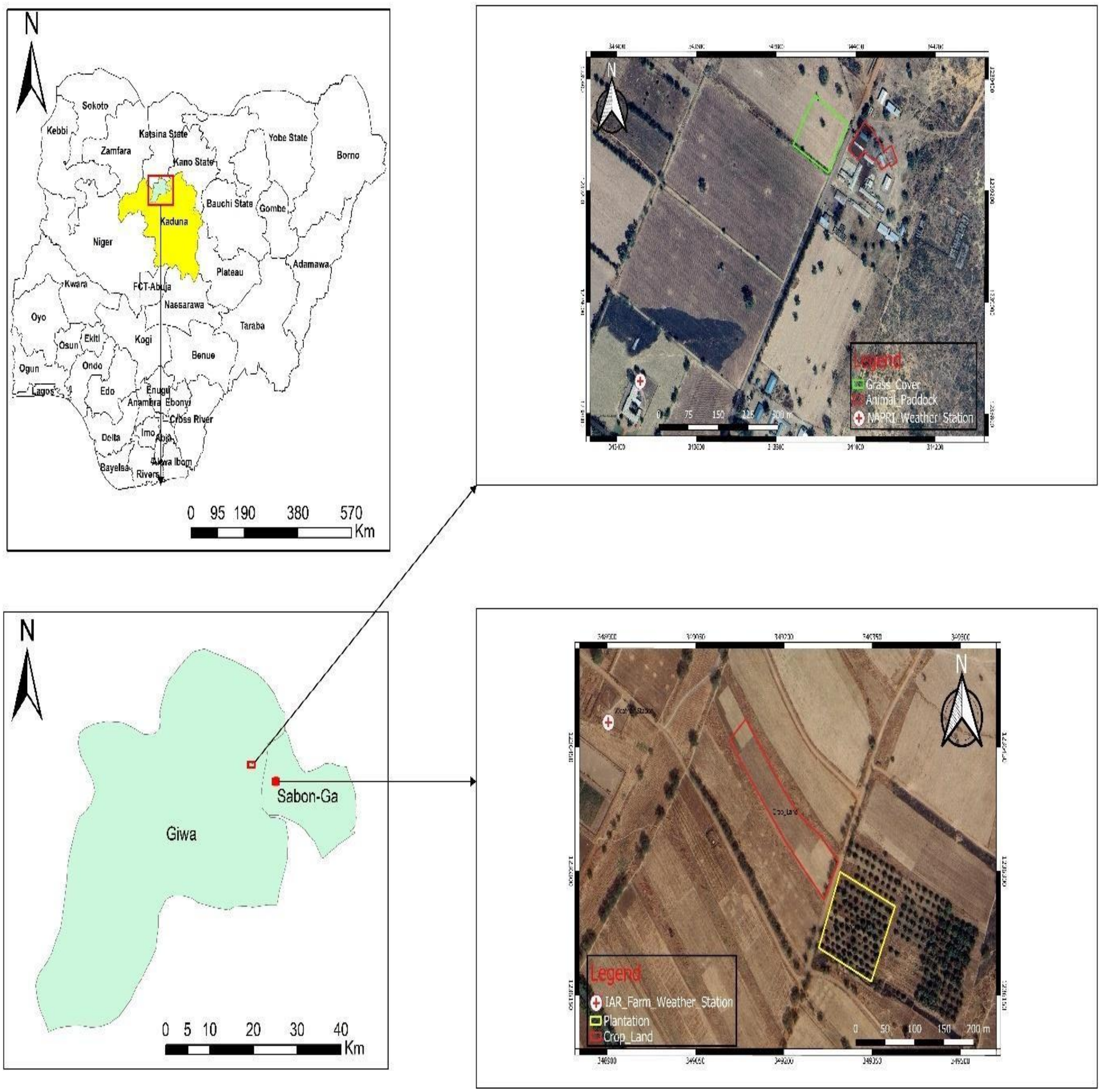

Figure 1. Map cluster showing Nigerian map, Kaduna State, Sabon gari and Giwa local governments and the location of the study units. In this figure, the four land use treatments considered are shown: cropland (maize/cowpea intercrop) – thin red border, and plantation (mango trees) – yellow border in IAR research farm (up), and Grasscover (*Digitaria smutsii*) – green border and animal paddock thick red border in NAPRI research farm (down)

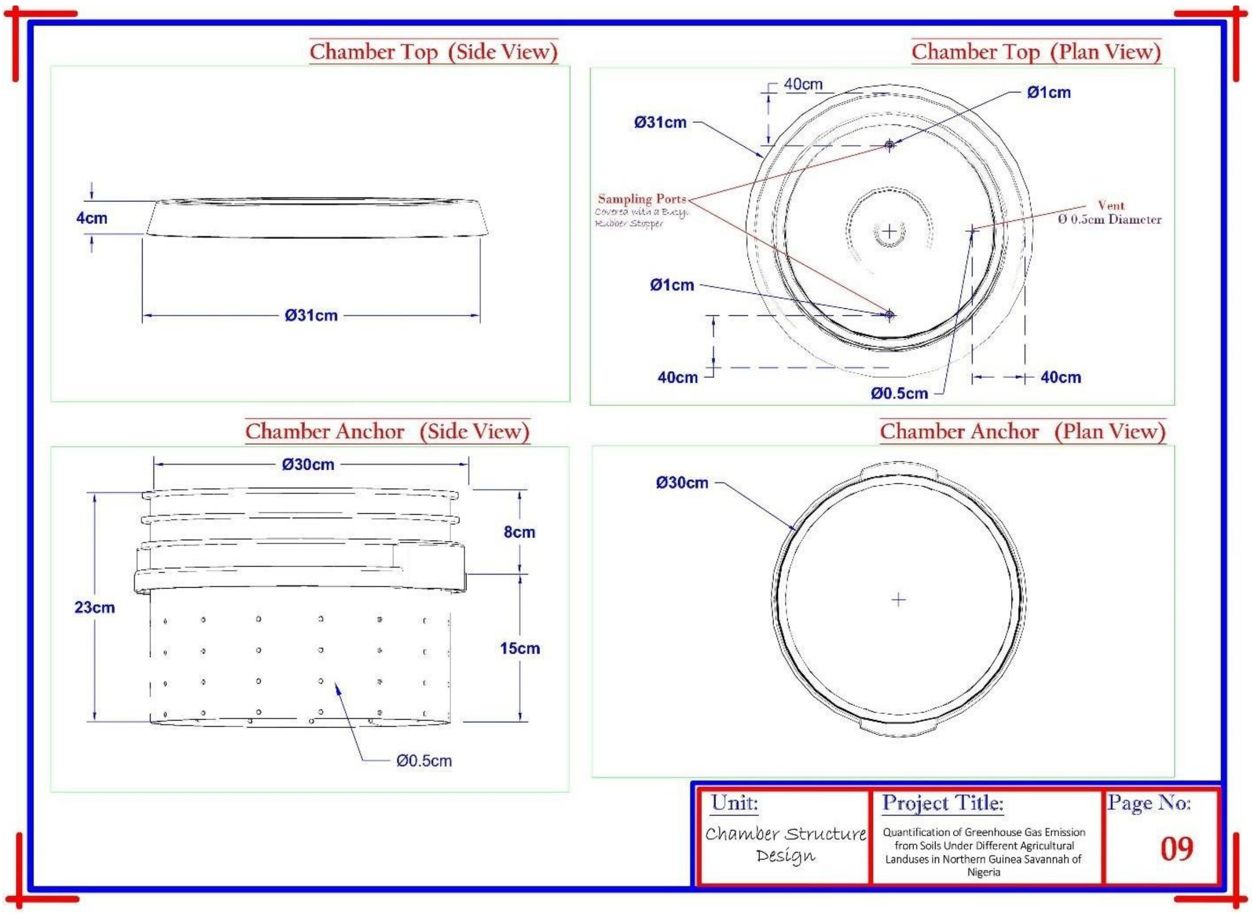

Figure 2. Schematic diagram of the fabricated chamber anchor and chamber top

2.2.2 Chamber placement

Chamber anchors were placed in four sampling points, systematically at 20 meters interval, after discarding the first 10 meters from one end of the farm to avoid border row effect. Such systematic chamber deployment and selection of study farms with homogenous physiography (topography, vegetation, surface feature) aimed to minimize spatial variability. However, in the animal paddock land use system, one chamber was placed per paddock, as schematically shown in Fig. 3. All chamber anchors were installed into a 15 cm soil depth to ensure that the chamber anchor is completely buried into the soil, while the remaining 8 cm unperforated part was left above the soil for optimal gas trapping. Installation of chamber anchors was done a week to first sampling to undo the effect of soil disturbance. The use of short white chambers was in order to allow for easy detection of CH_4 and N_2O, as suggested by Clough *et al*. (2012) and Parkin & Venterea (2010).

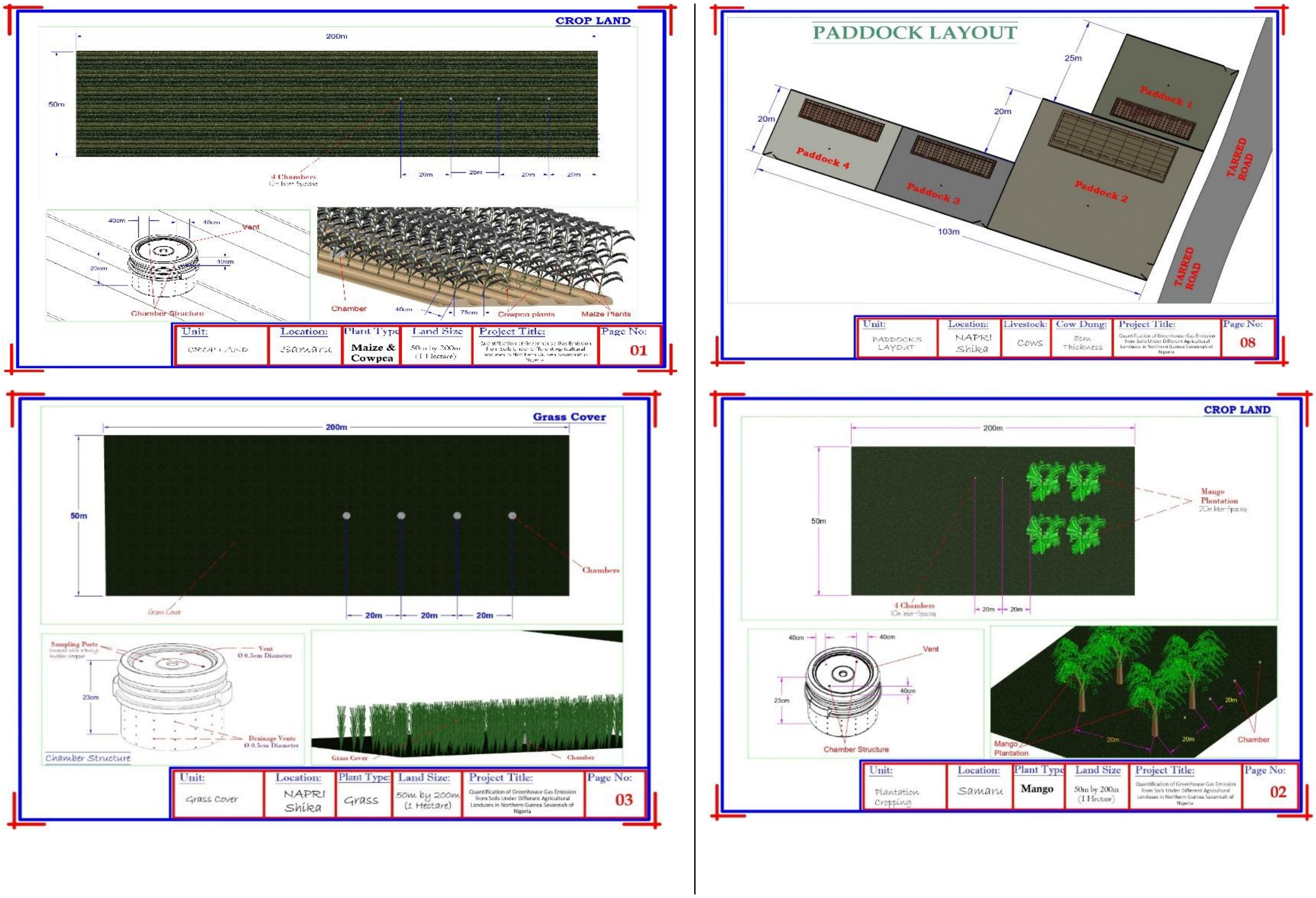

Figure 3. These are schematic descriptions of how chambers were placed at 20-meter fixed intervals for the three other land use systems, while in the animal paddock system, one chamber was placed in each of the 4 clustered paddocks due to their partitioned design.

2.2.3 Gas Sampling time and frequency

The research was conducted during the wet and cold dry seasons between August, 2025 and February, 2026. In order to obtain reliable and robust GHG measurement data, four gas samples were collected from each of the four chambers at 15 minutes intervals (0.0, 15, 30 and 45 minutes); at mid-morning hours (10:00 and 11:30 am) as in Table 1. Therefore, measurements in the early morning hours were avoided in order to reduce a high degree of uncertainty as recommended by Minamikawa et al. (2015); Rosenstock et al. (2016). Sampling was conducted weekly for 3 consecutive months in each season, and the time span covered a complete active growing season for maize and grass. Summarily, the experiment was designed in a Randomized Complete Block Design with four replications and four time sets, exceeding the minimum benchmark of three replications and three time intervals, respectively, for increased data precision and reliability. Weekly measurement is an intensive sampling schedule that ensures a sufficient sample size and a high degree of data certainty.

2.2.4 Sampling procedure

Immediately after chamber closure, a 10-mL capacity syringe was used to collect gas through the rubber stopper (sampling port) and transfer the gas into a 10-mL capacity pressurized glass vial, which is pre-evacuated (free from redundant gases) as demonstrated in plate 1.

Plate 1(a)

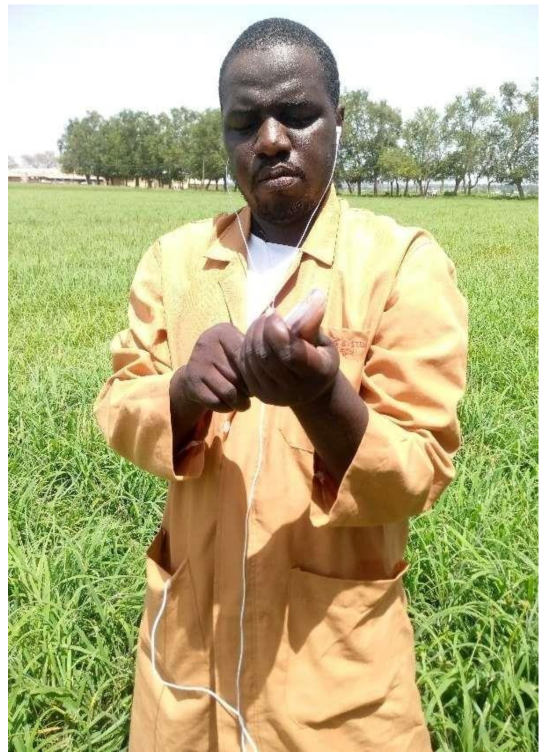

Plate 1(b)

Figure 4. Field scientist collecting a gas sample in grass-covered LU (Plate 1.a), and Field scientist transferring collected gas sample into a 10-mL vial (Plate 1.b)

2.2.5 GHG analysis

Collected samples were analyzed using newly procured customized SKY-2000-M gas detectors of Shenzhen Yuante Tech Ltd, China, thus assuaging concerns of sensor degradation and accuracy drifting due to aging as raised by Chew et al. (2025). The study explored the used of detector series which reliably and cost-effectively detect CO_2, CH_4 and N_2O as reported by Karuna et al. (2023); Park et al. (2024); Rajasekar & Selvi (2022) and Suhendar et al. (2024). Appropriately, 5 mL of gas samples were carefully drawn from the gas-tight vials using a brand new syringe and directly injected into the instrument's air chamber through the inlet for instant detection. The values displayed on the monitor in PPM were recorded. The instrument, which has a detection resolution of 0.01 ppm, was calibrated by exposing it to clean air in a serene laboratory condition for four (4) minutes. This was done following selection of 'CL- calibration, and 'CHAN' - channel and subsequent "Zero calibration" which set the value to 0.00. A SPAN calibration has been conducted earlier by the company using standard gas. All precautionary measures before and during the analysis were improvised to ensure accuracy. Temperature and humidity could be a source of bias and reading inaccuracy during measurement; as such, it was ensured that all measurements were done within the working temperature and humidity of the detector, specifically, 21 – 22.5 °C and 75 – 77%, respectively

2.2.6 Determination of CO2, CH4 and N2O emissions rate

Gas fluxes were calculated from the rate of change of the concentration of CO2, CH4 and N2O in the chamber headspace using a linear regression method. Since the units of gas standards are in ppm, the standard curve relationship was applied to calculate gas concentrations of the samples in ppm as volume vs. time (IPCC, 2006). The slope was then transformed using equation 1 below to mass per unit area per unit time (mg m^{-2} hr^{-1}) (Gaihre *et al.,* 2020; 2013; Mofijul Islama *et al.,* 2020).

$$CO_{2,}\ CH_4\ and\ N_2O\ emision\ rate\ (mg\ m^{-2}d^{-1}) = \frac{Slope\ (ppm^{-1}) \times VC \times MW \times 60}{22.4 \times \left(273 + \frac{T}{273}\right) \times AC \times 1000} \qquad \text{equation (1)}$$

Where:
VC = volume of the gas chamber in litres (L),
MW = molecular weight of the respective gas,
60 = minute h^{-1},
22.4 = volume of 1 mol of gas in L at standard temperature and pressure,
273 = standard temperature in °K,
T = temperature inside the chamber in °C,
AC = area of the chamber in m^2, and 1000 = mg^{-1}.

2.3 Soil Sampling and Preparation

A total of twenty-five disturbed soil samples were collected at 0-15 cm depth from each LU, five from each corner and center of the LU. Each sample set was mixed thoroughly to form a single composite sample, giving a total of five composite soil samples per LU. The samples were collected using a screw auger by gently drilling it into the soil in a clockwise direction and later prepared by air drying, gentle crushing using a porcelain mortar and pestle and sieving through a 2-mm mesh.

3. Results and Discussion

3.1 Effects of Land Uses on Soil Chemical Properties

Soil pH data as contained in Table 1 ranged from 6.53 to 8.47, indicating acidity to alkalinity zones respectively. All the land uses (LUs) fall within the acidic soil zone (mean = 6.72) except the animal paddock, which had the highest pH value (8.47), representing 26.04% pH level higher than the others. Organic carbon (OC) and Total nitrogen (TN) content depicted similar trends across the treatment with respective ranges of 4.01 - 56.12 and 0.711 - 4.11 g kg^{-1}. In the two mentioned parameters, the animal paddock recorded the highest while cropland recorded the lowest at a significance level of 0.001. Results of the exchangeable bases (K^+ and Ca^{2+}) followed a perfect pattern among the soils of the treatment LUs. Accordingly, the concentration of K and Ca in the animal paddock exceeded those in cropland by 33.5 and 7.12 times, indicating their huge release from the cow dung decomposition. Plantation LU seconded animal paddock by recording a higher concentration of the exchangeable bases compared to grass cover and cropland, which obviously showed the effect of long-term releases from litter decomposition and mineralization over time. The mechanism involving soil pH increase by organic matter is biochemically related. In the animal paddock LU, the organic matter likely becomes comprehensively solubilized, and H+ is removed from its carboxylic acid functional group, which eventually reacts with OH^- to form water while making the carboxylic fraction on the humus exchange sites to be dominated by negative charges. This ultimately increases the pH status of the soil. Also, products from the cow dung decomposition chemically consume both free moving H^+ and Al^{3+}, while releasing Ca and Mg to improve the soil acidity as highlighted by FAO (2026)

Available phosphorus (Av. P) showed a remarkable variation at $P < 0.05$, where the animal paddock recorded 5.4 folds the combined amount of Av. P in the other three LUs (160.82 vs 30.00 mg kg $^{-1}$). Although cropland was not statistically higher in Av. P over plantation and grasscover, but the numerical greatness indicated the possible contribution of mineral P addition. Abile et al. (2025), Idris et al. (2019), Joseph et al. (2019) and Obumselu et al. (2024) had reported similar findings where untampered forested LU significantly outperformed cultivated LU in TN, OC, CEC and exchangeable bases, which the authors attributed to exhaustive fertility depletion from continuous cropping. In general, farm-based ecological differences, prominently manure deposition, litter accumulation, soil disturbance and soil wetness were the drivers of the chemical variability.

Table 1. Antecedent soil properties of soil in the different land uses

Treatment	pH	OC	TN	K	Av. P	Ca
Land use		g kg $^{-1}$		cmol kg $^{-1}$	mg kg $^{-1}$	cmol kg $^{-1}$
Cropland	6.79b	4.01d	0.711c	0.357c	12.74b	2.95c
Plantation	6.98b	18.03b	1.48b	0.945b	9.182b	5.93b
Grasscover	6.53b	10.17c	0.955c	0.272c	8.090b	3.87c
Animal Paddock	8.47a	56.12a	4.110a	11.980a	160.82a	21.10a
SE±	0.230	2.3241	0.5924	0.535	3.138	0.8715
P-value	0.00028	9.32e-09	3.92e-06	4.29e-09	8.32e-08	5.926e-10
LOS	***	***	**	***	***	***

Note: OC = organic carbon, total nitrogen, K = potassium, Av. P = available, Ca = calcium, LOS = level of significance, SE = standard error, *, **, *** = significance at P ≤ 0.05, 0.01 and 0.001, respectively.

3.2 GHG Emissions Based on Land Use Systems

3.2.1 CO_2 Flux based on land use systems

Results for CO_2 flux under the different land uses demonstrated a significant variation during wet and dry seasons. Cropland emitted between 12.11 and 75.07 mg m − 2 hr − 1 of CO_2-C across the 12-week period of the wet season. According to the results, the highest emissions took place at week 4 (75.07 mg m − 2 hr − 1) and week 5 (51.86 mg m − 2 hr − 1), coinciding with tillage and fertilizer application schedules. From week 1 to week 12, cropland emitted significantly higher CO2-C compared to plantation and grass cover LUs, whose peak CO2-C emissions were 52.41 and 22.3, 43.2% and 236.6% lower than that of cropland, respectively. However, CO2-C emission (15.64 – 62.39) from animal paddock was partly statistically similar to those from cropland (e.g., in week 6,7,9, 10 and 11) and partly significantly higher than those from cropland (e.g., in week 1,2,3, 8 and 12). In general, the results demonstrate that cropland and animal paddock were the highest CO2-C emitters while grass cover was the lowest, recording negative emissions in weeks 1, 2 and 3.

During the dry season, plantation LU having recorded 1.92 – 13.5 mg m^{-2} hr^{-1} CO2-C emission range, outcompeted cropland and grasscover LUs throughout the season, except in week 2, 3 and 4 in which non-significant differences were observed. In the first and last week of the measurement (week 1 and week 12), CO2-C emitted from the plantation was 41.6 % and 71.43 %, and 92.03% and 36.17 % greater relative to cropland and grasscover LUs, respectively. Notwithstanding, the animal paddock exhibited superior CO2-C fluxes that were statistically similar to those in the plantation.

Table 2. CO2-C flux (mg m^{-2} hr^{-2}) from soil under four selected land uses during wet season for week 1 to week 6

Treatment	WK1	WK2	WK3	WK4	WK5	WK6
CO2-C (mg m^{-2} hr^{-1})						
Cropland	41.58b	37.84b	51.86b	75.07a	43.45a	31.50a
Plantation	26.58c	23.85c	32.15c	52.41b	23.11c	21.88b
Grasscover	-4.86d	-9.89d	-18.76d	10.31c	16.23d	13.57c
Animal Paddock	55.99a	62.39a	61.36a	46.38b	32.36b	26.34ab
SE±	1.766	3.964	2.851	4.4506	1.837	1.952
P-Value	1.9e-10	2.71e-07	6.78e-10	2.662e-06	1.342e-06	0.000221
LOS	***	***	***	***	***	***

Note: WK = week, LOS = level of significance, SE = standard error, *, **, *** = significance at P ≤ 0.05, 0.01 and 0.001, respectively. Values bearing different letter column wise, are significantly different at P ≤ 0.05.

Evolution and release of huge CO2 from animal paddock land use can be basically connected to continuous heterotrophic respiration and fast decomposition of cow dung that takes place in the system, since enteric fermentation might have partially broken down fibre products in the grasses ingested. Enteric fermentation in the gastrointestinal tract of cows alters all materials in the ingested feed, including carbohydrates, making defecated cow dung an easily decomposable material. Kuzyakov (2006) hinted that soil organic matter (SOM) decomposition and respiration by microbes form a key category from which CO2 is biogenically derived from the soil. Further, considerable nutrient and fibre-rich cow dung deposits might have provided adequate consumable organic and mineral substrates to the large microbial colonies recorded in the animal paddock to cause production of CO_2. Biochemically, the conversion pathway of long-chain organic material, namely lignin, cellulose and hemicellulose, releases considerable CO_2 through anaerobic conversion. According to Ratminingsih & Jumadi (2020), when anaerobic degradation of fibre persists, 25 – 30 % of CO_2 evolves from a unit cowdung. Early findings by Jones et al. (2004) concurred that soil respiration from a heavily-manured plot emitted up to 1.65 times more CO_2 than a plot that received mineral fertilizers.

Table 3. CO_2-C flux (mg m^{-2} hr^{-1}) from soil under four selected land uses during wet season for week 7 to week 12

Treatment	WK7	WK8	WK9	WK10	WK11	WK12
Land use			CO_2-C (mg m^{-2} hr^{-1})			
Cropland	26.43a	18.73b	19.39a	27.34a	13.34a	12.11b
Plantation	19.18b	8.59c	12.37b	6.59c	5.54b	7.30b
Grasscover	12.59c	7.67c	12.08b	22.30b	13.49a	6.57b
Animal Paddock	28.03a	23.07a	24.45a	23.87ab	17.59a	15.64a
SE±	2.110	1.159	1.6956	1.556	1.434	1.186
P-Value	0.000810	1.09e-06	0.00055	3.33e-06	0.00056	0.00045
LOS	***	***	***	***	***	***

Note: WK = week, LOS = level of significance, SE = standard error, *, **, *** = significance at P ≤ 0.05, 0.01 and 0.001, respectively. Values bearing different letter column wise, are significantly different at P ≤ 0.05.

Table 4. CO_2-C flux (mg m^{-2} hr^{-1}) from soil under four selected land uses during dry season for week 1 to week 6

Treatment	WK1	WK2	WK3	WK4	WK5	WK6
Land use			CO_2-C flux (mg m^{-2} hr^{-1})			
Cropland	9.53b	9.63	5.098	5.09	3.83d	4.26b
Plantation	13.50a	10.59	4.58	4.58	8.982a	8.42a
Grasscover	7.034b	11.26	4.66	4.67	5.04c	4.01b
Animal Paddock	13.30a	12.58ns	5.71ns	5.711ns	6.29b	5.139a
SE±	0.475	0.951	0.3823	0.3826	0.349	0.470
P-Value	1.04e-06	0.13121	0.1966	0.1966	1.632e-06	8.048e-05
LOS	***	Ns	Ns	Ns	**	***

Note: WK = week, LOS = level of significance, NS = not significant, SE = standard error, *, **, *** = significance at P ≤ 0.05, 0.01 and 0.001, respectively. Values bearing different letter column wise, are significantly different at P ≤ 0.05.

In the plantation, year-round root exudate release may have contributed profoundly to minimizing CO_2 emission as compared with the animal paddock. Higher aggregation, which translates to the provision of physical cover/protection to SOM, further minimizes the CO_2 evolution in plantation LU. However, root respiration might have outweighed the effect of root exudates and physical protection, making the plantation a net CO_2 source. Filser et al. (2016) and Pamminger et al. (2022) reported that earworm abundance in the soil often turns soil into a CO_2 source. This may hold true for the plantation LU, which harbors mites and earthworms in large quantities.

Table 5. CO_2-C flux (mg m^{-2} hr^{-1}) from soil under four selected land uses during dry season for week 7 to week 12

Treatment	WK7	WK8	WK9	WK10	WK11	WK12
Land use			CO_2-C flux (mg m^{-2} hr^{-1})			
Cropland	2.71b	5.303b	1.90bc	1.37b	1.92	1.12c
Plantation	4.35a	7.68a	2.22ab	3.49a	1.92	1.92a
Grasscover	3.67a	3.70c	1.7446	1.70b	1.42b	1.41bc
Animal Paddock	3.96a	5.32b	2.718a	3.45a	2.710a	1.74ab
SE±	0.240	0.439	0.138	0.212	0.187	0.151
P-Value	0.00269	0.00033	0.0016	1.05e-05	0.0005492	0.01393
LOS	**	**	**	***	**	*

Note: WK = week, LOS = level of significance, SE = standard error, *, **, *** = significance at $P \leq 0.05$, 0.01 and 0.001, respectively. Values bearing different letter column wise, are significantly different at $P \leq 0.05$.

In the grasscover which acted largely as a net sink of CO_2, carbon stabilization might have taken place due to long-term minimal soil disturbance. This occurred when a long-term sequestered C became stabilized such that it resists degradation and decomposition. Further, oxidative decay of crop residual leftovers might have been lowered due to zero tillage. This is in harmony with the findings of Feyissa et al. (2023), who observed better carbon stabilization in grassland in Southwestern China. The geometric increase in CO_2 uptake from week 1 to week 3 signifies intense carbon capture to support early growth and development of the grasses. From week 4 to Week 11, CO_2 emission spontaneously increased, most probably emanating from the respiratory activities of active microbes and roots of the grasses.

As per cropland, consistent soil disturbance through pre-planting tillage (harrowing, ridging and planting) and post-planting practices are the principal reasons for the CO_2 emission. From week 3 to week 7, the synergistic effect of 1st and 2nd hoe weeding as well as 1st and 2nd fertilizer applications was obviously responsible for the increased CO_2 emissions. Additionally, soil disturbance in the form of earthen-up – a practice of heaping up soil around mature maize plants to strengthen their anchorage against toppling likely aggravated CO_2 flux. Also, unprotected soil surface and poor soil hydrophysical condition such as low moisture status and less macro aggregation, favored CO_2 emissions. Previously, Amahnui et al. (2025) recorded higher CO_2 flux under conventional tillage and fertilizer treatment plot compared to a plot with no disturbance (zero tillage and unfertilized). They further noticed a significant upward flux during the tillage and fertilizer practices. According to Awe et al. (2024) and Min et al. (2020), research evidences have established that atmospheric temperature and low moisture retention favor net loss of soil C through CO_2 emission. Both prevailed in the cropland during the course of the study.

3.2.2 N_2O flux based on land use systems

According to Tables 6 & 7, N_2O-N maximum emissions for the cropland, plantation, grasscover and animal paddock LUs during the wet season were 11.53, 4.57, 19.56 and 19.56 ug m^{-2} hr^{-1}, respectively. The results further suggested that the animal paddock continuously emitted the highest N_2O -N, except in week 4 when grasscover superseded it by 43.5 %, likely due to urea application.

Table 6. N_2O flux (ug m^{-2} hr^{-1}) from soil under four selected land uses during wet season for week 1 to week 6

Treatment	WK1	WK2	WK3	WK4	WK5	WK6
Land use			N_2O-N flux (ug m^{-2} hr^{-1})			
Cropland	5.73bc	5.12b	3.67c	11.53c	2.66b	8.12a
Plantation	3.59c	4.57b	2.49c	0.990d	1.11b	1.00b
Grasscover	9.88b	11.99b	7.91b	19.56a	10.29a	6.89a
Animal Paddock	44.27a	43.82a	14.56a	13.63b	9.85a	7.82a
SE±	1.639	2.454	1.158	0.661	0.585	0.573
P-Value	1.51e-09	2.14e-07	3.47e-05	1.49e-09	9.59e-08	3.788e-06
LOS	***	***	***	***	***	***

Note: WK = week, LOS = level of significance, SE = standard error, *, **, *** = significance at P ≤ 0.05, 0.01 and 0.001, respectively. Values bearing different letter column wise, are significantly different at P ≤ 0.05.

Table 7. N_2O flux (ug m^{-2} hr^{-1}) from soil under four selected land uses during wet season for week 6 to week 12

Treatment	WK7	WK8	WK9	WK10	WK11	WK12
Land use			N_2O flux (ug m^{-2} hr^{-1})			
Cropland	2.64	3.21b	3.86b	-3.25	-2.69d	-3.34d
Plantation	0.94	0.65c	0.95c	0.54c	0.727c	-0.87c
Grasscover	7.19a	7.955a	4.37b	4.25b	3.38b	6.17b
Animal Paddock	7.04a	7.79a	6.12a	7.20a	14.23a	9.87a
SE±	0.520	0.701	0.387	0.377	0.32	0.4744
P-Value	2.55e-06	1.64e-05	6.52e-06	1.12e-09	7.399e-13	4.809e-10
LOS	***	***	***	***	***	***

Note: WK = week, LOS = level of significance, SE = standard error, *, **, *** = significance at P ≤ 0.05, 0.01 and 0.001, respectively. Values bearing different letter column wise, are significantly different at P ≤ 0.05.

Table 8. N2O flux (ug m^{-2} hr^{-1}) from soil under four selected land uses during dry season for week 1 to week 6

Treatment	WK1	WK2	WK3	WK4	WK5	WK6
Land use			N2O flux (ug m^{-2} hr^{-1})			
Cropland	-11.57c	-12.39	-6.57c	-2.789c	-2.010c	-1.375c
Plantation	0.274b	0.29b	0.382b	0.283b	1.073b	0.775b
Grasscover	-8.03c	-6.88c	-6.48c	-4.782	-3.083d	-3.042d
Animal Paddock	7.28a	6.050a	5.51a	4.031a	3.161a	1.577a
SE±	0.646	0.399	0.45640	0.229	0.2075	0.158
P-Value	4.02e-10	2.39e-12	5.15e-10	2.209e-11	2.253e-10	3.611e-10
LOS	***	***	***	***	***	***

Note: WK = week, LOS = level of significance, SE = standard error, *, **, *** = significance at P ≤ 0.05, 0.01 and 0.001, respectively. Values bearing different letter column wise, are significantly different at P ≤ 0.05.

In the dry season, Animal paddock N2O -N emission behavioral trend remained unchanged, having depicted the highest value throughout with a range of 1.07 to 7.28 ug m^{-2} hr^{-1} Table 8 & 9. Furthermore, grasscover recorded negative emission (-1.16 to -8.03 ug m^{-2} hr^{-1}) throughout the sampling period, serving as an N2O -N sink. Similarly, cropland showed N2O-N consumption for the first 8 weeks, then emitted little N2O-N (1.138 - 2.69 ug m^{-2} hr^{-1}) towards the end of the experiment (week 9 – week 12). In contrast, plantation land use had shown N2O -N emission from week 1 to week 6, recording a peak value of 1.073 ug m^{-2} hr^{-1} before transiting to negative emissions in the remaining six weeks (max. = -5.34 ug m^{-2} hr^{-1}).

N2O-N flux under cropland LU during the wet season was facilitated by aeration and application of N-containing fertilizers. For instance, the N2O-N emission surge observed in weeks 3 and 6 coincided with the application of 20-10-10 NPK and 46 %N-urea, respectively. Astonishingly, although higher N was applied during the second application, N2O-N flux was less compared to the flux that followed the first application. This is probably connected to the increased nutrient consumption power of maize at the rapid vegetative phase (V10) due to higher metabolic demand and robust rooting system as pointed out by Alam et al. (2021) and Kuunya et al. (2021). Negative N2O-N flux began at week 10 and progressed to week 12, which may be tightly connected to legume N-fixation by the intercopped cowpea planted at week 7. According to results reported by Danso et al. (2025), nodulation occurs at 20 – 40 days after planting, to effectively cause N-uptake at the tail end of the wet season.

Substantially rich N and C content, coupled with warm conditions from a high temperature regime, are the possible precursors of high N2O-N evolvement in the animal paddock system during the wet season. In virtually all days without rain, the moisture content was sufficient to provide adequate O2 to facilitate the denitrification of NO3− and NH3 to N2O, which are reasonably substantial in the cow dung as recorded.

Table 9. N_2O flux (ug m^{-2} hr^{-1}) from soil under four selected land uses during dry season for week 7 to week 12

Treatment	WK7	WK8	WK9	WK10	WK11	WK12
Land use			N_2O flux (ug m^{-2} hr^{-1})			
Cropland	-1.21b	-1.159b	2.69a	1.623a	1.138a	1.411a
Plantation	-5.13d	-4.53c	-5.34d	-3.28c	-2.23c	-1.143b
Grasscover	-2.009c	-1.27b	-1.23c	-1.16b	-1.17b	-1.170
Animal Paddock	1.55a	1.159a	1.068b	1.193a	1.240a	1.131a
SE±	0.1881	0.198	0.288	0.2088	0.109	0.144
P-Value	1.15e-10	1.31e-09	1.03e-09	3.494e-09	4.885e-11	1.095e-08
LOS	**	***	***	***	**	**

Note: WK = week, LOS = level of significance, SE = standard error, *, **, *** = significance at P ≤ 0.05, 0.01 and 0.001, respectively. Values bearing different letter column wise are significantly different at P ≤ 0.05.

According to Sawyer (2019), the pH level of an animal paddock (8.47), high NH3 is formed at a 10 % ratio to NH4. van der Weerden et al. (2023) equally reported similar observations where they described cattle manure as a considerable source of N2O-N. Higher N2O turnover recorded in the early phase of the measurement (week 1 and 2) may be a reflection of the density of N and C in the tender grass that the cattle fed upon during the early days of the rainy season. Accordingly, Binalf et al. (2025) and Meel et al. (2025) reported the highest crude protein and the least fibre content significantly in young super Napier grass and Setaria pumila Grass, respectively, which cascades to the cow dung nutrient richness. Also, microbial abundance, which by far surpassed that in other LUs based on the measured microbial count, is indicative of the possible higher denitrifier count in the animal paddock. Results presented by Meng et al. (2019) revealed three denitrifying genes (nirK, nirS and nosZ) in *Rhizobiales*, *Burkholderiales*, *Pseudomonadales* and *Alteromonadales* normally abundantly found in cowdung. Also owing to the fact that denitrifiers are fast-growing communities that thrive both in aerobic and anaerobic conditions, a high N2O-N emission pulse in an animal paddock is justified. This is in accordance with finding of Ayadi et al. (2015) who observed high N2O concentration (0.50 ppm ± 0.03) in a laboratory experiment, while Dangal et al. (2019) simulated that livestock excreta was responsible for ½ of the total N2O-N emission in intensive and extensive grassland systems, hence recording the highest N2O-N in most parts of the experiment. Jones et al. 2004 previously revealed that N2O-N emission from well-manured plot was higher consistently, reaching up to 3488 g N2O –N ha^{-1} day^{-1}.

Soil organic matter (SOM) decomposition is the most probable reason for the N2O emissions observed in both plantation and grasscover LUs. In addition to that, removal of off-type pasture and hand-weeding operation might have collaborated with one-time off application of N-containing fertilizer to cause N_2O-N upward trend at week 4 and 5 in the grasscover system. This finding agrees with Dangal et al. (2019), who found pasture and well-managed rangeland as a prominent N_2O-N source. Short-duration N_2O-N peakness due to fertilizer application in managed grassland was earlier reported by Jones et al. (2004). In the plantation, low positive emission and sudden negative N_2O-N emission was noticed at the final week (week 12), probably attributable to N_2O-N microbial consumption due to limited NO_3 – N assimilate. This finding agrees with Wang et al. (2023), who observed the lowest N_2O-N flux in plots well-mulched with organic material.

3.2.3 CH_4 flux based on land use systems

CH_4-C flux revealed significant variations among the considered LUs both during wet and dry seasons. During the wet season, the emission ranges found for cropland, plantation, grasscover and animal paddock were -2.19 – 2.54; - 1.328 – 3.66; -2.12 – 2.69 and 11.19 – 19.42 mg m^{-2} hr^{-1}, respectively. The CH_4-C flux from the animal paddock system revealed significantly greater emission throughout the 12-week wet season, with no single negative flux. In this LU, the emission depicted an increasing trend which peaked at week 6 to record 19.42 mg m^{-2} hr^{-1}, 74.6% higher than the lowest emission, which occurred at week 12. For cropland and grasscover LUs, the peak CH_4-C flux (2.54 and 2.69 mg m^{-2} hr^{-1}, respectively) took place at week 6 when the second fertilizer dose was applied. However, the mentioned peak values were lower than those observed in the plantation (3.66 mg m – 2 hr – 1) and in the animal paddock (19.42 mg m^{-2} hr^{-1}).

Table 10. CH_4 flux (mg m^{-2} hr^{-1}) from soil under four selected land uses during wet season for week 1 to week 6

Treatment	WK1	WK2	WK3	WK4	WK5	WK6
Land use			CH_4 flux (mg m^{-2} hr^{-1})			
Cropland	-2.17c	-2.19c	-1.256c	1.194b	0.847b	2.54b
Plantation	-1.328b	-1.07b	-0.788b	-1.16c	1.059b	1.30c
Grasscover	-2.12c	-2.12c	-1.329c	1.52b	1.641b	2.69b
Animal Paddock	14.49a	15.14a	15.98a	17.22a	17.55a	19.42a
SE±	0.188	0.240	0.110	0.254	0.315	0.456
P-Value	2.67e-16	3.16e-15	2.2e-16	6.64e-15	1.25e-13	5.277e-12
LOS	***	***	***	***	***	***

Note: WK = week, LOS = level of significance, SE = standard error, *, **, *** = significance at P ≤ 0.05, 0.01 and 0.001, respectively. Values bearing different letter column wise, are significantly different at P ≤ 0.05.

When the dry season set in, the CH_4-C emission became drastically lower across the LUs, but the highest emissions across the weeks in the animal system, compared to the others, remained unchanged. In the animal paddock, the emission witnessed a gradual but steady increase from week 1 to week 6 (4.497 – 9.39) before curving down sharply at week 8 (5.021 mg m^{-2} hr^{-1}), which further lowered to 1.196 mg m^{-2} hr^{-1} at week 12. On the other hand, plantation recorded the least CH_4-C emission, which were all negative. The pattern of the uptake was, however, broken with a sharp decline observed in week 3 when it reduced by 190.26% compared to the week 2 uptake. Cropland and grasscover were statistically similar as per the CH_4 -C emission in many weeks, and also took the same trend by recording negative emission only at weeks 1 and 2.

Table 11. CH4 flux (mg m $^{-2}$ hr $^{-1}$) from soil under four selected land uses during wet season for week 7 to week 12

Treatment	WK7	WK8	WK9	WK10	WK11	WK12
Land use	CH4 flux (mg m $^{-2}$ hr $^{-1}$)					
Cropland	2.11	1.168c	1.135b	0.72c	0.58c	0.28c
Plantation	3.66b	3.29b	1.48b	1.360b	1.24b	0.607b
Grasscover	2.30	1.167c	1.130b	1.19b	0.731c	0.27c
Animal Paddock	19.39a	15.02a	13.66a	13.527a	13.42a	11.19a
SE±	0.145	0.183	0.127	0.098	0.112	0.0545
P-Value	2.2e-16	2.24e-15	2.2e-16	2.2e-16	2.2e-16	2.2e-16
LOS	***	***	***	***	***	***

Note: WK = week, LOS = level of significance, SE = standard error, *, **, *** = significance at P ≤ 0.05, 0.01 and 0.001, respectively. Values bearing different letter column wise, are significantly different at P ≤ 0.05.

Table 12. CH_4 flux (mg m $^{-2}$ hr $^{-1}$) from soil under four selected land uses during dry season for week 1 to week 6

Treatment	WK1	WK2	WK3	WK4	WK5	WK6
Land use	CH_4 flux (mg m $^{-2}$ hr $^{-1}$)					
Cropland	-0.173b	-0.19b	0.256b	0.194b	0.197b	0.547b
Plantation	-1.78c	-1.55c	-0.534c	-0.6411c	-0.661c	-0.309c
Grasscover	-0.591b	-1.13c	0.329b	0.4187b	0.438b	0.693b
Animal Paddock	4.497a	5.148a	5.985a	7.221a	7.121a	9.422a
SE±	0.030	0.0270	0.015	0.025	0.025	0.0454
P-Value	2.73e-08	1.87e-09	4.07e-14	1.75e-10	1.758e-10	9.043e-09
LOS	**	**	***	**	**	**

Note: WK = week, LOS = level of significance, SE = standard error, *, **, *** = significance at P ≤ 0.05, 0.01 and 0.001, respectively. Values bearing different letter column wise, are significantly different at P ≤ 0.05.

CH4-C huge and significantly highest emissions observed in animal paddock relative to other treatments across all the weeks is not unexpected due to huge cow dung deposit of averagely 12 cm thickness, as well as pronounced microbial abundance that indicates the possibility of higher methanogens. According to Ratminingsih & Jumadi (2020), CH4-C concentration from cow dung compare to other gases can be as high as 7:3. The actual CH4-C concentrate is largely dependent on the thermal state of the system. In this experiment highest soil temperature, which tallied with the optimum temperature requirement for methane-producing bacteria (30 - 40°C) as related by Ibeaja et al. (2023), was observed in the animal paddock. According to Ghatak & Mahanata (2018), CH4 production involves activities of mesophilic and thermophilic bacteria, hence optimum activities are favored when the temperature is between 25 - 50°C. Ghatak & Mahanata (2018) reported a linear positive relation between CH4-C and system temperature.

Table 13. CH4 flux (mg m $^{-2}$ hr $^{-1}$) from soil under four selected land uses during dry season for week 7 to week 12

Treatment	WK7	WK8	WK9	WK10	WK11	WK12
Land use			CH4 flux (mg m $^{-2}$ hr $^{-1}$)			
Cropland	0.119b	0.168b	0.136b	0.174b	0.141b	0.141b
Plantation	-0.661c	-1.043c	-0.488c	-0.360c	-0.122c	-0.255c
Grasscover	0.306b	0.167b	0.136b	0.122b	0.156b	0.132b
Animal Paddock	9.397a	5.021a	3.66a	3.527a	3.42a	1.196a
SE±	0.015	0.012	0.012	0.0862	0.0107	0.0461
P-Value	7.65e-15	2.52e-11	9.23e-11	1.77e-12	4.982e-11	1.493e-10
LOS	**	**	***	**	***	***

Note: WK = week, LOS = level of significance, SE = standard error, *, **, *** = significance at P ≤ 0.05, 0.01 and 0.001, respectively. Values bearing different letter column wise, are significantly different at P ≤ 0.05.

They concluded that faster CH4-C production was noted when the temperature was increased, likely due to the quick breakage of lignin and stimulated microbial activities. Increased soil wetness, capable of causing slurry when a rain event occurred, possibly increased CH4-C production. Research findings by Putri et al. (2012) concurred that in a 1:3 manure: water ratio set-up, the system produces the highest volume of CH4-C. This is technically because water molecules are critically needed to facilitate hydrolysis reactions at acetogenesis, acetogenesis, and methanogenesis stages for the conversion of complex organic compounds into CH4. Since methanogens assimilate hydrogen and CO2 as an energy source to produce CH4-C, as established by Ishak et al. (2022), fresh cow dung abundant in the animal paddock could serve as a medium for the proliferation and activities of methanogens. The CH4-C flux upsurge at the mid of the wet season further reinforces moisture influence due to increasing moisture content. Considerable CH4-C emission from tropical ruminant systems has been associated with the feed intake that is classically below maintenance requirements, which becomes obvious in the dry season (Goopy et al., 2020).

In the cropland, plantation, and grasscover land uses, negative CH4-C emissions dominated the first three weeks during the dry season, which can be connected to low carbon compounds; carbohydrate, protein and lipid sources, as well as an unconducive environment for methanogenesis to take place at the beginning of the wet season. Further, a possible limited number of hydrogenase-producing microorganisms (archaebacteria), crucially involved in methane production, may explain why uptake dominates these LUs. According to Volles et al. (2025), grassland becomes a CH4-C sink due to a possible lower number of hydrogenases and predominance of methanotrophs. From the middle to the end of the experiment, however, improvement in N, P and C inputs through fertilizer application, in the case of cropland and grasscover and through mineralization of decomposed litter in the case of plantation, as well as occasional water residence, changed the land uses into a meagre source of CH_4-C.

Aggregate results of GHG fluxes hold a remarkable implication by evidencing the global warming threat status of each land use. The results categorically identified animal paddock and grasscover as LUs with the biggest and mildest global warming threat. Similarly, the weekly emission pattern for each LU provides a time-based emission mitigation target for pragmatic land-use-specific GHG emission reduction efforts.

4. Limitations and Future Directions

The study was limited in several aspects. First, it only covered the four most prominent land uses (LUs), which represent barely a few of the many existing crop-based LUs in the country. Second, the spatial scope was constrained to only the Northern Guinea Savannah, which represents 1/6 of the major agroecological zones in the country. Third, the study was not able to delve deeply into the biology and chemistry of soil systems that are related to GHG production, uptake and flow processes.

In the future, similar studies should be extended to cover more important LUs and farming systems as well as other ecologies, particularly those with contrasting climate, vegetation and soil nature. Furthermore, studies on microbial strain identification/isolation targeting methanogens and methanotrophs colonies, as well as redox potential for each LUs, should be undertaken so as to foster scientifically-grounded explanations regarding GHG production mechanisms.

5. Conclusion

Land use-specific Greenhouse Gases quantification is a pedestal for proper GHG inventory to guide informed climate change mitigation strides. Through the use of the static chamber method, emissions contributions of the four most prominent land uses (LUs) were determined. Results proved that animal paddock is the greatest contributor of N_2O-N and CH_4-C GHG species, in both wet and dry seasons. In the dry season, the plantation was concluded to be the highest CO_2 emitter, while cropland, plantation and grasscover acted as N_2O-N sink. The findings inferred that hot emission moments in cropland and grasscover LUs tallied with specific critical management practices. Mitigation measures should target optimizing fertilizer use efficiency, utilization of cow dung sludge in organo-mineral fertilizer development and litter management in cropland, animal paddock and plantation LUs, respectively. The outcomes of this study will cause a paradigm shift in Nigeria's greenhouse emission accounting from a generalized rough estimate to a more specific and high-resolution empirical data, thereby empowering policy makers and scientists to undertake strategic steps in mitigating climate change. The seasonal and temporal emission trends presented in this study are critically helpful for targeting emission hot moments, which could be the most effective short-term and low-cost mitigation measure. In the long run, the study could serve as a foundational basis to actualization of an upgraded national GHG emission inventory and reporting mission.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The authors declare that ChatGPT (OpenAI) was used only as an auxiliary tool during manuscript preparation, mainly for language polishing, wording refinement, and translation support. All outputs generated with AI assistance were critically evaluated, verified, and substantially modified by the authors. The authors remain fully accountable for the accuracy, originality, integrity, and academic content of the manuscript.

Authorship Contribution Statement

All the authors have contributed technically and considerably in the research work and article development.

Declaration of Competing Interest

There is a lack of conflict of interest whatsoever among the authors that may have appeared to affect the outcome of this work.

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