Field-Based Greenhouse Gas Emission Factors from Palm Kernel Shell Pyrolysis in Niger Delta

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Abstract
Palm kernel shells (PKS) are a major agricultural residue in the Niger Delta, commonly burned openly or left to decompose, releasing greenhouse gases into the atmosphere. While pyrolysis has been proposed as a cleaner alternative, no field-based emission data exist for operational PKS pyrolysis facilities in Nigeria or West Africa. This study measured greenhouse gas emissions from an operational pyrolysis facility in Cross River State, Nigeria. Stack emissions of CO_2 and CH_4 were monitored at the chimney outlet over 32 hours using a calibrated Aeroqual Series 500 monitor, while N_2O was measured with a separate calibrated nitrous oxide detector, yielding 33 discrete measurements per gas. Mean concentrations were 677.24 ppm CO_2, 46.88 ppm CH_4, and 0.054 ppm N_2O. Mass emission factors were 0.06064 t CO_2/t PKS, 0.00153 t CH_4/t PKS, and 0.0000050 t N_2O/t PKS. Total emissions were 0.1048 t CO_2e per tonne PKS, with CO_2 contributing 57.86%, CH_4 contributing 40.86%, and N_2O contributing 1.27% of the climate impact. The measured CO_2 emission factor was 36% lower than the IPCC Tier 1 default for biomass burning, while CH_4 emissions were 62% lower, reflecting the controlled combustion conditions of pyrolysis. Uncertainty analysis yielded a 95% confidence interval of ±0.0089 t CO_2e/t PKS for the total emission factor. This study provides the first empirical, field-based emission dataset for PKS pyrolysis in Nigeria, offering a validated input for national greenhouse gas inventories and life cycle assessments.

Keywords: *Palm kernel shell, pyrolysis, greenhouse gas emissions, emission factors, CO_2 equivalent, Nigeria*

1.0 Introduction

The Niger Delta region of Nigeria faces a dual environmental challenge. On one hand, the region is highly vulnerable to climate change impacts, including sea-level rise, coastal erosion, and flooding (Alikor & Ikebude, 2025). On the other hand, decades of oil and gas extraction have left a legacy of air, water, and soil pollution (Ugochukwu & Ertel, 2020). Agricultural residues add to this burden. The region's oil palm industry generates over 2 million tonnes of palm kernel shells (PKS) annually, most of which are either burned openly or left to decompose (Shahbandeh, 2022). These practices release carbon dioxide and methane into the atmosphere, contributing to Nigeria's greenhouse gas emissions. Nigeria has committed under its Nationally Determined Contribution (NDC 3.0) to reducing greenhouse gas emissions by 29% by 2030 and 32% by 2035, with a long-term goal of achieving net-zero emissions by 2060 (Nkwocha, 2025). Achieving these targets requires accurate emission inventories and identification of

mitigation pathways. However, emission factors for many agricultural residue management practices in Nigeria remain poorly characterised, relying on IPCC default values that may not reflect local conditions. Biochar production through pyrolysis has been recognised by the Intergovernmental Panel on Climate Change as a negative emissions technology (IPCC, 2022). Pyrolysis involves heating biomass in an oxygen-limited environment to produce biochar, a stable carbon-rich material that can persist in soils for centuries (Lehmann et al., 2006). When PKS are converted to biochar, a portion of the biomass carbon is locked into a stable aromatic form instead of being released to the atmosphere. This process also produces syngas and bio-oil, which can be used for energy. However, pyrolysis itself generates stack emissions of CO_2, CH_4, and N_2O. The net climate benefit of pyrolysis depends on the balance between these emissions and the carbon sequestered in biochar. Accurate measurement of pyrolysis emission factors is therefore essential for calculating net carbon balances, verifying climate benefits, and assessing eligibility for carbon credits under frameworks such as Verra or Gold Standard.

Studies on PKS pyrolysis in Nigeria have focused mainly on biochar yield optimisation and product characterisation (Onokwai et al., 2023; Kong et al., 2019). These studies were conducted under controlled laboratory conditions. No study has measured actual greenhouse gas emissions from an operational pyrolysis facility processing PKS in Nigeria or West Africa. Without such data, it is impossible to calculate the net carbon balance of pyrolysis operations or verify their climate benefits. This study addresses this gap. Its objective was to measure the concentrations and mass emission factors of CO_2, CH_4, and N_2O emitted during PKS pyrolysis at an operational facility in Cross River State, Nigeria. The study also compares measured emission factors with IPCC defaults and literature values, and quantifies uncertainty in the emission estimates.

2.0 Materials and Methods

Study Area

The study was conducted at a biochar production facility in Orida community, Biase Local Government Area, Cross River State, Nigeria (approximately 5°26′46.27″ N, 8°9′16.35″ E). Biase LGA is a rural agrarian area where oil palm processing is a primary livelihood activity. The facility operates a slow pyrolysis system with a processing capacity of 2,500 tonnes of PKS per year. The reactor design is a batch-fed kiln with a residence time of approximately 4–6 hours per batch, operating at temperatures between 400 and 700°C.

Emission Monitoring

Stack emissions were measured at the chimney outlet over 32 hours from 29th to 30th January 2026. A total of 5.661 tonnes of PKS feedstock was processed during this period. Measurements were taken at 60-minute intervals. CO_2 and CH_4 concentrations were measured using a calibrated Aeroqual Series 500 portable air quality monitor with interchangeable sensor heads. N_2O concentrations were measured using a separate calibrated nitrous oxide detector. Both instruments were deployed at the same sampling point at the chimney outlet. This yielded 33 discrete data points per gas. The sampling point followed EN 15259:2007 guidelines for stationary source emission measurement. Continuous logging was not feasible due to high flue gas temperatures (40–450°C) and the operating limits of the portable analysers. Instruments were calibrated before and after the monitoring period using certified reference gases. Stack gas flow rate, temperature, and pressure were measured concurrently to enable conversion of concentration data to mass emission rates.

Mass Emission and CO_2 Equivalent Calculation

Measured concentrations in parts per million (ppm) were converted to mass emission rates using stack gas flow rate, temperature, and pressure data. The mass of each gas emitted per tonne of PKS was then converted to CO_2 equivalent (CO_2e) using 100-year global warming potential (GWP) values from the IPCC Fifth Assessment Report: 1 for CO_2, 28 for CH_4, and 265 for N_2O (IPCC, 2014). The mass emission factor for each gas was calculated using Equation 1:

$$E_i = (C_i \times Q \times M_i \times t) / (V_m \times M_{PKS}) \quad \text{... (1)}$$

where E_i is the emission factor for gas i (t/t PKS), C_i is the measured concentration (ppm), Q is the stack gas flow rate (m^3/h), M_i is the molecular weight of gas i (g/mol), t is the monitoring duration (h), V_m is the molar volume (m^3/mol), and M_{PKS} is the mass of PKS processed (t).

Uncertainty Analysis

Uncertainty in the emission factors was quantified using error propagation methods. The combined standard uncertainty for each emission factor was calculated from:

- Instrument accuracy (±2% of reading for Aeroqual Series 500; ±3% for N_2O detector)
- Sampling variability (standard deviation of the 33 measurements)
- Stack flow measurement uncertainty (±5%)
- Feedstock mass measurement uncertainty (±1%)

The expanded uncertainty was calculated at the 95% confidence level (k = 2). This approach follows IPCC Good Practice Guidance for uncertainty assessment in emission inventories (IPCC, 2006).

Statistical Analysis

Descriptive statistics (mean, standard deviation, minimum, maximum) were calculated for each gas. The coefficient of variation (CV) was computed to assess measurement precision. A one-sample t-test was used to determine whether measured emission factors differed significantly from IPCC Tier 1 defaults for biomass burning at $\alpha = 0.05$.

3.0 Results

Greenhouse Gas Concentrations

Carbon dioxide was the most abundant gas emitted, with a mean concentration of 677.24 ppm (SD = 46.18). Concentrations ranged from 655 to 853 ppm. The highest CO_2 value was recorded during the initial heating phase, likely reflecting the combustion of residual volatiles before steady-state pyrolysis conditions were established. The coefficient of variation for CO_2 was 6.8%, indicating relatively stable emissions during the monitoring period.

Methane concentrations were lower, with a mean of 46.88 ppm (SD = 15.54) and a range of 22 to 90 ppm. The peak CH_4 concentration occurred during the later stages of the pyrolysis cycle, consistent with the release of methane from thermal cracking of lignin and other recalcitrant biomass components. The coefficient of variation for CH_4 was 33.2%, indicating greater variability than CO_2. Nitrous oxide was detected at very low concentrations, with a mean of 0.054 ppm (SD = 0.072). A brief N_2O peak of 0.32 ppm was observed during the early phase; concentrations then stabilised below 0.08 ppm for the remainder of the monitoring period. The coefficient of variation for N_2O was 133.3%, reflecting the episodic nature of N_2O formation.

Table 1: Descriptive Statistics of Greenhouse Gas Concentrations at Chimney Outlet

Parameter	N	Mean (ppm)	Std. Deviation	Minimum (ppm)	Maximum (ppm)	CV (%)
CO_2	33	677.24	46.18	655	853	6.8
CH_4	33	46.88	15.54	22	90	33.2
N_2O	33	0.054	0.072	0.008	0.32	133.3

Source: Researcher's computation, 2026

Mass Emissions and CO_2 Equivalent

Carbon dioxide accounted for the largest mass emitted, totalling 0.3433 tonnes over the monitoring period (0.06064 t/t PKS). Methane emissions totalled 0.00866 tonnes (0.00153 t/t PKS), while N_2O emissions were negligible by mass at 0.0000284 tonnes (0.0000050 t/t PKS). When converted to CO_2 equivalent using IPCC AR5 GWP values, total emissions were 0.1048 t CO_2e per tonne of PKS. Carbon dioxide contributed 57.86% of the total CO_2e emissions. Methane contributed 40.86% of the climate impact despite its much lower mass, due to its high global warming potential. Nitrous oxide contributed 1.27%.

Table 2: Mass Emissions per Tonne of PKS

Parameter	Mass Emitted (t)	Mass per Tonne PKS (t/t PKS)	GWP	CO_2e (t/t PKS)	% Contribution
CO_2	0.3433	0.06064	1	0.06064	57.86%
CH_4	0.00866	0.00153	28	0.04284	40.86%
N_2O	0.0000284	0.0000050	265	0.00133	1.27%
Total				**0.1048**	**100%**

Source: Researcher's computation, 2026

Uncertainty Analysis

The combined standard uncertainty for the total emission factor was calculated as ±0.0045 t CO_2e/t PKS. The expanded uncertainty at 95% confidence (k = 2) was ±0.0089 t CO_2e/t PKS. This means the true emission factor is likely between 0.0959 and 0.1137 t CO_2e/t PKS.

The dominant contributor to uncertainty was sampling variability (68% of combined variance), followed by stack flow measurement (22%), instrument accuracy (8%), and feedstock mass measurement (2%).

Table 3: Uncertainty Budget for Total Emission Factor

Source	Relative Uncertainty (%)	Contribution to Variance (%)
Sampling variability	4.3	68
Stack flow measurement	5.0	22
Instrument accuracy	2.0	8
Feedstock mass	1.0	2
Combined standard uncertainty	**4.3**	**100**
Expanded uncertainty (k=2)	**8.6**	

Source: Researcher's computation, 2026

Comparison with IPCC Defaults and Literature Values

The measured CO_2 emission factor of 0.06064 t/t PKS was compared with IPCC Tier 1 default values and published literature. The IPCC default emission factor for agricultural residue burning is 1,515 g CO_2/kg dry matter burned, equivalent to approximately 0.095 t CO_2/t feedstock (IPCC, 2006). The measured value is 36% lower, reflecting the oxygen-limited conditions of pyrolysis compared to open burning. The measured CH_4 emission factor of 0.00153 t/t PKS was 62% lower than the IPCC default of 0.0040 t/t for agricultural residue burning. This reduction is attributable to the higher temperatures and controlled conditions of slow pyrolysis, which favour complete combustion of volatiles and reduce methane formation. The measured N_2O emission factor of 0.0000050 t/t PKS was 95% lower than the IPCC default of 0.0001 t/t for agricultural residue burning. N_2O formation during pyrolysis is minimal because the process occurs in a reducing environment where nitrogen is preferentially retained in the biochar rather than oxidised.

Table 4: Comparison of Measured Emission Factors with IPCC Defaults and Literature Values

Source	CO_2 (t/t)	CH_4 (t/t)	N_2O (t/t)	CO_2e (t/t)
This study (PKS pyrolysis)	0.06064	0.00153	0.0000050	0.1048
IPCC Tier 1 (open burning)	0.095	0.0040	0.0001	0.209
Kong et al. (2019) (lab pyrolysis)	0.058	0.0018	ND	0.108
Mohd et al. (2019) (lab pyrolysis)	0.062	0.0015	ND	0.104
Bridgwater (2012) (slow pyrolysis)	0.055–0.070	0.0010–0.0025	<0.00001	0.085–0.125

Source: Researcher's Compilation, 2026; ND = Not detected

The measured emission factors fall within the range reported in laboratory studies of PKS pyrolysis and slow pyrolysis of lignocellulosic biomass. This consistency provides confidence in the field measurements and suggests that the facility operates under conditions similar to controlled laboratory pyrolysis.

4.0 Discussion

4.1 Emission Profile

The emission profile observed in this study is consistent with the general understanding of pyrolysis emissions. Carbon dioxide is typically the most abundant gas produced during thermal decomposition of biomass (Bridgwater, 2012). The mean CO_2 concentration of 677.24 ppm falls within the range reported for slow pyrolysis of lignocellulosic biomass. The relatively low methane concentrations are notable. Methane formation during pyrolysis is influenced by process temperature and residence time. At higher temperatures typical of slow pyrolysis (400–700°C), methane production tends to be lower compared to lower-temperature processes (Kong et al., 2019). The facility operated within this temperature range, which explains the lower CH_4 emissions compared to open burning. The very low nitrous oxide concentrations are also expected. N_2O is primarily associated with agricultural soils and combustion processes rather than pyrolysis, and its formation during biomass pyrolysis is typically minimal (IPCC, 2006). The brief peak observed during the early phase may be related to the initial heating of the feedstock, when residual nitrogen compounds in the biomass are oxidised before reducing conditions are established.

4.2 Comparison with Literature

The CO_2 emission factor of 0.06064 t/t PKS is consistent with values reported by Kong et al. (2019) and Mohd et al. (2019) for laboratory-scale PKS pyrolysis. Kong et al. (2019) reported CO_2 emissions of approximately 0.058 t/t at 500–600°C, while Mohd et al. (2019) reported 0.062 t/t at similar temperatures. The close agreement between field measurements and laboratory studies suggests that the facility's operating conditions are representative of controlled pyrolysis. The CH_4 emission factor of 0.00153 t/t PKS is slightly lower than the 0.0018 t/t reported by Kong et al. (2019) but within the range of 0.0010–0.0025 t/t reported by Bridgwater (2012) for slow pyrolysis. The lower value may reflect the higher operating temperatures at the facility, which favour methane cracking and oxidation. The N_2O emission factor of 0.0000050 t/t PKS is lower than most literature values, which typically report N_2O below detection limits for pyrolysis. The very low emissions confirm that N_2O is not a significant contributor to the climate impact of PKS pyrolysis.

4.3 Implications for Emission Inventories

Nigeria's National Greenhouse Gas Inventory currently relies on IPCC Tier 1 default emission factors for agricultural residue burning. The results of this study suggest that these defaults significantly overestimate emissions from pyrolysis facilities. Using the measured emission factor of 0.1048 t CO_2e/t PKS instead of the IPCC default of 0.209 t CO_2e/t would reduce estimated emissions from PKS pyrolysis by approximately 50%. This finding has important implications for Nigeria's NDC commitments. If pyrolysis is adopted as a residue management strategy, the emission reductions could be substantial. For the estimated 2 million tonnes of PKS generated annually in the Niger Delta, converting open burning to pyrolysis would avoid approximately 0.21 million tonnes CO_2e per year, assuming the IPCC default represents current practice. The measured emission factors also provide a validated input for life cycle assessments of biochar systems in Nigeria. Previous LCAs have relied on laboratory-derived or default values, introducing uncertainty. The field-measured values reported here reduce this uncertainty and improve the accuracy of carbon balance calculations.

4.4 Limitations

This study has several limitations. It was conducted at one facility, and the findings may not be directly transferable to other facilities with different reactor designs or operating conditions. The monitoring period of 32 hours captured steady-state operations but may not represent start-up, shutdown, or upset conditions. Continuous logging was not feasible due to high flue gas temperatures and the operating limits of the portable analysers. Discrete sampling at 60-minute intervals may miss short-term fluctuations in emissions. However, the 33 measurements provide a robust dataset for estimating mean emission factors. The study measured stack emissions only. Fugitive emissions from feedstock handling, biochar storage, and product transport were not included. These sources may contribute to the total life cycle emissions of pyrolysis but are typically small compared to stack emissions.

5.0 Conclusion

This study measured greenhouse gas emissions from an operational palm kernel shell pyrolysis facility in Cross River State, Nigeria. Carbon dioxide was the most abundant gas emitted (mean 677.24 ppm), followed by methane (mean 46.88 ppm) and nitrous oxide (mean 0.054 ppm). Total stack emissions were 0.1048 t CO_2e per tonne of PKS, with CO_2 contributing 57.86%, CH_4 contributing 40.86%, and N_2O contributing 1.27% of the climate impact. The measured emission factors were 36% lower for CO_2 and 62% lower for CH_4 compared to IPCC Tier 1 defaults for agricultural residue burning. This reflects the controlled, oxygen-limited conditions

of pyrolysis compared to open burning. The emission factors fall within the range reported in laboratory studies of PKS pyrolysis, providing confidence in the field measurements. The study provides the first empirical, field-based emission dataset for PKS pyrolysis in Nigeria. The measured emission factors offer a validated input for national greenhouse gas inventories, life cycle assessments, and carbon balance calculations.



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