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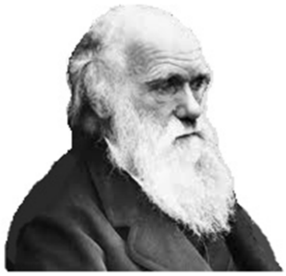

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Comparative analysis of CO_2/SO_2 emissions of *Khaya ivorensis* A.Chev. and *Terminalia superba* Engl. & Diels wood waste using ultimate analysis techniques

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ABSTRACT

The increasing dependence on wood residues as a sustainable biomass energy source highlights the need for precise evaluation of their combustion-related pollutants to advance environmentally responsible energy solutions. This research conducts a comparative analysis of carbon dioxide (CO_2) and sulfur dioxide (SO_2) emissions from two tropical hardwood wastes - Mahogany (*Khaya ivorensis*) and Afara (*Terminalia superba*) - through ultimate analysis methods. Samples of these wood wastes were gathered from sawmill disposal sites in Asaba, Nigeria, and examined using X-Ray fluorescence (XRF) spectroscopy to identify their elemental makeup. The analysis showed carbon levels of 47.08% in K. ivorensis and 45.49% in T. superba, with hydrogen at 4.76% and 4.59%, respectively. Sulfur concentrations were particularly minimal, recorded at 0.10% for Mahogany and 0.08% for Afara. Calculations based on stoichiometric combustion indicated CO_2 emission rates of 18.795% (wet basis) and 21.214% (dry basis) for Mahogany, while Afara yielded 19.16% (wet) and 22.50% (dry). SO_2 emissions remained extremely low across both wood types, falling between 0.010% and 0.017% on wet and dry bases.These findings confirm that both hardwood residues possess desirable combustion qualities, including very limited SO_2 output, positioning them as environmentally preferable options compared to conventional fossil fuels. While Afara generated marginally higher CO_2 levels, both materials hold considerable promise as viable biomass resources for energy generation across Nigeria and similar tropical areas. The study delivers valuable insights for predicting emissions and encourages the productive reuse of waste from the timber sector.

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***Keywords*:** Ultimate analysis, Wood waste, CO_2 emissions, SO_2 emissions, *Khaya ivorensis*, *Terminalia superba*, Biomass combustion

1. INTRODUCTION

The use of wood waste as a biomass energy resource has become increasingly important as both an effective waste management approach and a viable renewable energy solution. This is particularly relevant in tropical areas such as West Africa, where timber processing generates significant volumes of residues from sawmilling and related industries. Mahogany (*Khaya ivorensis* and closely related species) and Afara (*Terminalia superba*) are two major tropical hardwoods widely found in Nigeria and across sub-Saharan Africa. These species generate large amounts of waste during sawmilling, furniture production, and construction. Although this waste presents valuable opportunities for energy recovery, burning it releases greenhouse gases like carbon dioxide (CO_2) and pollutants such as sulfur dioxide (SO_2), which contribute to climate change and air quality concerns (Orhorhoro et al., 2024; Aliu et al., 2020; Mitchual et al., 2014).

According to Onochie et al. (2024), ultimate analysis - which measures the elemental makeup of biomass including carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O) - is a key method for forecasting emission patterns. The carbon level helps predict potential CO_2 output through stoichiometric calculations, while sulfur content directly indicates possible SO_2 formation. This analytical approach allows for meaningful comparisons between different wood types, helping stakeholders choose feedstocks with lower emissions and develop more efficient, cleaner burning technologies (Kaoke et al., 2024; Akhator et al., 2017).

Several recent investigations have employed ultimate analysis to assess the fuel characteristics and environmental effects of these wood species and their residues. For instance, Erokare et al. (2025) conducted an elemental analysis on Afara wood, providing detailed composition data and estimating combustion gas percentages, including SO_2, under both dry and wet conditions. Previous comparative studies on Nigerian tropical hardwoods such as Mahogany and Afara have noted their characteristically low sulfur levels (generally below 0.2–0.3%), which suggest limited SO_2 emissions, along with carbon contents typically between 50% and 58% that determine CO_2 release. Additional research on torrefied Mahogany waste has explored how changes in its elemental profile influence both emission behavior and energy value (Akinola et al., 2025; Aliu et al., 2020). The present study performs a comparative evaluation of CO_2 and SO_2 emissions from Mahogany and Afara wood wastes through ultimate analysis. By establishing their elemental compositions and deriving emission factors, this work offers useful information on their relative environmental footprints. These insights support the responsible use of timber industry residues for energy generation while reducing atmospheric pollution, especially in developing regions with limited resources.

2. MATERIALS AND METHODS

2. 1. Material Collection

The wood waste samples were gathered from a sawmill dumpsite in Asaba Metropolis, Nigeria. The collected materials consisted of *Khaya ivorensis* (Mahogany) and *Terminalia* *superba* (Afara). These samples were subsequently transported to a research institute in Benin City for accurate botanical identification.

2. 2. Material Preparation

Following sample collection, the wood wastes were thoroughly washed and sun-dried for one week to eliminate dirt and other impurities while lowering their moisture levels. The materials were then reduced into fine particles measuring between 0.3 and 0.5 micrometers. These prepared samples were subsequently utilized for the experimental analysis.

2. 3. Method

2. 3. 1. Ultimate Analysis

The ultimate analysis of the biomass samples reveals their elemental chemical composition and serves as a reliable indicator of fuel quality. This technique quantifies the percentage composition of key elements, including carbon, hydrogen, nitrogen, and sulfur, using X-Ray fluorescence spectroscopy (Xenemetrix Genius-IF series). Such analysis is essential for estimating the quantity of air needed for complete combustion, predicting the volume and makeup of resulting combustion gases, and calculating the heat value of the fuel, which is largely influenced by its carbon and hydrogen contents.

The standard operating procedures followed are outlined below:

Prepare a sample cup fitted with a smooth Prolene thin film layer.

Fill the thin film-covered cup with the wood sample to approximately one-third of its capacity (about 10–15 g).

Secure the lid tightly on the sample cup, ensuring no leaks, loose particles, or irregularities on the thin film surface.

Place the prepared sample into the sample turret of the Genius-IF XRF analyzer (for pelletized samples, confirm the surface is free of cracks or loose debris).

Preheat the X-Ray lamp.

In the RUN tab, adjust the voltage and emission current to maintain the observed dead time within the 35–40% range; discontinue acquisition if the dead time falls outside this range.

Initiate the analysis to generate the spectrum.

Launch the XRS-FP software.

Upload the Master Oxide.tfr file.

Upload the acquired spectrum file for the sample.

Select Process > Process Spectrum.

Select Process > Analyze Spectrum.

Retrieve the results and save them by printing to file.

2. 4. Chemical and Combustion Performance Analysis of Wood Samples

The chemical composition of wood samples was determined from ultimate analysis results to provide insights into their elemental makeup for combustion assessment. This will be inserted into Equation (1)

$C_aH_bO_dN_eS_f$ ……………………………………………………………………………………… (1)

The combustion analysis of various wood samples (Mahogany, Danta, Obeche, Afara and Okwen) was evaluated using Equation (2). Now, since oxygen is supplied as air, the associated N_2 will appear in the Equation as:

$C_aH_bO_dN_eS_f + y_1\,[O_2 + (79/21)N_2] \rightarrow p_1CO_2 + q_1H_2O + r_1SO_2 + [t_1 + y_1(79/21)N_2]$………(2)

2. 5. Combustion Emission Analysis of wood sample

The percentage of each product emitted from the stoichiometric combustion of wood samples in the wet and dry emission analysis was calculated using equations (3) and (4), respectively.

For wet analysis:

$$\%\text{ of gas emitted is} = \frac{n_i}{n_{CO_2} + n_{SO_2} + n_{H_2O} + n_{N_2}} \times \frac{100}{1} \quad \text{……… (3)}$$

For dry analysis;

$$\%\text{ of gas emitted is} = \frac{n_i}{n_{CO_2} + n_{SO_2} + n_{N_2}} \times \frac{100}{1} \quad \text{……… (4)}$$

where n_i is the amount (in kmol) of the product of emission under consideration and n_{CO_2}, n_{SO_2}, n_{H_2O} *and* n_{N_2} represents the amount (in kmol) of carbon dioxide, sulphur dioxide, water vapour and nitrogen gas emitted respectively.

3. RESULTS AND DISCUSSION

3. 1. Ultimate Analysis Results Samples

The ultimate analysis results shown in Table 1 provide a detailed breakdown of the elemental composition of *Khaya ivorensis* and *Terminalia superba* wood wastes, offering valuable information on their fuel characteristics and potential environmental impact. The two species recorded carbon contents of 47.08% and 45.49%, respectively, which are typical for tropical hardwood biomass (generally falling between 45% and 55%). Their hydrogen levels (4.76% for Mahogany and 4.59% for Afara) and oxygen contents (40.14% and 42.09%) align well with those commonly observed in lignocellulosic materials, pointing to strong combustion performance (Quartey, 2025; Yanan, 2025; Yunusa et al., 2024).

Khaya ivorensis waste displayed marginally higher carbon and hydrogen levels compared to *Terminalia superba*. This difference implies a slightly greater energy content and potentially higher CO_2 output per unit of mass during full combustion, since CO_2 production is directly proportional to carbon content. Based on standard emission calculations, *Khaya ivorensis* is estimated to generate roughly 3–4% more theoretical CO_2 than *Terminalia superba* when burned under the same conditions (Erokare et al., 2025; Aliu et al., 2020).

Both samples demonstrated very low sulfur concentrations (0.10% in *Khaya ivorensis* and 0.08% in *Terminalia superba*), highlighting their clear environmental edge over fossil fuels. These low sulfur figures are consistent with other Nigerian tropical wood wastes and correspond to negligible SO_2 emissions during combustion (typically below 0.015%).

Terminalia superba, with its even lower sulfur level, stands out as a better choice in situations where minimizing SO_2 and acid rain risks is a priority. Nitrogen contents were also minimal (0.55% and 0.46%), indicating limited potential for NO_X formation (Orhorhoro et al., 2024; Shrestha et al., 2024; Aliu et al., 2020).

Overall, these findings confirm that both wood wastes represent promising cleaner-burning biomass options. Comparable results for *Terminalia superba* were documented by Erokare et al. (2025) in combustion research carried out in Benin City, Nigeria, which noted low SO_2 release and good energy values. Broader studies on tropical hardwoods continue to show similar low-sulfur profiles, supporting the integration of such wastes into eco-friendly energy solutions that help curb air pollution.

The higher oxygen content observed in *Terminalia superba* could promote more efficient burning, though it may result in a modestly lower heating value relative to *Khaya ivorensis*. In summary, the data endorse the utilization of these wood residues for energy production, with *Khaya ivorensis* providing greater energy density and *Terminalia superba* offering better low-emission qualities.

This research strengthens strategies for converting timber industry by-products into valuable energy resources in wood-abundant regions such as Nigeria.

Table 1. Ultimate analysis results of wood samples.

Component	***Khaya ivorensis***	***Terminalia superba***
Carbon (%)	47.08	45.49
Nitrogen (%)	0.55	0.46
Sulphur (%)	0.10	0.08
Hydrogen (%)	4.76	4.59
Oxygen (%)	40.14	42.09

3. 2. Chemical Formulas for Tropical Wood Samples

The end analysis results in Table 1 determined the equivalent chemical composition [$C_aH_bO_dN_eS_f$] by mass for each wood sample as stated in equation 1. Consequently, data encompassing the several elements (carbon, hydrogen, oxygen, nitrogen, and sulphur) was utilized to assess the unknown variables (a, b, d, e, and f) to ascertain the chemical formula of each sample.

3. 2. 1. Chemical formula of *Khaya ivorensis* wood sample

i. For Carbon:

$12a = 47.08$; $a = 3.9233$

ii. For Hydrogen:

$1b = 4.76$; $b = 4.76$

iii. For Oxygen:

$16d = 40.14$; $d = 2.50875$

iv. For Nitrogen:

$14e = 0.46$; $e = 0.0392$

v. For Sulphur:

$32f = 0.10$; $f = 0.003125$

Therefore, the chemical formula of the *Khaya ivorensis* wood sample is $C_{3.9233}\ H_{4.76}\ O_{2.50875}\ N_{0.03923}\ S_{0.003125}$.

3. 2. 2. Chemical formula of *Terminalia superba* wood sample

i. For Carbon:

$12a = 45.49$; $a = 3.7908$

ii. For Hydrogen:

$1b = 4.59$; $b = 4.59$

iii. For Oxygen:

$16d = 42.09$; $d = 2.6306$

iv. For Nitrogen:

$14e = 0.55$; $e = 0.0392$

v. For Sulphur:

$32f = 0.08$; $f = 0.0025$

Therefore, the chemical formula of the *Terminalia superba* wood sample is $C_{3.7908}\ H_{4.59}\ O_{2.6306}\ N_{0.0392}\ S_{0.0025}$. The chemical formula summary for the wood fuel samples is shown in Table 2.

Table 2. Atomic Number of Constituent Elements and Chemical formula of wood samples.

Wood Samples	C	H	O	N	S	Chemical Formula
Khaya ivorensis	3.9233	4.76	2.50875	0.0392	0.003125	$C_{3.9233}H_{4.76}O_{2.50875}N_{0.03923}S_{0.003125}$

Terminalia superba	3.7908	4.59	2.6306	0.0392	0.0025	$C_{3.7908}H_{4.59}O_{2.6306}N_{0.0329}S_{0.0025}$

3. 3. Combustion Emission Analysis of wood samples

According to Onochie et al. (2024), combustion is a chemical reaction in which fuel reacts with oxygen to produce burning and release heat energy. The same authors emphasized that examining fuels for combustion involves assessing the levels of carbon, hydrogen, nitrogen, and sulfur present. Ramesh et al. (2022) highlighted combustion analysis as an essential aspect for effectively controlling and optimizing combustion operations. Anufriev et al. (2021) stressed that safe and efficient combustion requires supplying the correct proportion and blend of fuel and oxygen to the burner.

As a result, Equation 2 was applied to perform stoichiometric combustion calculations for the five wood samples, while Equations 3 and 4 were used to determine the total amounts of wet products and dry products in kmol for each sample.

3. 3. 1. Combustion emission of CO_2 and SO_2 of *Khaya ivorensis* wood sample

The flue gas analysis for combusted *Khaya ivorensis* wood waste revealed the following composition on a wet basis: CO_2 18.795%, H_2O 11.402%, SO_2 0.015%, and N_2 69.79%. On a dry basis, the values were CO_2 21.214%, SO_2 0.017%, and N_2 78.77%. These results are illustrated in Figures 1 and 2, which present the percentage breakdown of both wet and dry flue gas components for *Khaya ivorensis*.

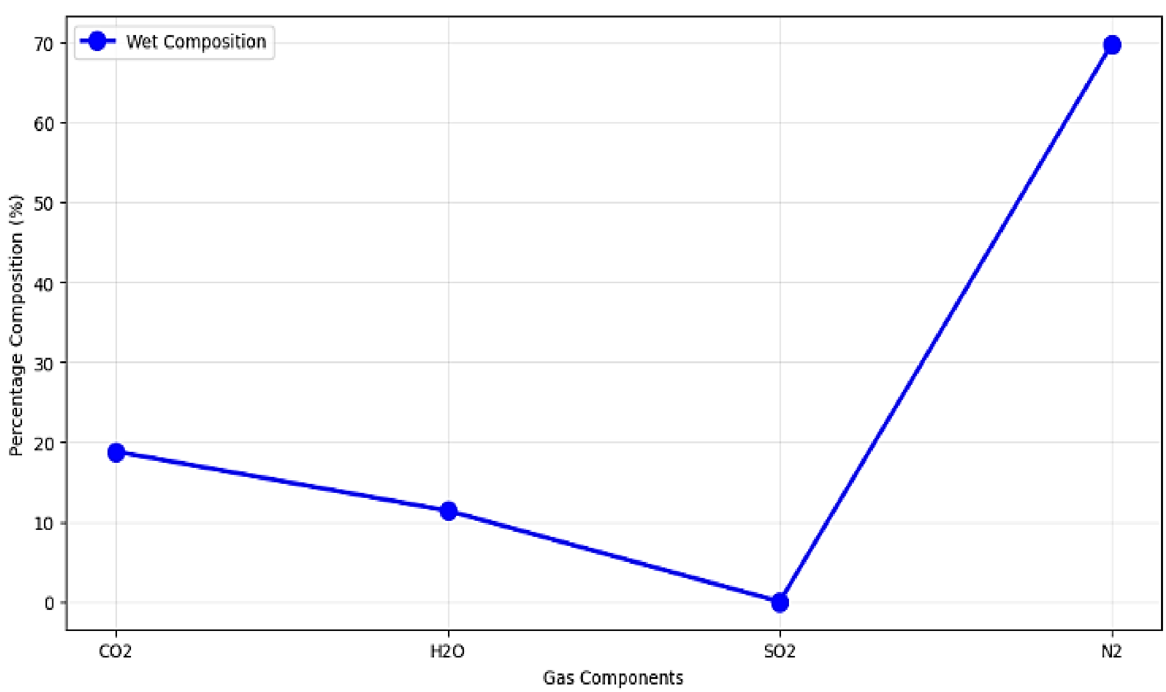

Figure 1. Wet Composition emission analysis *Khaya ivorensis* wood sample.

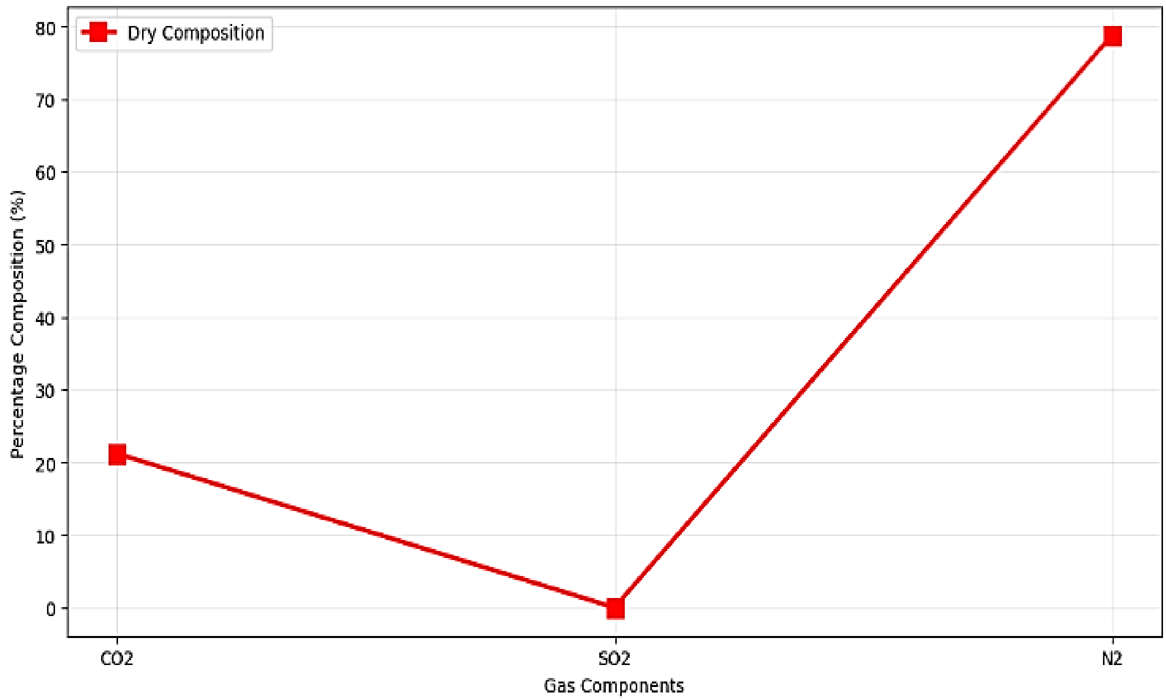

Figure 2. Dry emission percentage analysis *Khaya ivorensis* wood sample.

The remarkably low SO_2 levels (0.0”5–0.017%) reflect the minimal sulfur content typical of woody biomass, which is substantially lower than levels found in fossil fuels (Tsai et al., 2021; Rokni et al., 2018). This significantly lowers the potential for acid rain formation and reduces the necessity for desulfurization processes, enhancing its overall environmental acceptability.

The presence of 11.402% H_2O in the wet flue gas points to a moderate moisture level in the fuel. Although this is within acceptable limits, pre-drying the material is recommended to lower moisture content, thereby improving combustion efficiency and overall energy output (Othman et al., 2019).

The observed CO_2 concentrations (18.795–21.214%) are consistent with those typically generated during biomass combustion. When harvested and managed sustainably, Khaya ivorensis wood is considered nearly carbon-neutral because of its participation in the natural biogenic carbon cycle (IEA Bioenergy, 2023).

3. 3. 2. Combustion emission of CO_2 and SO_2 of *Terminalia superba* wood sample

Figures 3 and 4 illustrate the flue gas analysis of the combusted *Terminalia superba* wood sample, revealing the following composition (wet basis): CO_2 19.16%, H_2O 11.60%, SO_2 0.01%, N_2 69.11%. On a dry basis: CO_2 22.50%, SO_2 0.017%, N_2 77.48%. Figure 3 depicts the wet composition, whereas Figure 4 displays the dry composition of the emission analysis. The remarkably low SO_2 values (0.01% wet and 0.017% dry) validate the minimal sulphur content characteristic of tropical hardwoods like *Terminalia superba* (Aliu *et al*., 2020; Erokare *et al*., 2025). This is evident in both Figure 3 and Figure 4, demonstrating a negligible risk of acid rain and a reduced need for desulfurization equipment.

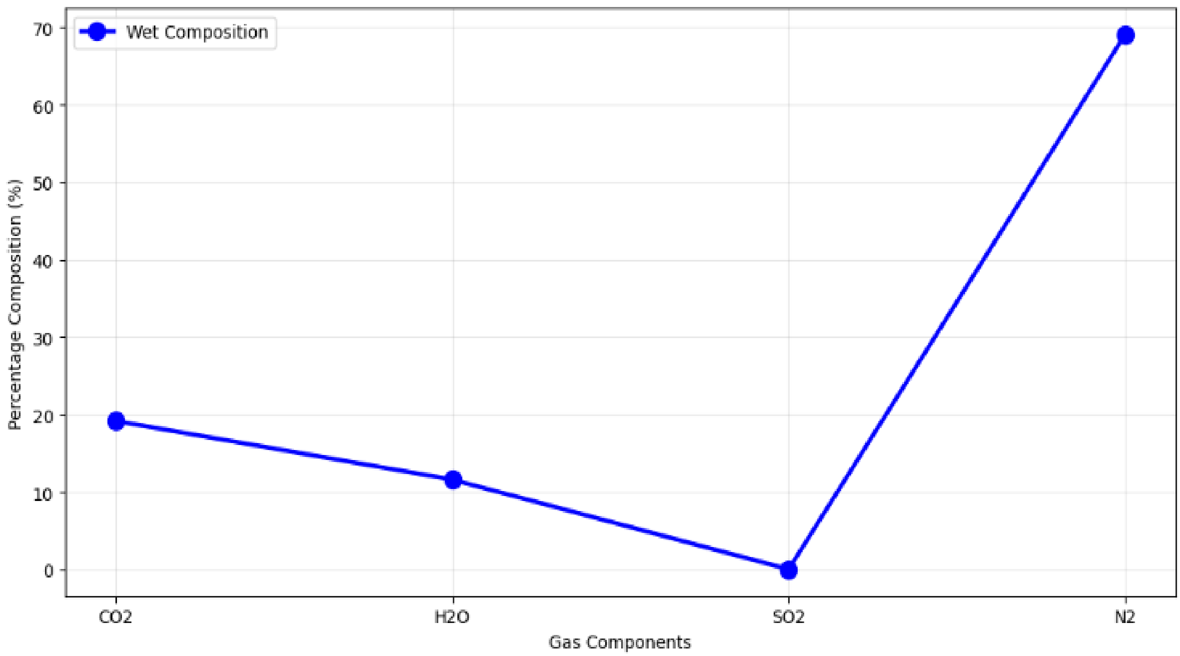

Figure 3. Emission analysis *Terminalia superba* wood sample (Wet Composition).

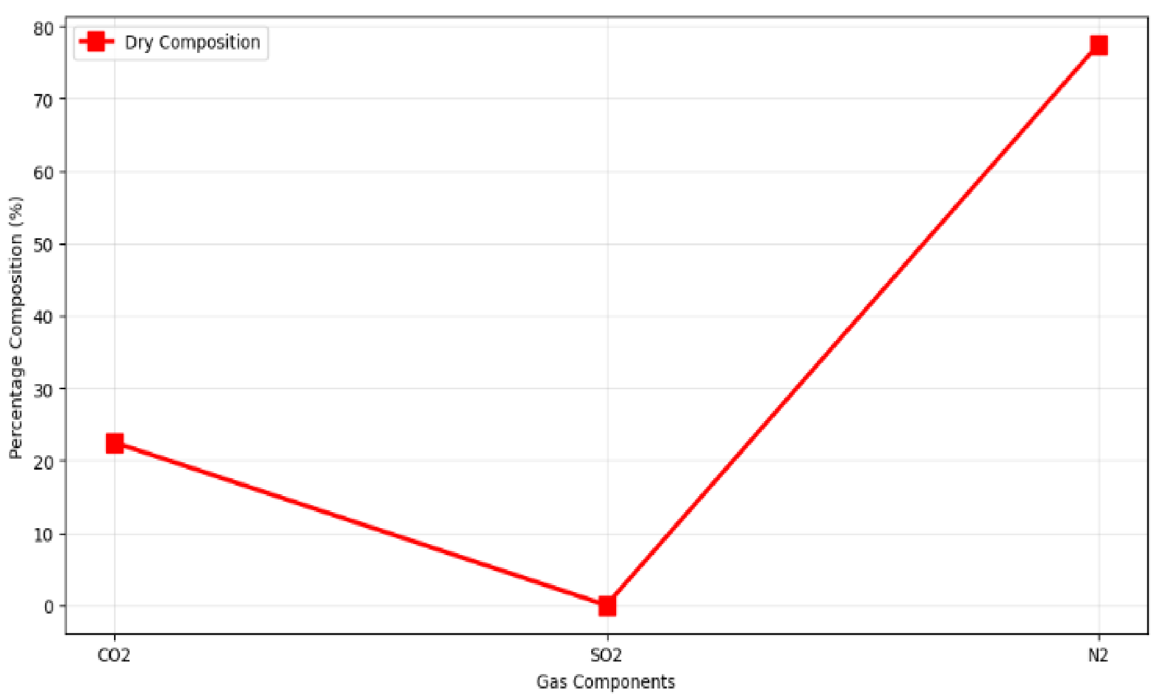

Figure 4. Emission analysis *Terminalia superba* wood sample (Dry Composition).

The 11.60% H_2O percentage in the wet flue gas (Figure 3) indicates a moderate moisture level, typical of air-dried biomass. Pre-combustion drying is advised to improve efficiency (Orhorhoro *et al*., 2024; Othman *et al*., 2019). The CO_2 concentrations (19.16% wet and 22.50% dry) fall within the anticipated range for wood biomass combustion (Orhorhoro *et al*., 2024; Erokare *et al*., 2025). When harvested sustainably, *Terminalia superba* wood facilitates nearly carbon-neutral energy generation. The findings illustrated in Figures 3 and 4 substantiate *Terminalia superba* wood as a clean and appropriate biomass feedstock for energy use in Nigeria, especially for direct combustion and co-firing applications.

3. 4. Comparative Analysis of CO_2 and SO_2 Emissions of wood Samples

3. 4. 1. Comparative Analysis of CO_2 emissions for wet and dry bases

The comparative analysis of CO_2 emissions from Mahogany (*Khaya ivorensis*) and Afara (*Terminalia superba*) wood waste, as displayed in Figure 5, shows slightly higher values for Afara on both wet (19.16%) and dry (22.50%) bases compared to Mahogany (18.795% wet and 21.214% dry). This trend aligns with the higher oxygen and marginally lower carbon content observed in Afara from the ultimate analysis, which influences stoichiometric combustion calculations (Asibor, et al., 2019).

These CO_2 emission percentages are consistent with reported values for tropical hardwoods in Nigeria and West Africa. Studies on similar species report theoretical dry-basis CO_2 emissions ranging between 20–24% for various tropical woods, driven primarily by carbon content (typically 45–55%). The dry basis values in this study fall comfortably within this range, validating the results (Akinrinola, et al., 2014; Mitchual et al., 2014).

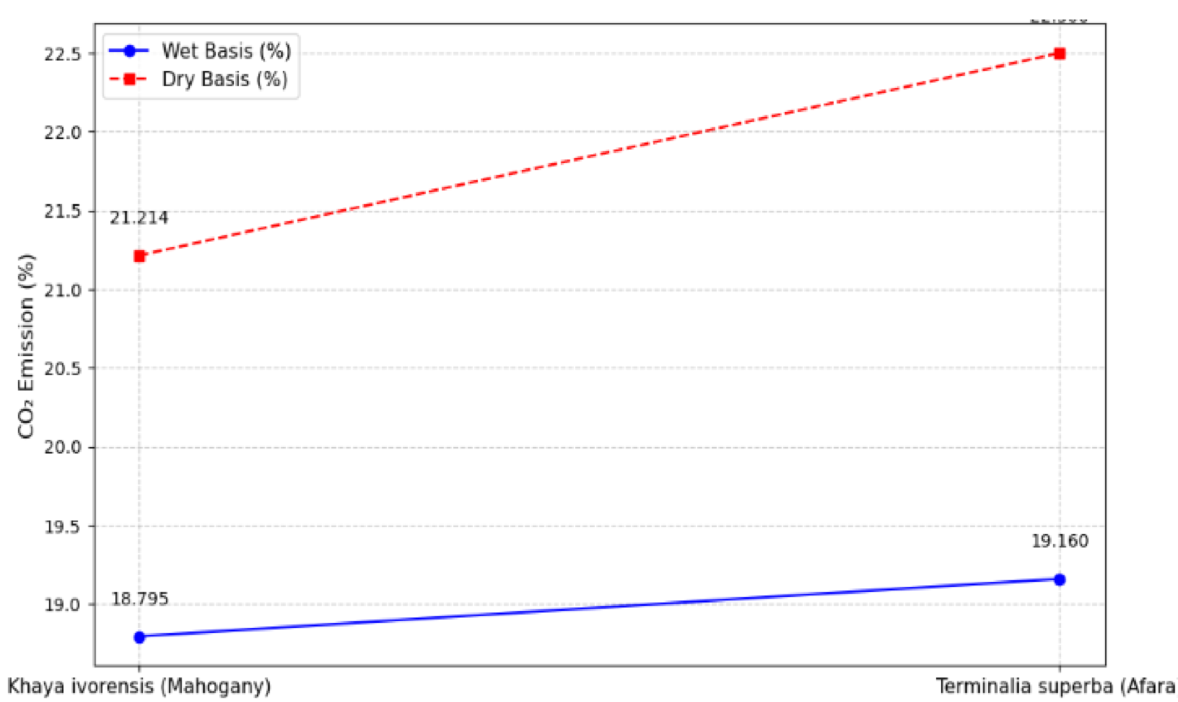

Figure 5. Comparative CO_2 Emissions of *Khaya ivorensis and Terminalia superba* on wet and dry bases.

The difference between wet and dry bases (approximately 2.4–3.3 percentage points) is expected due to moisture dilution in wet samples, a phenomenon well documented in biomass combustion research. Afara's slightly higher emissions may be attributed to species-specific compositional variations, as noted in comparative fuel property studies of *Terminalia superba* and other Nigerian hardwoods (Akinrinola, et al., 2014; Yazdani et al., 2012).

3. 4. 2. Comparative Analysis of SO_2 emissions for wet and dry bases

The SO_2 emission values for Mahogany (*Khaya ivorensis*) and Afara (*Terminalia superba*) wood waste are very low, ranging from 0.010% to 0.017% on both wet and dry bases, as shown in Figure 6. This is consistent with the low sulphur content (0.08–0.10%) observed in the ultimate analysis, confirming minimal SO_2 formation during combustion. (Akinrinola et al., 2020). On a dry-basis, both species exhibit identical SO_2 emissions (0.017%), indicating comparable sulphur-related behavior under moisture-free conditions. On a wet basis, Mahogany releases slightly more SO_2 (0.015%) than Afara (0.01%), likely due to minor differences in sulphur concentration and moisture interaction. These values are typical for tropical hardwoods and significantly lower than those from coal or other high-sulfur fuels (Suyatno et al., 2025). These results align well with recent studies on Nigerian biomass. Akinrinola et al. (2020) reported sulfur contents below detection limits (<0.1%) in *Terminalia superba* and other tropical woods, resulting in negligible SO_2 emissions. Erokare et al. (2025) similarly reported very low SO_2 levels (0.0126–0.017%) in Afara and related Nigerian wood wastes during combustion analysis. Both wood wastes demonstrate excellent environmental performance in terms of SO_2 emissions, supporting their use as cleaner biomass fuels compared to fossil alternatives. The findings validate the low-pollution potential of these species for sustainable energy applications in West Africa.

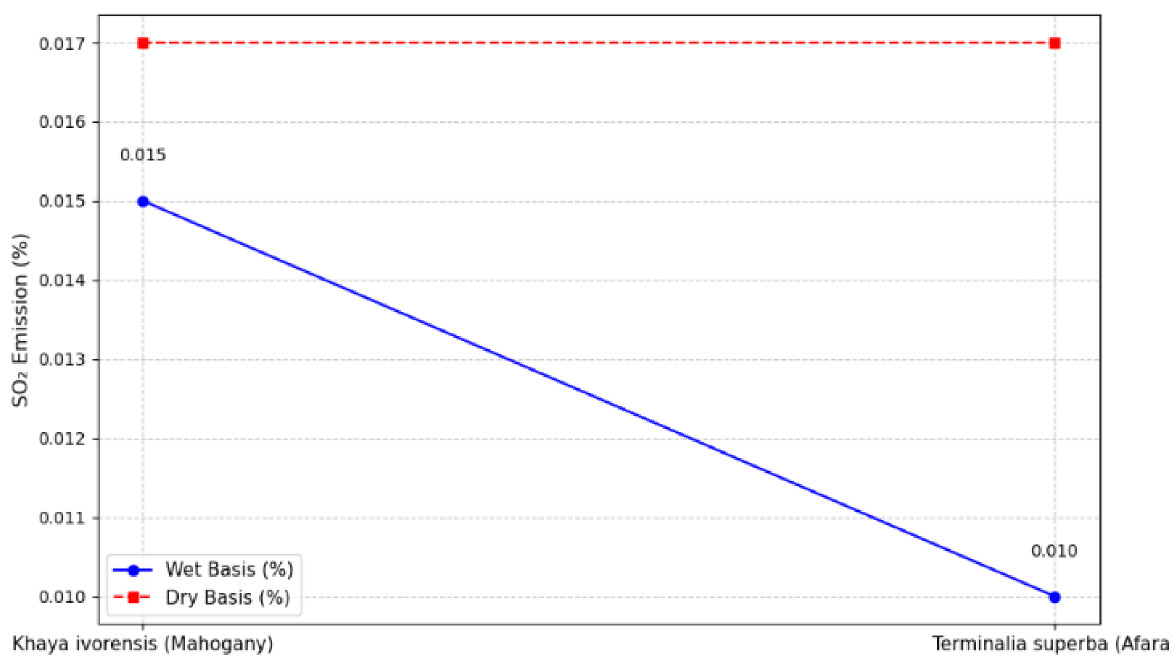

Figure 6. Comparative SO_2 Emissions of *Khaya ivorensis and Terminalia superba* on wet and dry bases.

4. CONCLUSIONS

This study successfully conducted a comparative analysis of CO_2 and SO_2 emissions from Mahogany (*Khaya ivorensis*) and Afara (*Terminalia superba*) wood wastes using ultimate analysis techniques. The results confirm that both tropical hardwood wastes possess favorable fuel properties suitable for sustainable energy applications. Carbon contents of 47.08% and 45.49%, combined with low sulfur levels (0.10% and 0.08%), resulted in moderate CO_2 emissions and exceptionally low SO_2 emissions (0.010–0.017%) on both wet and dry bases.

Notably, *Terminalia superba* exhibited slightly higher CO_2 emissions (19.16% wet and 22.50% dry) compared to *Khaya ivorensis*, while both species demonstrated nearly identical and minimal SO_2 emissions on a dry basis. These findings validate the environmental advantage of these wood wastes over fossil fuels, particularly their reduced potential to cause acid rain due to their negligible sulfur content.

The study underscores the viability of utilizing sawmill-generated wood wastes as cleaner biomass feedstocks for energy recovery in Nigeria and other tropical regions. By promoting the valorization of these abundant residues, this approach simultaneously addresses waste management challenges, supports renewable energy goals and contributes to a nearly carbon-neutral energy cycle when sourced sustainably.

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