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Physicochemical Characterization, Energy Potential, and CO_2/SO_2 Emission Assessment of Tropical Wood Wastes from Sawmill Dumpsites

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Abstract

This research assessed the physicochemical characteristics, energy potential, and CO_2/SO_2 emissions of five tropical wood wastes (Mahogany, Afara, Danta, Okwen, and Obeche) sourced from sawmill dumpsites in Benin, Nigeria. Calorific values varied from 20,476 kJ/kg for Obeche to 25,721 kJ/kg for Mahogany. Proximate analysis revealed a low ash level (0.76–1.99%) and a high volatile matter concentration. Comprehensive analysis indicated little sulfur (0.08–0.10%) and nitrogen concentrations. Combustion emission investigation revealed remarkably low SO_2 emissions (0.01–0.02%) on both wet and dry bases. The findings indicate that these wood wastes are viable renewable biomass resources for electricity production in Nigeria.

Keywords: Tropical timber waste; Biomass energy; Heating value; Combustion emissions; Sawmill byproducts

1. Introduction

The abundant biomass resources in Nigeria, specifically wood chips and wood pellets, could serve as a cheap, renewable energy source. [1,2] reported that wood pellets and wood chips have substantially higher fuel heat content per dollar compared to many fossil fuels. Biomass is a renewable energy resource that occurs naturally. It may be harvested without significant depletion if properly managed.

In Nigeria, logging activities in the forests and wood processing at the various wood processing industries generate a huge volume of wood waste annually across cities in the country. The figure for wood wastes generated from Nigerian sawmills was reported to be about 5.2 million tonnes per year [1].

Umubigho *et al*. [3] reported that biomass resources take different forms, but wood is considered the most common. In [4] and [5], energy generation and utilisation from wood waste were reported to enhance economic development, encourage a green economy and gradually replace the use of fossil fuels such as coal, gasoline, 2natural gas and oil for energy purposes. According to [6], converting wood waste into briquettes will go a long way toward reducing waste disposal problems in the majority of wood processing industries, such as sawmills. Onochie *et al*. [7] also proposed, in their study, transforming loose biomass (i.e., wood waste generated at sawmills) into briquettes as an effective way to address issues associated with open burning at sawmills. He further reported that briquetting would promote energy from waste wood while mitigating environmental degradation. Onochie et al [7] stated that, rather than open burning, these wastes can be converted to useful energy, generating heat for power (electricity), hot water for heating and cool media for cooling.

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Erokare *et al.* [1] reported that, in recent years, the use of waste wood for heat and electricity generation has rapidly increased. Wood waste is everywhere, both in developed and developing countries. Tropical wood wastes are abundant in Nigeria. These wastes are generated in sawmills and are openly burned. Gases emitted during open burning (combustion) at the sawmill are greenhouse gases (Erokare *et al*. [1]; Orhorhoro et al. [2]). These include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Oony-iye [8]) further reported that supporters of wood waste suggest it is a relatively economical and easy way to supply renewable energy, which is beneficial to forest industries and the global climate. Ali *et al*. [9] also stated that biomass energy, such as wood waste, can reduce net carbon dioxide and other greenhouse gas emissions. However, to its critics, wood waste emits more greenhouse gases during combustion than the fossil fuel it is intended to replace. Furthermore, it is worth noting that in Nigeria, knowledge and use of wood waste as an energy source remain very low compared to other developing and developed countries. Akhator *et al*. [10] reported that while wood species such as spruce and willows, on account of their energy content and properties, are specially grown and harnessed for energy generation in most parts of Europe, the same cannot be said of Nigeria, as salient information on the type of wood species in the country for energy production is not known.

Consequently, this study aims to characterize the five tropical wood wastes in terms of their calorific values and physico-chemical properties from sawmills in Benin, Edo State, Nigeria. The results from the physico-chemical properties will be used to evaluate the combustion CO_2 and SO_2 emissions from the wood wastes. This is aimed at providing valuable information on the energy potential of wood waste species in Benin to aid in formulating long-term policies and planning effective ways to exploit and utilize wood waste for energy generation.

2. Materials and methods

2.1. Material Collection

Five different samples of wood waste were collected from sawmill dumpsites in Benin Metropolis, Nigeria. These samples are Mahogany **(***Khaya ivorensis* or *Khaya senegalensis***)**, Danta (*Nesogordonia kabingaensis*), Obeche (Triplochiton scleroxylon), Afara (*Terminalia superba*) and Okwen (*Brachystegia nigerica*).

2.2. Material Preparation

After collecting the samples, they were sun-dried for one week to reduce their moisture content and thereafter chopped into particles of 0.3 to 0.5 micrometers. The samples prepared were used for the experimental analysis.

2.3. Method

Analyses were carried out in accordance with ASTM standards. The analyses include calorific value, moisture content and proximate and ultimate analyses. ASTM-D 4442 for direct moisture content, ASTM-E 872 for volatile matter, and ASTM-E 1755 for ash content in wood samples were used. Data generated from the analyses were used to evaluate the possible CO_2 emissions from the combustion of the wood waste samples.

2.3.1. Calorific Value

5g of the sample was weighed and carefully placed in a combustion crucible inside the bomb. The bomb was filled with oxygen at high pressure (approximately 25-30 atm). The bomb was submerged in a mass of water and ignited by an electric spark. The initial and the final temperature of the water were recorded, and the temperature rise was generated automatically in kJ/Kg

$$\mathrm{CV} = \frac{(W+w)}{m} \times \Delta T \qquad (1)$$

W = water equivalent of the calorimeter (mass x specific heat of water)
w = Mass of water in the calorimeter
ΔT = rise in water temperature (^{0}C)
m = mass of fuel (g)

2.3.2. Proximate Analysis of the fuel sample

For the proximate analysis, the Steriox model equipment was used. This entails the physical properties of the fuel pellets, including moisture, ash, volatile matter, and fixed carbon.

i Volatile matter of fuel sample (VM): A clean, dry and weighed empty crucible was noted as (W1). 1g of the sample was placed in a crucible and noted as (W2). This was covered with a lid and placed in a preheated furnace at 950 °C for 10 minutes to ensure complete combustion. It was removed and cooled in a desiccator and weighed as (W3). The results were obtained.

Calculation:

$$\mathrm{VM} = \frac{(W2-W3)}{(W2-W1)} x\ 100 \ldots\ldots (2)$$

W1- weight of empty crucible
W2- weight of crucible+ dry sample
W3- weight of crucible+ residue after heating

ii Ash content of fuel sample (AS): A clean, dry and weighed empty crucible was noted as (W1). 1g of sample was placed in a crucible (W2) and heated to 700 °C in a furnace for 1 hour to complete combustion, until a whitish appearance was observed. It was removed and cooled in a desiccator. The ash and the crucible were weighed and noted as (W3). The results were obtained.

$$\text{Calculation: } \mathrm{AC} = \frac{(\mathrm{W2-W3})}{(\mathrm{W2-W1})} x\ 100 \ldots\ldots (3)$$

iv Moisture content analysis (MC): Gallenkhamp model was used to determine the moisture content. A clean, dry and weighed empty container was noted as (W1). 1g of the sample was placed in a container and noted as (W2). This was placed in a hot-air oven at 105 °C for 1 hour until a constant weight was obtained for complete combustion. It was removed and cooled in a desiccator and weighed as (W3). The results were obtained.

$$\text{Calculation: } \mathrm{MC} = \frac{(\mathrm{W2-W3})}{(\mathrm{W2-W1})} x\ 100 \ldots\ldots (4)$$

W1- weight of empty container

W2- weight of container+ wet sample

W3- weight of container+ dry sample

iii Fixed carbon of fuel sample (FC): The fixed carbon was determined using the formula.

$$FC = 100 - (\%VM + \%AC + \%MC) \ \ldots\ldots (5)$$

Where VM, AC and MC are volatile matter, ash content and moisture content, respectively.

2.3.3. Ultimate Analysis

The ultimate analysis of the fuel sample provides details on its elemental chemical composition. It provides a means to estimate fuel quality. The percentage contents of constituents (carbon, hydrogen, nitrogen, and sulphur) were determined using a X-ray fluorescene (Xenemetrix Genius-IF series). This analysis helps determine the amount of air required for complete combustion, the volume and composition of combustion gases, and the heat of combustion of the sample, which is primarily determined by its carbon and hydrogen content. The standard operating procedures are stated below:

- Prepare a sample cup with Prolene thin film. Ensure the thin film surface is smooth.
- Pour wood sample/s into a thin film-covered cup. Ensure the sample is filled to a third of the sample cup (approx. 10 –15g).
- Cover the lid of the sample cup. Ensure there are no leaks or loose particles on the thin film layer, and that the lids are tightly sealed.
- Insert sample in sample turret of Genius-IF XRF. (if sample is pelletized, ensure there are no cracks or loose particles on the surface)
- Warm X-ray Lamp

- On the RUN tab, set voltage and emission current values to ensure that observed dead time is between 35-40kv; Stop Acquisition if observed dead time is below or above required range.
- Run analysis to obtain spectrum.
- Open XRS-FP Software
- Upload Master Oxide.tfr file
- Upload obtained Spectra file of sample
- Process > Process Spectrum
- Process > Analyze Spectrum
- Obtain results and print to save 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 (6)

$$C_aH_bO_dN_eS_f \quad \ldots\ldots (6)$$

The combustion analysis of various wood samples (Mahogany, Danta, Obeche, Afara and Okwen) was evaluated using Equation (7). Now, since oxygen is supplied as air, the associated N_2 will appear in the Equation as:

$$C_aH_bO_dN_eS_f + y_1\,[O_2 + (79/21)N_2\,] \rightarrow p_1CO_2 + q_1H_2O + r1SO_2 + [t1 + y1(79/21)N_2\,] \ldots (7)$$

2.5. Combustion Emission Analysis of wood sample

The percentage of each product emitted from the stoichiometric combustion of wood samples 1, 2, 3, 4 and 5 in the wet and dry emission analysis was calculated using equations (8) and (9), respectively.

For wet analysis;

$$\%\text{ of gas emitted is} = \frac{n_i}{n_{Co_2} + n_{So_2} + n_{H_2O} + n_{N_2}} \times \frac{100}{1} \qquad (8)$$

For dry analysis;

$$\%\text{ of gas emitted is} = \frac{n_i}{n_{Co_2} + n_{So_2} + n_{N_2}} \times \frac{100}{1} \qquad (9)$$

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. Calorific Value

The calorific values of the wood samples varied from 20,476.28 kJ/kg for Obeche to 25,721.48 kJ/kg for Mahogany. Mahogany exhibited the highest energy potential, succeeded by Okwen (24,875.80 kJ/kg), whereas Obeche demonstrated the lowest value. The results align with the standard range documented for tropical hardwoods in Nigeria (18,500–25,000 kJ/kg), affirming their viability as biomass resources for energy production. [1,2]. The observed variation aligns with earlier research on Nigerian tropical woods, indicating that denser species, such as Mahogany, typically have higher calorific values than lighter species, such as Obeche. This pattern, as illustrated in Table 1 and Figure 1, is mostly ascribed to variations in lignin concentration, density, and extractives among the species. The results confirm that these wood wastes have significant energy potential for boiler applications and other thermochemical conversion processes. (Asibor *et al*. [11]; Ogunsola *et al*. [12]).

Table 1 Calorific values of wood samples

Wood samples	**Mahogany**	**Okwen**	**Afara**	**Danta**	**Obeche**
Calorific Value (kJ/Kg)	25721.48	24875.80	23546.35	22654.67	20476.28

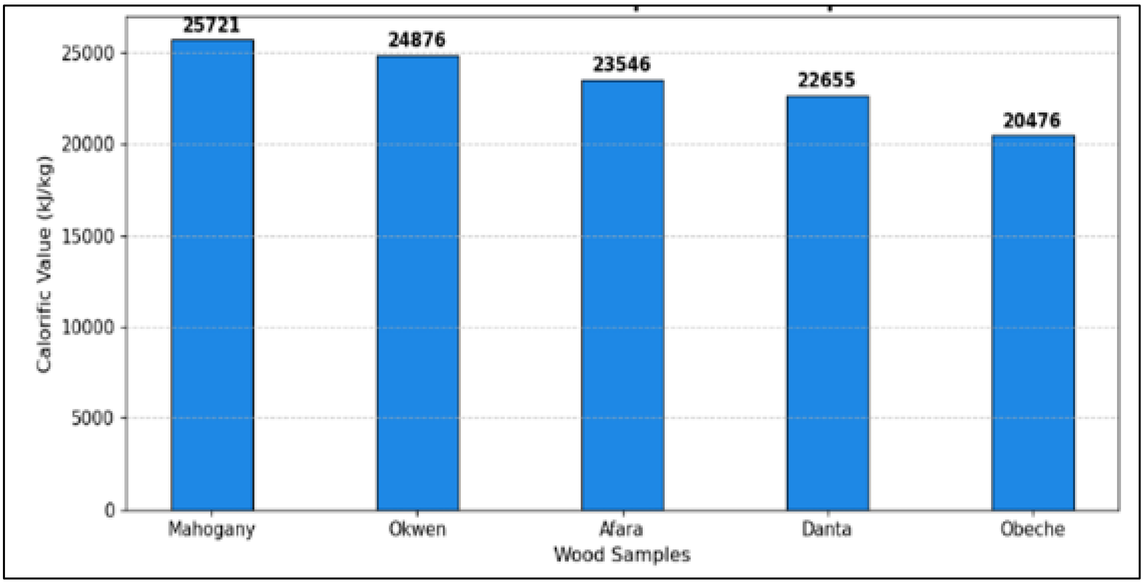


Figure 1 Calorific Values of wood samples

3.2. Proximate Analysis

The proximate composition of Mahogany, Afara, Danta, Okwen, and Obeche wood samples was evaluated as shown in Table 2 and Figures 2, 3, and 4. Figure 2 illustrates the Moisture content of various wood samples, ranging from 8.56% (Okwen) to 10.49% (Obeche), consistent with air-dried tropical hardwoods (Christian *et al.* [13]). Figure 3 shows that the Ash content of wood waste samples was low across all species (0.76–1.99%), with Danta exhibiting the lowest value, which is desirable for reducing slagging and corrosion during combustion (Orhorhoro *et al.* [2]; Onokwai *et al.* [14]. Volatile matter was high (79.46–88.74%) as noticed in Figure 4, indicating good ignition characteristics, though Obeche's value (79.46%) was lower than previously reported (Onokwai *et al.* [14]. Fixed carbon varied from 10.97% (Danta) to 17.21% (Okwen), suggesting Okwen and Mahogany (15.62%) have superior char-forming potential. Overall, all five species are suitable for thermal conversion, with species-specific variations influencing their application in combustion or pyrolysis systems.

Table 2 Proximate analysis of wood samples

Wood samples	**Moisture (%)**	**Ash (%)**	**Volatile matter (%)**	**Fixed carbon (%)**
Mahogany	8.73	1.04	88.74	15.62
Afara	9.12	1.92	87.09	11.23
Danta	8.60	0.76	86.77	10.97
Okwen	8.56	0.95	87.09	17.21
Obeche	10.49	1.99	79.46	12.96

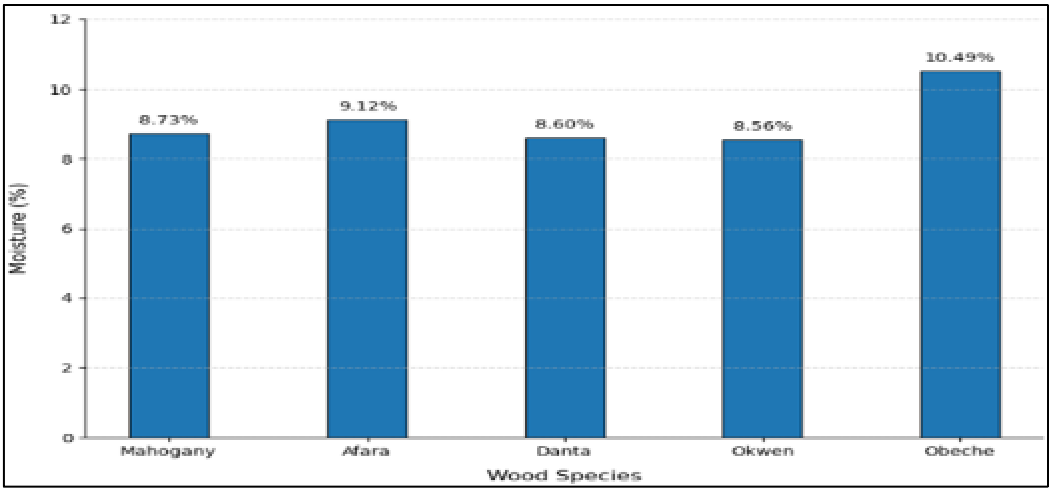


Figure 2 Moisture Content Values of wood samples

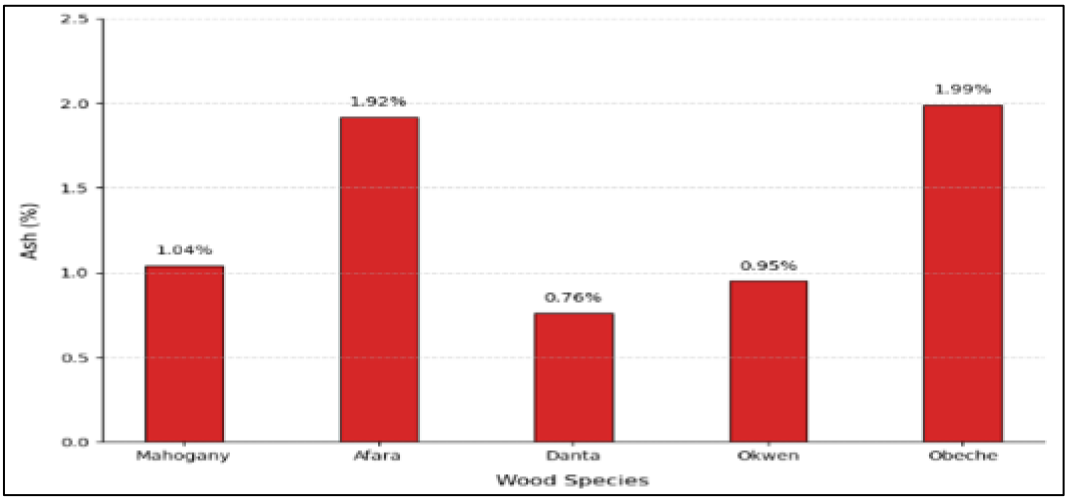


Figure 3 Ash Content of Wood Samples

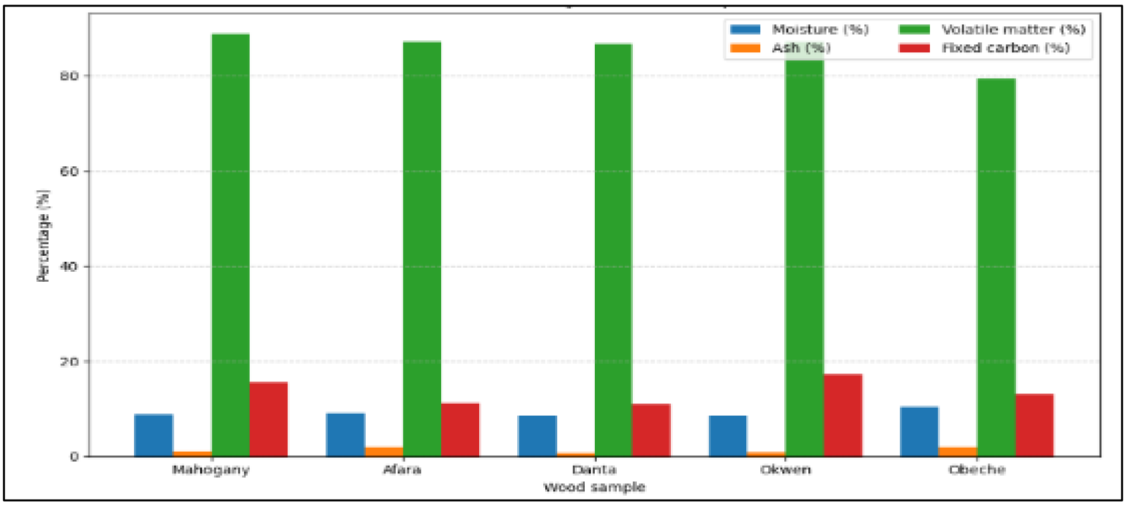


Figure 4 Proximate analysis of Tropical wood samples

3.3. Ultimate Analysis of Tropical Wood Samples

Table 2 presents a comprehensive examination of the elemental composition of the wood species. The data is graphically contextualized by the trends depicted in the line and bar graphs of Figure 5, facilitating a direct comparison study of their carbon, hydrogen, oxygen, nitrogen, and sulphur content. Carbon (C): The documented values of 42.28% to 47.08% fall within the 45–50% range established in the literature for woody biomass. (Erokare *et al.* [1]; Ozomadu *et al.* [15]). Mahogany's composition of approximately 47% corresponds to the approximately 47% conversion factor frequently used to measure carbon in forest biomass (Oony-iye *et al.* [16]; Kiman *et al.* [17]). Figure 5 illustrates the divergent profiles of Mahogany and Obeche, with the latter demonstrating the lowest carbon content and the highest oxygen content, a correlation that significantly influences the material's heating value. The oxygen concentration ranges from 40.14% to 45.62%, within the normal range of 40-45% for wood (Akhator *et al.* [18]). The negative relationship between O and C, a universal characteristic of biomass, is visually apparent in Figure 5. The elevated oxygen concentration of Obeche (45.62%) is a primary factor influencing its somewhat diminished energy potential (Asibor *et al.* [19]). Hydrogen (H): Ranging from 4.18% to 4.76%, these values approximate the average 4.5–6% range seen in wood suitable for combustion in steam boilers (Orhorhoro *et al.* [2]). Although all species span the general spectrum, the slightly lower hydrogen content in Obeche (4.18%) further substantiates its lower energy density compared to other species. Nitrogen (N) and Sulphur (S): All five species exhibit outstanding environmental compatibility. Their nitrogen content (0.38–0.55%) and sulphur levels (0.08–0.10%) are exceedingly low. Similar investigations have revealed low nitrogen levels (e.g., <1.0%) and minimal sulphur content in associated hardwoods (Kiman *et al.* [17]). This trait renders the analyzed wood species an advantageous feedstock, as the transformation of fuel-bound nitrogen into the pollutant NO_x is a significant issue during thermal combustion.

Table 3 Ultimate analysis of wood samples

Component	Mahogany	Afara	Danta	Okwen	Obeche
Carbon (%)	47.08	45.49	46.16	46.94	42.28
Nitrogen (%)	0.55	0.46	0.38	0.46	0.45
Sulphur (%)	0.10	0.08	0.08	0.10	0.08
Hydrogen (%)	4.76	4.59	4.62	4.73	4.18
Oxygen (%)	40.14	42.09	41.06	40.51	45.62

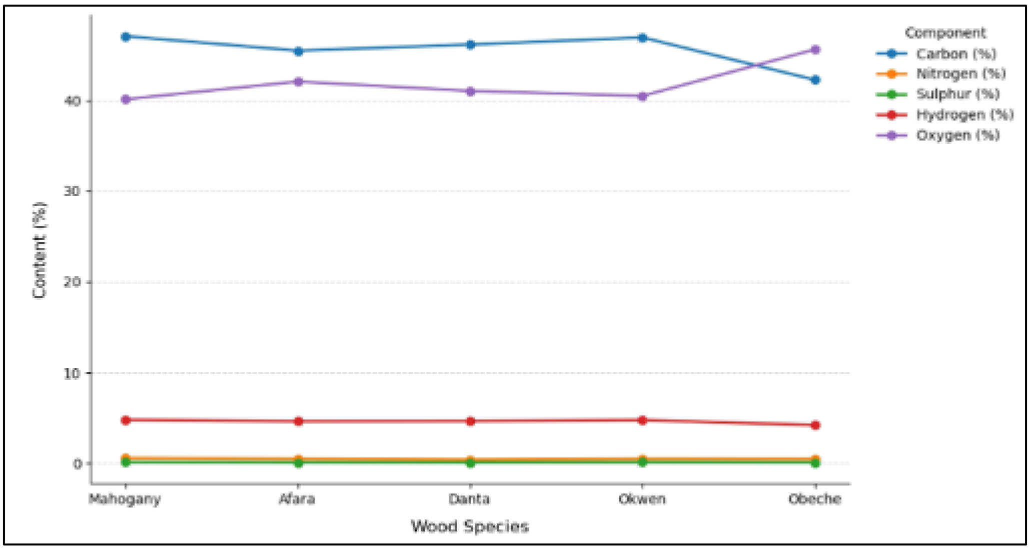


Figure 5 Ultimate analysis of the wood sample

3.4. Chemical Formulas for Tropical Wood Samples

The end analysis results in Table 3 determined the equivalent chemical composition [$C_aH_bO_dN_eS_f$] by mass for each wood sample as stated in equation 6. 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.

3.4.1. Chemical formula of Mahogany wood sample

- For Carbon:

12a = 47.08; a = 3.9233

- For Hydrogen:

1b = 4.76; b = 4.76

- For Oxygen:

16d = 40.14; d = 2.50875

- For Nitrogen:

14e = 0.55; e = 0.0392

- For Sulphur:

32f = 0.10; f = 0.003125

Therefore, the chemical formula of the Mahogany wood sample is $C_{3.9233}H_{4.76}O_{2.50875}N_{0.03923}S_{0.003125}$. The calculations for Afara, Danta, Okwen and Obeche wood samples are the same as above, and their chemical formulas are $C_{3.791}H_{4.59}O_{2.63063}N_{0.0329}S_{0.0025}$; $C_{3.791}H_{4.59}O_{2.63063}N_{0.0329}S_{0.0025}$; $C_{3.9117}H_{4.73}O_{2.5318}N_{0.0329}S_{0.003125}$ and $C_{2.6425}H_{4.18}O_{2.8513}N_{0.0321}S_{0.0025}$, respectively. The chemical formula summary for the various fuel pellets is shown in Table 4.

Table 4 Chemical formula of wood samples

Fuel wood samples	Chemical formula
Mahogany	$C_{3.9233}H_{4.76}O_{2.50875}N_{0.03923}S_{0.003125}$
Afara	$C_{3.791}H_{4.59}O_{2.63063}N_{0.0329}S_{0.0025}$
Danta	$C_{3.8467}H_{4.62}O_{2.56625}N_{0.0271}S_{0.0025}$
Okwen	$C_{3.9117}H_{4.73}O_{2.5318}N_{0.0329}S_{0.003125}$
Obeche	$C_{2.6425}H_{4.18}O_{2.8513}N_{0.0321}S_{0.0025}$

3.5. Combustion Emission Analysis of wood samples

Onochie *et al*. [19] defines combustion as a chemical process in which fuel combines with oxygen, leading to burning and the generation of heat. Onochie *et al*. [19] asserted that the study of fuel intended for burning pertains to the concentrations of carbon, hydrogen, nitrogen, and sulphur. Ramesh *et al*. [20] identified combustion analysis as a critical factor in the management and regulation of combustion processes. Anufriev *et al*. [21] asserted that for combustion to be both safe and effective, an appropriate quantity and mixture of fuel and oxygen must be supplied to the burner. Consequently, equation 7 is used for the stoichiometric combustion of the five wood samples, while equations 8 and 9 were used to obtain the total amount of wet products in kmol and the total amount of dry products in kmol, respectively. Sub-sections 3.5.1 to 3.5.5 present and analyze the impact of combustion emissions, CO_2 and SO_2 from the five wood samples.

3.5.1. Combustion emission of CO_2 and SO_2 of Mahogany wood sample

The flue gas analysis of combusted mahogany wood indicated the following compositions (wet basis): CO_2 18.795%, H_2O 11.402%, SO_2 0.015%, N_2 69.79%. On a dry basis: CO_2 21.214%, SO_2 0.017%, N_2 78.77%. This is seen in Figures 6 and 7. Figures 6 and 7 depict the percentage composition of both wet and dry gases in Mahogany wood. The exceedingly low SO_2 values (0.015–0.017%) signify negligible sulphur content, characteristic of woody biomass and far lower than that of fossil fuels (Tsai *et al*. [22]; Rokni *et al*. [23]). This reduces the risk of acid rain and the need for desulfurization, thereby improving environmental compatibility. The 11.402% H_2O in wet flue gas indicates moderate fuel moisture content. While acceptable, it is advisable to pre-dry to reduce moisture to optimize combustion efficiency and heating value (Othman *et al*. [24]). CO_2 concentrations (18.795–21.214%) align with biomass combustion in the atmosphere. When sourced sustainably, mahogany wood is regarded as nearly carbon-neutral due to the biogenic carbon cycle (IEA Bioenergy, [25]). Mahogany wood demonstrates substantial energy potential, with calorific values reported at approximately 19–25 MJ/kg, comparable to those of other hardwoods (Chukwuneke *et al*. [26]; Wardani *et al*. [27]). Its clean combustion characteristics and low sulphur concentration enhance its suitability for direct combustion, co-firing, or thermochemical conversion processes.

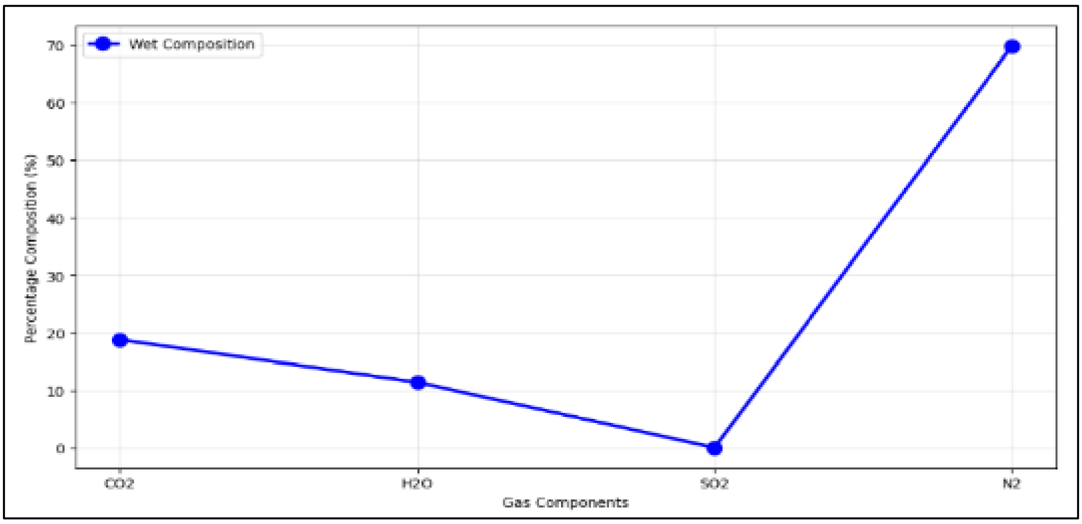


Figure 6 Wet Composition emission analysis Mahogany wood sample

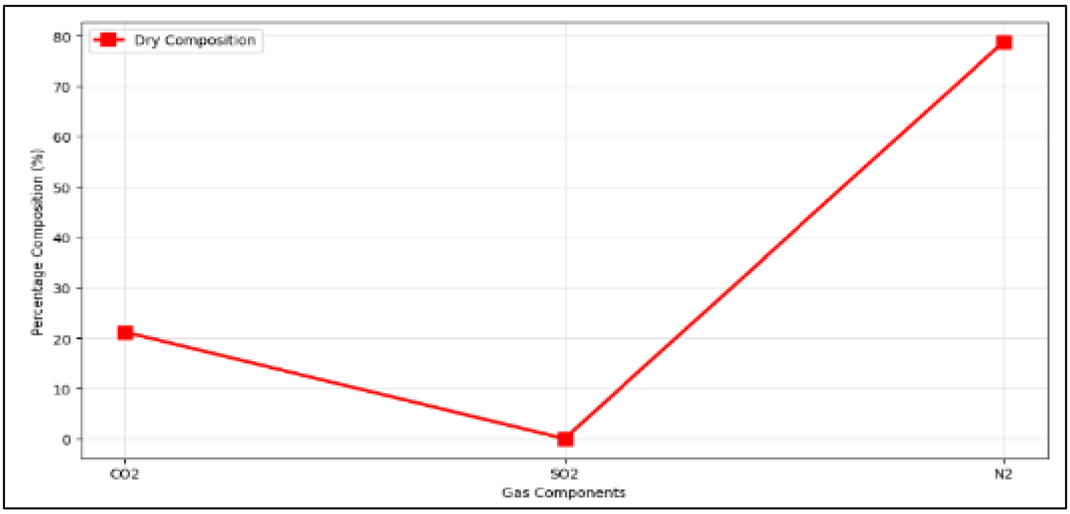


Figure 7 Dry emission percentage analysis Mahogany wood sample

3.5.2. Combustion emission of CO_2 and SO_2 of Afara wood sample

Figures 8 and 9 illustrate the flue gas analysis of the combusted Afara 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 8 depicts the wet composition, whereas Figure 9 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*. [28]; Erokare *et al*. [1]). This is evident in both Figure 8 and Figure 9, demonstrating a negligible risk of acid rain and a reduced need for desulfurization equipment. The 11.60% H_2O

percentage in the wet flue gas (Figure 8) indicates a moderate moisture level, typical of air-dried biomass. Pre-combustion drying is advised to improve efficiency (Orhorhoro *et al.* [2]; Othman *et al.*, [24]). The CO_2 concentrations (19.16% wet and 22.50% dry) fall within the anticipated range for wood biomass combustion (Orhorhoro *et al.* [2]; Erokare *et al.* [1]). When harvested sustainably, Afara wood facilitates nearly carbon-neutral energy generation. The findings illustrated in Figures 8 and 9 substantiate Afara wood as a clean and appropriate biomass feedstock for energy use in Nigeria, especially for direct combustion and co-firing applications.

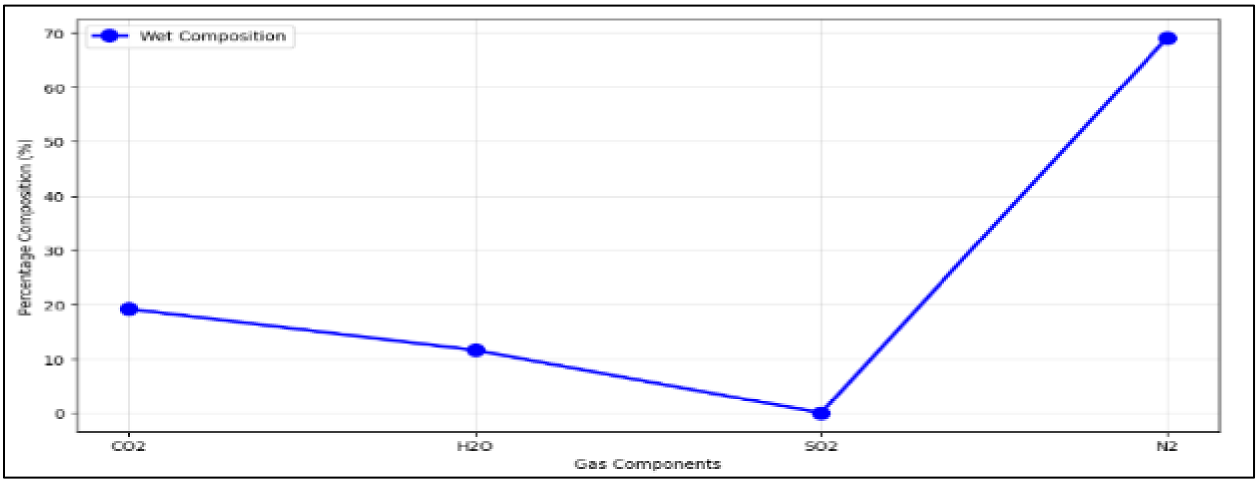


Figure 8 Emission analysis Afara wood sample (Wet Composition)

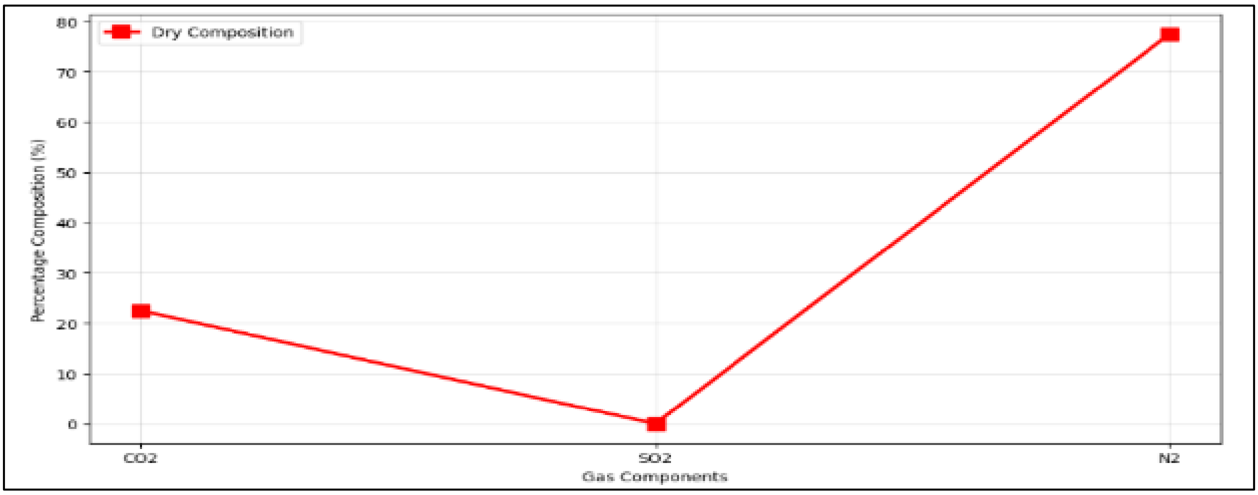


Figure 9 Emission analysis Afara wood sample (Dry Composition)

3.5.3. Combustion emission of CO_2 and SO_2 of Danta wood sample

The percentage composition of moist gases is as follows: CO_2, 19.06%; H_2O, 11.44%; SO_2, 0.01%; and N_2, 69.49%. The percentage composition of the dry gases is as follows: CO_2, 21.52%; SO2, 0.01%; and N2, 78.47%. This is seen in Figures 10 and 11. Figures 10 and 11 illustrate the percentage composition of wet and dry gases in Danta wood. For the wet analysis, the possible CO_2 emissions are 19.06%, while the SO_2 emissions are 0.01%. Other gases emitted during the combustion of wood include nitrogen and water vapor, comprising 69.49% and 11.44%, respectively. The results indicated that the sulphur oxide content in Danta wood is minimal and suitable for combustion in boilers. In the dry base study, the percentage composition of CO_2 and SO_2 in Danta wood was 21.52% and 0.01%, respectively. The SO_2 concentration once more decreases below the value stated by the Bureau of Energy Efficiency [25]. This indicates that, in both wet and dry tests, the Danta wood sample is suitable for combustion in boilers, while the CO_2 emissions will be absorbed by growing trees. (Aliu *et al.* [28]).

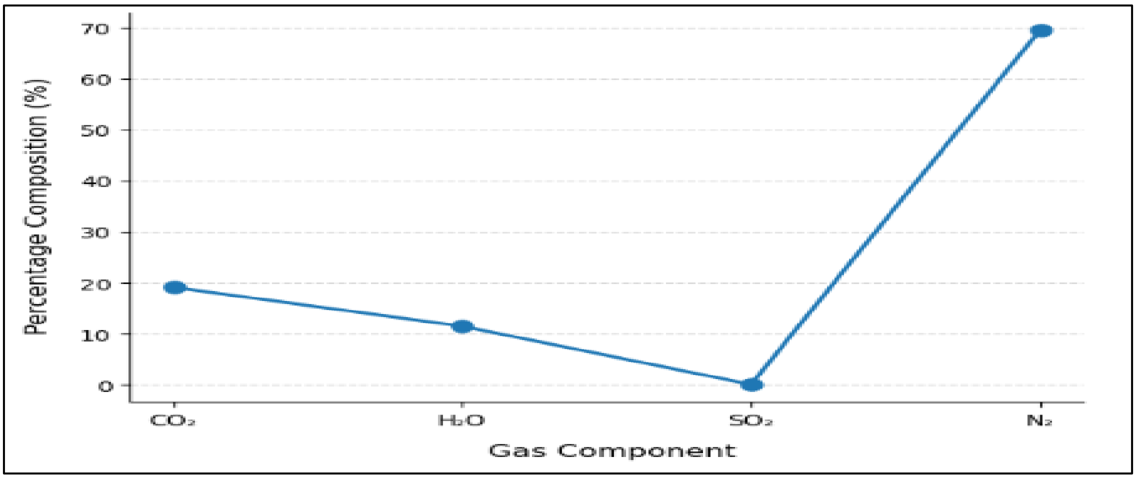


Figure 10 Emission analysis Danta wood sample (Wet Composition)

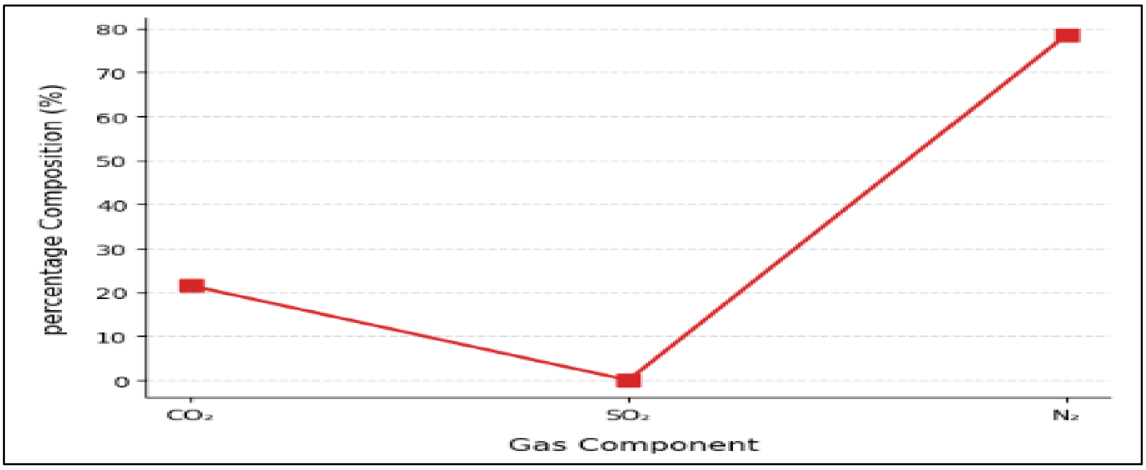
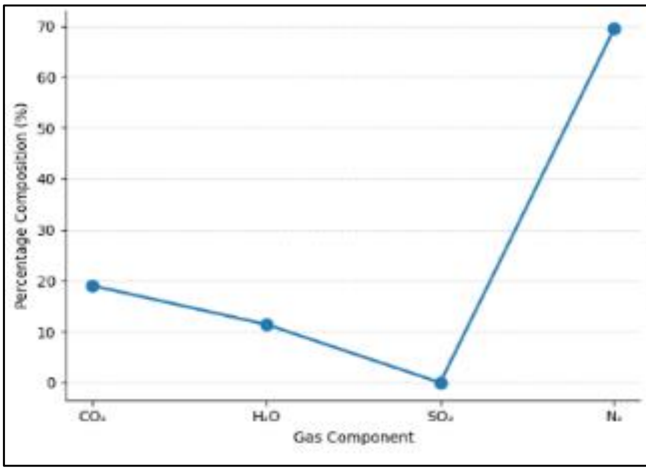


Figure 11 Emission analysis Danta wood sample (Dry Composition)

3.5.4. Combustion emission of CO_2 and SO_2 of Okwen wood sample

The flue gas composition resulting from the combustion of the Okwen wood sample is illustrated in Figures 12 and 13. The gas composition on a wet basis comprises CO_2 (18.87%), H_2O (11.41%), SO_2 (0.02%), and N_2 (69.70%). The composition on a dry basis consists of CO_2 (21.30%), SO_2 (0.02%), and N_2 (78.69%). In the wet study, CO_2 emissions were 18.87%, and SO_2 was notably low at 0.02%. Nitrogen and water vapor comprised 69.70% and 11.41% of the moist flue gas, respectively. The exceedingly low SO_2 concentration indicates that Okwen wood has negligible sulphur content, making it particularly suitable for boiler combustion with a lower risk of acid rain and equipment damage (Akinrinola *et al.* [29]; Erokare *et al.* [1]). The concentrations of CO_2 and SO_2, on a dry basis, were 21.30% and 0.02%, respectively. The SO_2 concentration is much below the thresholds established by the Bureau of Energy Efficiency (BEE, [25]), hence reaffirming the sample's clean combustion properties. The findings from both wet and dry tests indicate that Okwen wood is an appropriate biomass feedstock for energy use, characterized by low pollutant emissions and advantageous combustion qualities.



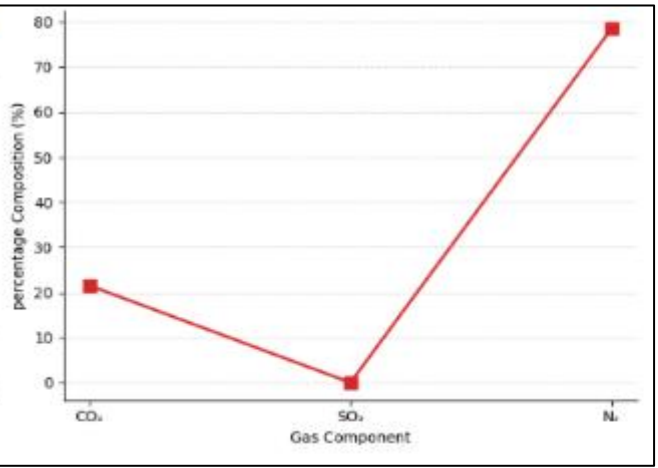
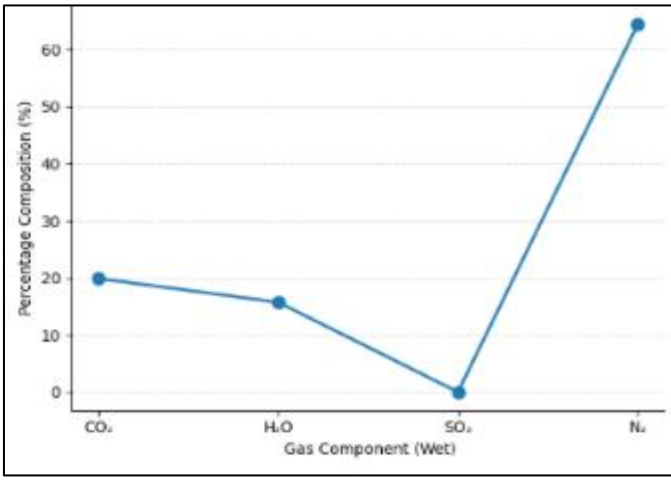


Figure 12 Wet Composition **Figure 13** Dry Composition

3.5.5. Combustion emission of CO_2 and SO_2 of Obeche wood sample

The flue gas composition of the Obeche wood (Triplochiton scleroxylon) sample is illustrated in Figures 14 and 15. The gas composition on a moist basis comprises CO_2 (19.89%), H_2O (15.73%), SO_2 (0.02%), and N_2 (64.36%). The composition on a dry basis consists of CO_2 (23.60%), SO_2 (0.02%), and N_2 (76.37%). In the wet analysis, the potential CO_2 emission was 19.89%, although SO_2 was markedly low at 0.02%. Nitrogen and water vapor comprised 64.36% and 15.73% of the moist flue gas, respectively. The remarkably low SO_2 percentage underscores the low sulphur concentration in Obeche wood, making it particularly suitable for boiler combustion with reduced concerns about acid rain and equipment corrosion (Alabi *et al*. [30]; Ibitoye *et al*. [31]). On a dry basis, the concentrations of CO_2 and SO_2 were 23.60% and 0.02%, respectively. The SO_2 level is well below regulatory thresholds for biomass burning (Tsai *et al*. [22]; Energy Efficiency, [25]). The findings from both wet and dry investigations validate that Obeche wood is an appropriate biomass feedstock for energy utilization. Its minimal pollution emissions make it suitable for residential heating and industrial energy generation.



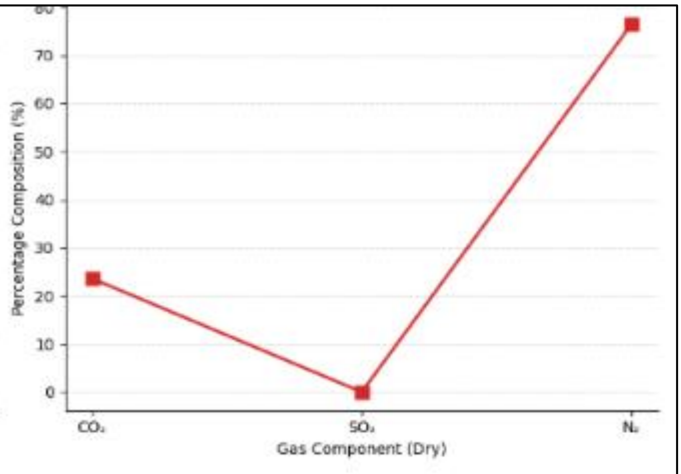


Figure 14 Wet Composition **Figure 15** Dry Composition

4. Conclusion

The five tropical wood wastes demonstrated significant energy potential, with Mahogany exhibiting the highest calorific value of 25,721.48 kJ/kg. All species exhibited advantageous fuel characteristics, including minimal ash and sulfur levels. Combustion analysis indicated minimal SO_2 emissions (0.01–0.02%), affirming their environmental compatibility. The results confirm the viability of Mahogany, Afara, Danta, Okwen, and Obeche wood residues as sustainable biomass feedstock for home and industrial energy applications. The effective management of this trash can substantially reduce open burning and promote the advancement of renewable energy in Nigeria.

Compliance with ethical standards

Statement of Ethical Approval

All procedures involving data handling and analysis were conducted responsibly and in accordance with standard academic and institutional guidelines.

Declaration of Conflict of Interest

The authors declare that no known conflict of interest or personal relationships have influenced the work reported in this paper.

Declaration of Data Availability Statement

The data that are used in this research are available upon request from the Corresponding Author.

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