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Characterising Emissions from Sawdust-Coal Pellets Combustion Using Ultimate Analysis Techniques

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Abstract

The combustion of pure coal contributes significantly to greenhouse gas emissions (GHGs), particularly carbon dioxide (CO_2), driving global warming. This study explores the potential of enhancing coal combustion by incorporating sawdust biomass to reduce harmful emissions while maintaining thermal performance. Ultimate analyses were conducted on coal and sawdust pellets, with seven samples (Sample 1 – Sample 7) prepared using hand-mixed process in ratios of 100:0, 90:10, 80:20, 70:30, 60:40, 50:50 and 0:100 consisting of coal and sawdust respectively, and resin (the epoxy type) as binder suggesting coal-sawdust pellet possessing high mechanical strength. Calorific tests revealed calorific values ranging from 14.85 MJ/kg to 22.07 MJ/kg, demonstrating their viability as fuel sources. Emissions analysis showed CO_2 emissions were highest in Sample 1, while Sulphur dioxide (SO_2) peaked in Sample 7 exhibited the highest water vapour emissions. Nitrogen emissions generally decreased with increasing sawdust content, except for an anomaly in Sample 4. The study also revealed that the amount of carbon dioxide, sulphur dioxide, nitrogen, and water vapour emitted depends on the sawdust-coal mixed ratios. These results suggest that coal-sawdust blends can significantly reduce CO_2 emissions, aligning with Sustainable Development Goals 13.

1.0 Introduction

Coal is a primary (fossil) fuel which is formed originally from the vegetation of the carboniferous era which was protected from absolute decay, after the process of carbonization, the vegetable materials are converted into peat coal, bituminous and finally anthracite coal [1]. Coal is used primarily as a fuel in generating power in steam engines, factories and electric plants. Coal is mostly carbon with variable amounts of other element, mainly sulphur, hydrogen, oxygen and nitrogen [2]. Sawdust (or wood dust) is a primary fuel obtained as a by-product from wood, with unique combustion properties. When sawdust is fired together with coal, it has the potential to improve its thermal performance, such as ignition temperature, burnout efficiency and combustion kinetics. The combustion of coal and sawdust pellet will be examined with regards to emissions by characterization of the emissions from pellets combustion. The combustion of pure coal (without additives) accounts for about fourteen billion tonnes of carbon dioxide emitted in 2020, [3].Considering these emissions, there is the need for blending coal with sawdust. The emitted carbon dioxide (CO_2) into the atmosphere results in greenhouse gases (GHGs), which are referred to as the gases contained in the atmosphere which help to elevate the earth's surface temperature. A common distinguishing feature of greenhouse gases from other gases is their ability to absorb the wavelength of radiation that are emitted from a planet, thereby causing the greenhouse effect [4]. This therefore contributes to climate change and global warming, which increases the temperature of land and sea, storms increase and changes to ecosystems. Energy is the cornerstone of every nation's economic growth and stability [5]. Recent studies reported that waste biomass and binders can be used as part of coal and biomass briquette [6]. According to [6] and [7], cassava starch, coal and molasses have been used as binders for improving the qualities of briquettes.

Numerous studies conducted on the addition of sawdust biomass to coal such as proximate and ultimate analyses of bio coal briquettes of Nigerian's Ogboyaga and Okaba Sub-bituminous coal by [8], value addition of coal fines and sawdust to briquettes using molasses as a binder by [9], and assessment of the compatibility of biomass-coal blends for cleaner energy utilization and sustainable development by [10] made use of cassava starch gel, molasses and waste paper respectively as a binder. This study however made use of resin (Epoxy type) as a binder, which help to provide a good mechanical strength and effective combustion process of the pellets. The national energy policy aimed 2015 to launch of the use of coal briquettes as an alternative energy for both in small and medium-sized industries and households in 2050 [11]. The main drawback of coal is its emissions of compounds such as, nitrogen and carbon dioxide which are harmful to the environment when burned. The emission of carbon dioxide into the atmosphere has affected several processes and contributed to climate change [12]. Sawdust, which is from a biomass source, when burned in the air releases emissions that are low in carbon content when compared to fossil fuel (coal), since biomass generally contains low carbon content. [13] investigated the thermal behaviour of pine sawdust and coal during co- pyrolysis and co-combustion and reported that the proportion of pine sawdust and coal in the mixture, influenced the initial and final temperatures, both in the pyrolysis and combustion processes. According to [14] and [15], calorific value is defined as the thermal capacity of per unit weight of coal after complete combustion. [12] investigated the properties of bio-coal briquettes which consist of coal and prosopis African pods (biomass) and reported the range of calorific values of the briquette samples, A (100% Coal 0% Sawdust), B (80% Coal 20% Sawdust), C(60% Coal 40% Sawdust), D(40% Coal 60% Sawdust), E (20% Coal80% Sawdust) and F(0% Coal 100% Sawdust)to be (23.25MJ/kg, 21.12MJ/kg, 18.90MJ/kg, 18.27MJ/kg, 17.02MJ/kg and 16.25MJ/kg) respectively.[16] investigated the co-combustion characteristics of coal and different biomass. Such as corn straw, rice husk and rice straw with blend ratio of 20wt%, 40wt%, 60wt%, 80wt% of biomass. The method of thermogravimetric analysis was used to evaluate parameters such as combustion indices, ignition temperature and weight loss. The results from the combustion parameter suggested that as biomass is added, the combustion performance of the blend was improved. The compatibility of biomass coal blends was investigated by [10] and it was reported that, the co-fired pallets (consisting of biomass and coal) possess a high heating (calorific value), making them suitable for various heating operations such as boilers operations. The study also reported that there was a reduction in carbon dioxide (CO_2) and sulphur dioxide (SO_2) emissions from the various combination of the biomass (rice husk, coconut fibre, coconut shell and sawdust) and coal when compared to 100% coal. [17] studied the numerical simulation and experimental analysis on nitrogen and sulphur oxides emissions during the co-combustion of Longyan anthracite and sawmill sludge, and it was reported that Sulphur dioxide (SO_2) and Nitrogen oxide emissions were lower than that of Longyan lone combustion.

This study delves into augmenting coal combustion with sawdust in other to keep the thermal performance of sawdust-coal within a reasonable range and reduce emissions of carbon dioxide, since energy is a crucial factor which impacts economic development and subsequently contributes to the standard of living [18].

2.0. Materials And Method

2.1. Preparation of Coal Specimen

The coal used in this study was collected from Ogui area of Enugu State, Nigeria. The coal was sun dried for six days to reduce its moisture content, and ground into small particles. At first, 100g of coal was measured using a digital balance. Subsequently, the following masses were measure 90g coal, 80g coal, 70g coal, 60g and 50g of coal.

2.2. Preparation of Sawdust Specimen

The sawdust used was collected from sawmill in Ozoro, Isoko North Local Government, Delta State, Nigeria. The sawdust is by-product of wood which has been subjecting to series of mechanical operations, such as milling, cutting and grinding. The sawdust was sun-dried for three days to reduce moisture content and the following mass were taken and weighed carefully using digital balance; 10g, 20g, 30g, 40g,50g and 100g of sawdust.

2.3. Pellets (Specimen) Preparation

The Pellets used in this study is made up of sawdust and coal ground with resin. The pellets consist of varying percentages of weight of coal and sawdust. The various pellet specimens, samples 1-7 and their mixed ratios are shown in Table 1 and Figure 1 (a – g). The sun-dried coal particles were evenly mixed with sun- dried sawdust particles in ratios of 100:0, 90:10, 80:20, 70:30, 60:40, 50:50 and 0:100 consisting of coal and sawdust respectively. After a thorough hand-mixing process, the resin was introduced to the mixture, the resin added is composed of the epoxy type which comprises of a hardener, monomeric, accelerator and plasticizer. The mixture was further subjected to hand-mixing. Each of the specimen (pellets) was sun-dried for 48 hours to further reduce moisture content and improve its mechanical strength.

Table 1: Components of Pellets Feedstock

Pellet Samples	Coal (%)	Sawdust (%)
Sample 1	100	0
Sample 2	90	10
Sample 3	80	20
Sample 4	70	30
Sample 5	60	40
Sample 6	50	50
Sample 7	0	100

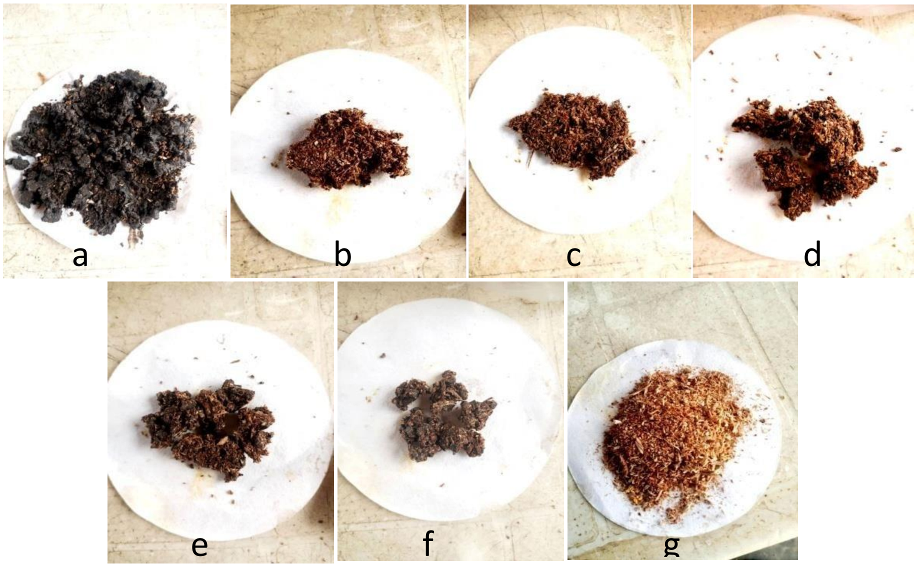

Figure1: (a = sample 1, b = sample 2, c = sample 3, d = sample 4, e = sample 5, f = sample 6 and g = sample 7)

2.4. Pellets Quality Assessment

2.4.1. Proximate Analysis and Calorimetry Test

The proximate analysis test was carried out on the pellets samples by heating them to a constant weight, at a standard of America Society for Testing Materials (ASTM conditions). The equipment used was lid, electric oven and test tube. Chemical compositions such as moisture, ash, fixed carbon and volatile matter were determined and obtained.

Calorimetry test conducted on the pellets samples labelled 1-7 was done by weighing the samples with a digital balance the sample was charged into the oxygen (O_2) bomb vessel in which the combustion charges can burn. The electrode was then connected to the vessel directly, the bomb and the bucket were then held in a calorimeter jacket which serves as a thermal shield. The machine was allowed to run for duration of 7 minutes for pellets combustion to take place.

2.4.2. Ultimate Analysis

In this method, the percentage composition of carbon, hydrogen, sulphur, nitrogen, and the oxygen available in the coal-sawdust pellets was determined. The ultimate analysis on the pellets samples was done using (ASTM) conditions.

The equipment used in the test analysis includes bomb calorimeter, necked flask and test tube. The various elemental compositions are determined as follows.

2.4.1.1 *Nitrogen*

Nitrogen content is determined by Kjeldahl's method [12]. In this method, the following procedures are followed.

i. Concentrated tetraoxosulphate (vi) acid (H_2SO_4) is heated with a given amount of powdered sawdust-coal in long necked flask.

ii. The nitrogen content of the sawdust-coal reacts with tetraoxosulphate (vi) acid (H_2SO_4) and is converted to Ammonium Sulphate. The reaction equation is shown in equation 1:

$$3H_{2_{(g)}} + H_2SO_{4_{(i)}} + 2N_{(g)} \rightarrow (NH_4)_2SO_4 \quad (1)$$

iii. The ammonium sulphate solution $(NH_4)_2SO_4$ is then heated with plethora of sodium hydroxide (NaOH). Ammonia (NH_3) is evolved; the evolved ammonia is absorbed in a given volume of N/10 HCl. The chemical equation for the above reaction is shown in equations 2 and 3;

(a) $$(NH_4)_2\,SO_4 + 2NaOH \rightarrow 2NH_3 + Na_2SO_4 + 2H_2O \quad (2)$$

(b) $$NH_3 + HCl \rightarrow NH_4Cl \quad (3)$$

(c) The unused volume of N/10 HCl is determined by titrating it against standard sodium hydroxide (NaOH) solution.

(d) The volume of hydrochloric acid (HCl) neutralized by the evolved ammonia (NH_3) from the sawdust-coal pellet is carefully determined.

iv. Nitrogen percentage is calculated as follows. Percentage of

Nitrogen % in the pellet =

$$\frac{V_A\ X\ 1.4\ X\ N_A}{W_P} \quad (4)$$

Where V_A is the volume of acid used, N_A is Normality and W_P is the Weight of Pellets

2.4.1.2 *Sulphur*

The sulphur content of the pellets samples was determined as follows.

i. A measured mass of sawdust-coal pellets is made to burn using a bomb calorimeter.
ii. Sulphur is then converted to sulphate which is then extracted using water (H_2O).
iii. Barium (ii) chloride $Bacl_2$ is used to treat the extracted sulphate and it precipitate out as $BaSO_4$.
iv. The $BaSo_4$ precipitate is filtered, dried and weighed.
v. After obtaining the weight of $BaSO_4$, the sulphur content in the sawdust-coal pellets is determined as follows.

Percentage of Sulphur in coal = $\frac{W_m B_a SO_4}{W_P}$ X $\frac{MBaSO_4}{233}$ (5)

Where.

W_m = Weight of $BaSO_4$

$MBaSo_4$ = Molar mass of $BaSO_4$ W_P = Weight of Pellets

2.4.1.3 *Carbon*

A weighed mass of pellet sample is subjected to a combustion process in the presence of oxygen (O_2) in a bomb calorimeter. The percentage composition of carbon of the pellet was determined as follows.

Percentage of carbon present in the sawdust-coal pellets =

$$\frac{IW_{KOH,\ tube}}{W_P}\ X\ \frac{12}{44}\ X\ \frac{100}{1} \quad (6)$$

where

I_W = Increase in weight of tube

W_P = Weight of sawdust-coal pellets

2.4.1.4 *Hydrogen*

A weighed mass of pellet sample is subjected to the combustion process in the presence of oxygen (O_2) in a bomb calorimeter, the percentage composition of hydrogen in the coal-sawdust pellets was determined as follows.

Percentage of hydrogen present in the sawdust-coal pellets =

$$\frac{IW_{Cacl2,\ tube}}{W_P}\ X\ \frac{12}{44}\ X\ \frac{100}{1} \quad (7)$$

Where

I_W = Increase in weight of tube

W_P = Weight of sawdust-coal pellets

The percentage of hydrogen composition of each of the pellet samples can also be determined using Equation 8:

% of hydrogen is = $100 - \Sigma\% \left(C_p + S_p + N_p + O_p + Ash_p\right)$ (8)

Where $100 - \Sigma\% \left(C_p + S_p + N_p + O_p + Ash_p\right)$ represents the expression for finding the percentage of hydrogen presents in each pellet samples.

C_P = Carbon content of pellets (%), S_P = Sulphur content of Pellets (%), N_P = Nitrogen content of pellets (%), O_P = Oxygen content of pellets (%)

2.4.1.3.Oxygen

The percentage composition of oxygen (O_2) in each pellet sample was determined using Equation 9:

Percentage of oxygen in coal = $\left[100 - \Sigma\% \left(C_p + H_p + N_p + S_p + Ash_p\right)\right]$ (9)

Where the expression $\left[100 - \Sigma\% \left(C_p + H_p + N_p + S_p + Ash_p\right)\right]$ represents the formula for finding the oxygen content in the pellet samples.

2.5. Determination of Number of Atoms in Each Molecule of the Pellets Constituents Elements

The number of atoms in each molecule of the pellet samples 1, 2, 3, 4, 5, 6 and 7 constituent elements was determined using Equation10:

$$E_m = A_n M_s \quad (10)$$

Where M_s, is the mass number of the element under consideration, A_n is the atomic number of the element in the constituent pellet to be determined and E_m is the mass percentage of the element obtained from the ultimate analysis test.

Determination of Pellet Sample 1 Chemical Formula

C = 45.83, H = 32.5, 0 = 3.09, S = 0.51

N = 1.07, Ash = 17.00

The hydrogen percentage is determined from the equation below;

$\%\ oxygen = 100 - (C + H + N + S + Ash)$

$3.09 = 100 - (45.83 + H + 1.07 + 0.51 + 17.00)$

$3.09 = 100 - (64.41 + H)$

$3.09 = 35.59 - H$

$H = 35.59 - 3.09 = 32.5$

$H = 32.5\%$

Assuming $C_x H_y O_t N_a S_q$ as the chemical formula, where x, y, t, a and q denotes the number of atoms in each molecule of the constituent element and is determined as follows.

Carbon (C); $12x = 45.83$

$\therefore x = \frac{45.83}{12} = 3.82$

Hydrogen (H); $1y = 32.5$

$\therefore y = \frac{32.5}{1} = 32.5$

Nitrogen (N); $14a = 1.07$

$\therefore a = \frac{1.07}{14} = 0.08$

Sulphur (S); $32q = 1.51$

$\therefore q = \frac{0.51}{32} = 0.016$

The chemical formula becomes;

$C_{3.82} H_{32.50} O_{0.19} N_{0.08} S_{0.016}$

The chemical formula of the subsequent pellets (Sample 2-7) is determined and obtained using the analytical method above and are shown in Table 2.

2.6. *Determination of Percentage of Pellets Combustion Emissions*

The percentage of each product emitted from the stoichiometric combustion of pellet samples 1, 2, 3, 4, 5, 6 and 7 in the wet and dry emission analysis was calculated using equations 11 and 12 respectively.

For wet analysis

$$\% \ of \ gas \ emitted \ is = \frac{n_i}{nCO_2 + nSO_2 + nH_2O + nN_2} X \frac{100}{1} \quad (Onochie\ et\ al., 2024) \qquad (11)$$

For dry analysis

$$\% \ of \ gas \ emitted \ is = \frac{n_i}{nCO_2 + nSO_2 + nN_2} X \frac{100}{1} \quad (Onochie\ et\ al., 2024) \qquad (12)$$

Where n_i is the amount (in kmol) of the particular product of emission under consideration and nCO_2, nSO_2, nH_2O and nN_2 represents the amount (in kmol) of carbon dioxide, sulphur dioxide, water vapour and nitrogen gas emitted respectively.

Wet Analysis of the Emissions

Total amount of substance produced from the combustion equation is

$3.82 + 16.25 + 0.016 + 44.79 = 64.88$kmol (as obtained from Table 5)

$$\text{Carbon Dioxide } (CO_2) = \frac{3.82}{64.88} X \frac{100}{1} = 5.89\%$$

$$\text{Sulphur Dioxide } (SO_2) = \frac{0.016}{64.88} X \frac{100}{1} = 0.03\%$$

$$\text{Water } (H_2O) = \frac{16.25}{64.88} X \frac{100}{1} = 25.05\%$$

$$\text{Nitrogen } (N_2) = \frac{44.79}{64.88} X \frac{100}{1} = 69.04\%$$

For dry analysis;

$CO_2 = 7.86\%$, $SO_2 = 0.03\%$ and $N_2 = 92.10\%$

Chemical Composition of Pellets Samples

The number of atoms of carbon (x), hydrogen (y), oxygen (t), nitrogen (a) and sulphur (q) in each of the pellet's samples were obtained using equation 10 and the chemical formula of the pellets are obtained from the values of x, y, t, a and q. The chemical formula of the pellets is generally written as $C_xH_yO_tN_aS_q$ [10]. The number of atoms of the constituent elements obtained and the chemical formula of each pellet sample are shown in Table 2.

Table 2: Atomic Number of Constituent Elements and Pellets Chemical Formula

Pellets	Cx	Hy	Ot	Na	S	Chemical Formula
Sample 1	3.82	32.5	0.19	0.08	0.016	$C3.82H32.50O0.19N0.08S0.016$
Sample 2	2.79	27.25	0.29	0.08	0.02	$C2.79H27.25O0.29N0.08S0.02$
Sample 3	2.50	33.23	0.33	0.07	0.03	$C2.50H33.23O0.33N0.07\ S0.03$
Sample 4	2.26	27.65	0.38	0.07	0.02	$C2.26H27.65O0.38N0.07S0.02$
Sample 5	1.66	33.88	0.26	0.10	0.06	$C1.66H33.88O0.26N0.10S0.06$
Sample 6	1.93	38.33	0.19	0.02	0.06	$C1.93H38.33O0.19N0.02S0.06$
Sample 7	0.84	74.68	0.38	0.02	0.22	$C0.84H74.68O0.38N0.02S0.22$

3.0. Results and Discussion

3.1. Calorimetry Test Results of Pellet Samples

The result obtained from the calorimetry test shown in Figure 2, indicated that Pellet Sample 5 has the highest calorific value (22.07MJ/kg) and Pellet Sample 2 has the lowest calorific value (14.85MJ/kg). However, the range calorific values obtained for pellet sample 1 – 7 is 14.85MJ/kg – 22.07MJ/kg which is having a strong agreement with the range of calorific values result reported by [19] and [10]. The range of the values of the calorific results of the pellets obtained, shows that they can be used conveniently as a fuel in different heat energy generation equipment. The result obtained (18.59MJ/kg) by [13] is within the range 14.85MJ/kg – 22.07MJ/kg obtained from this study.

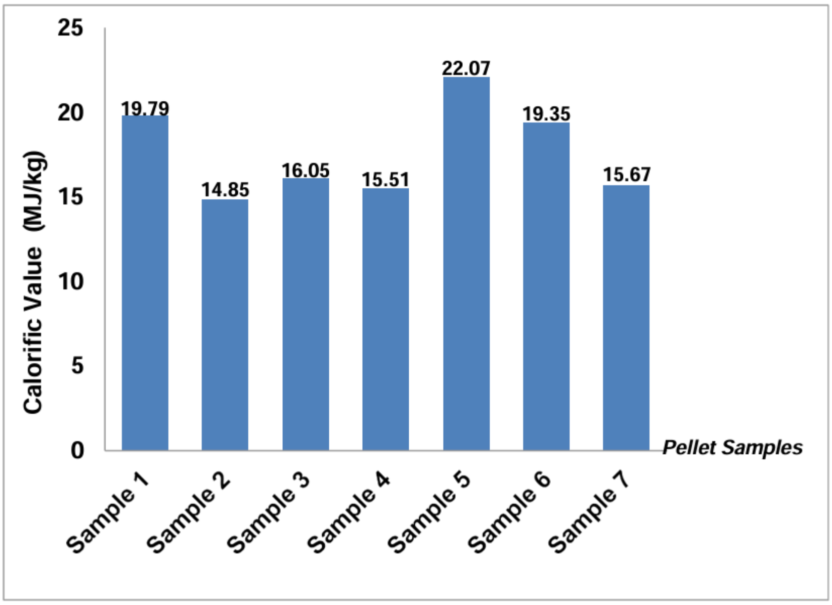

Figure 2: Calorific Values of Sawdust and Coal Blend from Calorimetry

According to [20], calorific value is the determinant of the energy content of briquettes samples, and it value is a function of the chemical composition and moisture content of the briquettes. The calorific value results obtained, and shown Figure 2 are very similar to the range of the calorific values obtained by [21] which is in the range of (25.2 – 26.8 MJ/kg), (11.3 – 14.6 MJ/kg) and (16.10 – 18.50 MJ/kg).

Table 3: Proximate Analysis Results

The proximate analysis test results carried out on the pellets samples are shown in Table 3.

Parameters	Sample 1 (%)	Sample 2 (%)	Sample 3 (%)	Sample 4 (%)	Sample 5 (%)	Sample 6 (%)	Sample 7 (%)
Moisture Content (Mt)	4.84	4.03	3.96	3.89	3.15	2.92	7.82
Volatile Matter (MV)	34.60	37.21	40.01	44.90	50.96	57.01	87.54
Ash Content (AC)	17.00	25.11	28.06	33.20	38.69	35.11	1.86
Fixed Carbon (FC)	43.56	32.90	27.01	17.90	8.80	4.96	2.78

The range of moisture contents obtained is in the range of 2.92% - 7.82%, with Pellet Sample 7 having the highest moisture content and pellet Sample 6 has the lowest moisture content. The value of the moisture content obtained in this study is coherent with the suggestion of [22] which says that briquette having moisture content greater than 10% are weak and poor. The range 2.92% to 7.82% of the moisture content of the pellets obtained also falls within the range 1.03% - 7.11% reported by [23] in their study of sesame seed stalk biomass and coal briquette. The range of volatile matter content obtained (34.6%) – 87.54% is in line with the results of [24] which is 4.99% - 47.01$ with the exception of pellet sample 5, 6 and 7 which is having a higher volatile matter content. The range of the volatile matter content suggest that they can be ignited easily and be used conveniently use as a fuel in boilers operations. The value of the ash content of the composite pellets obtained in the range (25.11 - 38.69%) falls within the range (5 - 40%) of boilers ash content percentage specified by the Bureau of Energy Efficiency (BEE). [25] asserted that ash content has a major influence on the transfer of thermal energy to the surface of boilers and also influence the transport of oxygen to the surface of a fuel during combustion of char. Since the range of ash content obtained in this study agreed with the report of BEE, it therefore suggests that the pellets which constitute of coal and sawdust biomass can be used as a fuel in boilers operations. The presence of high ash content in the fuel can also lead to slagging and clinker formation in combustion chambers. The general trend of the fixed carbon contents of the pellets samples suggested that the fixed carbon composition decreases with a decrease in coal percentage and an increase in sawdust composition. The results trend observed and shown in Table 3 support the result of [16] in their study of coal-combustion characteristics of typical biomass and coal blend using thermogravimetric analysis. [25] asserted that high fixed carbon content does not implies better combustion performance, although increased in fixed carbon content can initially improve combustion performance.

3.2. Ultimate Analysis Test Results of Pellets Samples

The ultimate analysis test carried out on the various pellet samples is shown in Table 4.

Table 4: Ultimate Analysis Results

S/N	Parameters (wt, %)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
1.	Sulphur	0.51	0.76	0.94	0.64	1.97	1.95	7.12
2.	Carbon	45.83	33.5	30.10	27.10	19.90	23.20	10.10
3.	Oxygen	3.09	4.56	5.21	6.09	4.11	3.06	6.02
4.	Nitrogen	1.07	1.08	1.02	1.01	1.45	0.30	0.22
5.	Hydrogen	32.5	27.25	33.23	27.65	33.88	38.33	74.68

3.3. Effects of Sulphur Contents of Pellet Samples

The percentage composition of sulphur content in each of the pellet samples is represented in Table 4 The general trend of the sulphur content of the pellet samples shows that the pellets containing the lowest percentage of sawdust biomass have the lowest sulphur content and the pellets with the highest percentage of sawdust biomass possess the highest sulphur content. The range of sulphur content obtained in Table 4 (0.51- 7.12%) is higher than that reported by [10] in the range (0.10 – 0.18%) from their ultimate results of pellets samples consisting of CSC, CFC, RHC, SDC and BC, where CSC denote coco shell coal, CFC is coconut fibre coal, RHC is rice husk coal, SDC is sawdust coal and BC is bio coal.

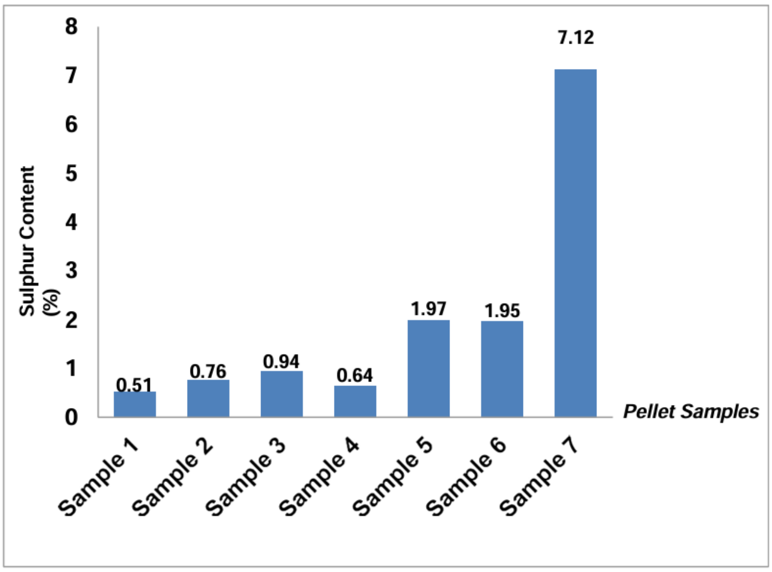

Figure 3: Sulphur Composition of Pellets

The sulphur content observed in the pellet's samples 1, 2, 3, 4, 5 and 6 (0.76 – 1.95%) as shown in Figure 3 are reasonably low and slightly higher than the values (0.6%) before addition of disulphuric agent reported by [8] and (0.16 – 0.47%) after addition of disulphuric agent. Again, from the findings of [27], the range of sulphur composition in the wood coal pellets from ultimate analysis was reported to be (0.22 – 2.26%). From the proximate and ultimate analyses of samples consisting of coal, coal and sawdust, rice straw and coal, rice husk and coal by [16], the sulphur composition was reported to be (0.11 – 0.32%) which is lower than (0.51 – 7.12%) obtained in this study. This shows that the pellet can be us conveniently as a fuel in both domestic and industrial settings. The implication of higher sulphur content observed in tis study compared to other studies is that it subsequently contributes to higher percentage of sulphur dioxide emissions. [8] pointed out that sulphur is a basic unwanted element in coal despite its contribution to calorific value. [10] and [8] asserted that the presence of sulphur in a fuel contributes to the corrosion of heating equipment such as boilers. The percentage of sulphur content in the pellet's samples in Table 4, and Figure 3 shows that they can be used conveniently as a fuel in different heating applications.

3.4. Effects of Carbon Contents of Pellets Samples

The carbon content in Table 4 and Figure 4 follows a diminishing order with an increased concentration of sawdust in the pellets. The carbon content decreases from (45.83%) in the sample 1 pellet to (10.10%) in the sample 7 pellets, as shown in Figure 4 which agrees with the reports of [8].

According to [28], carbon is the major combustible element of fuel, and it generates thermal energy which can be transformed into other forms of energy such as steam and electricity.

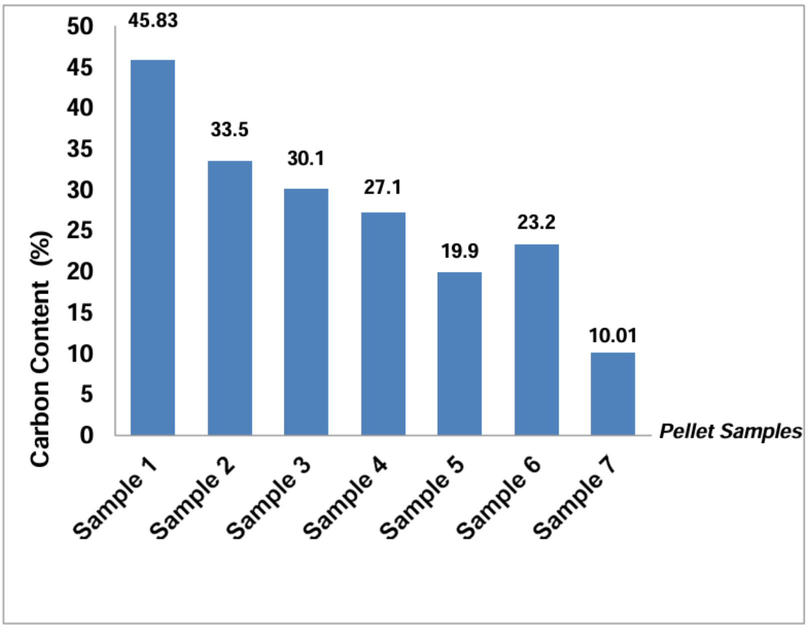

Figure 4: Carbon Composition of Pellets

The range of the carbon content obtained in Figure 4 above is within the range (10.50 – 78.20%) reported by [12].

3.5. Effects of Oxygen Contents of Pellets Samples

The range of the percentage composition of oxygen in the pellets is observed to be

3.06 – 6.09%, as observed in Table 4. The oxygen content of sample 6 pellet is the lowest while the sample 4 pellet possesses the highest oxygen content. On average, the oxygen content of sawdust biomass is higher than coal.

The range of the percentage composition of oxygen value observed in this study is lower than the range (9.90 – 73.97%) reported by [12]. The range (3.06 – 6.09%) of oxygen obtained as shown in Figure 5 is also in agreement with the range of (1.40 – 9.38%) reported by [10].

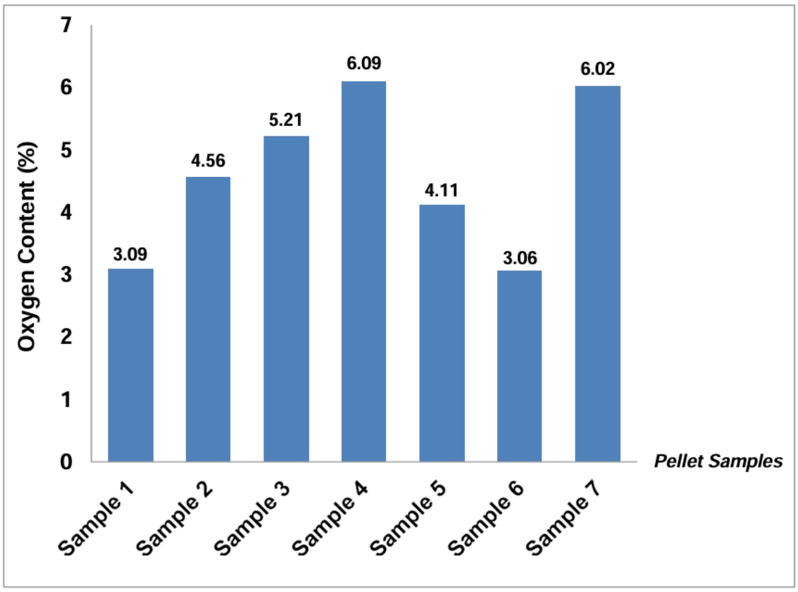

Figure 5: Oxygen Composition of Pellets

According to [29], the higher the oxygen content in a solid fuel, the better its combustion will be. The oxygen composition of the pellets in Table 4 and Figure 5 shows that they can burn very well and can be used as fuel.

3.6. Effects of Nitrogen Contents of Pellets Samples

The results in Figure 6 show that the nitrogen content in the sawdust coal pellets decreases with an increasing concentration of sawdust biomass in the pellets. The nitrogen content of the pellets was relatively low, and the range of the nitrogen composition of the pellets in Table 4 in the range of (0.22 – 1.45%) is slightly higher than the range (0.30 – 0.8%) of the values reported by [30].

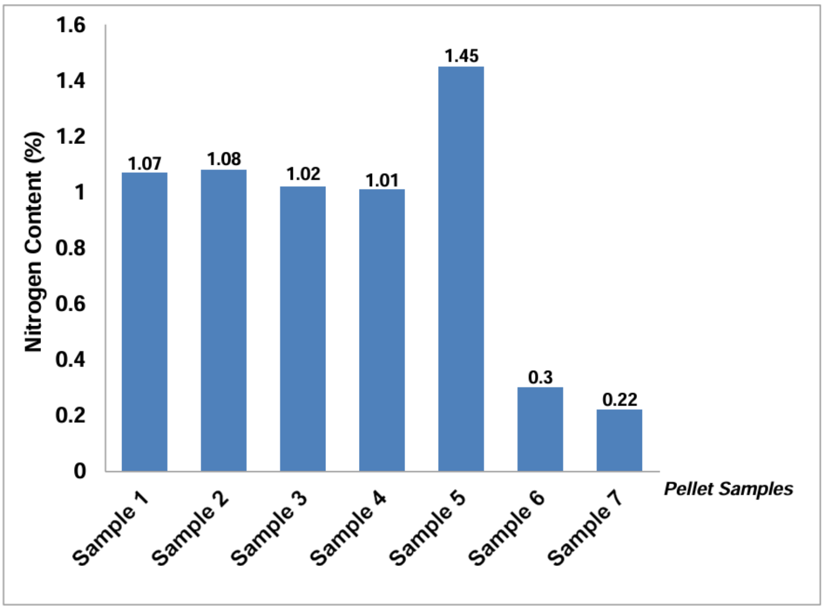

Figure 6: Nitrogen Composition of Pellets

The range of nitrogen content obtained in Figure 6 suggested that the pellets can be used as a fuel in different heating applications. [29] reported that nitrogen does not have a calorific value, but low nitrogen is required in coal.

3.7. Effects of Hydrogen Contents of Pellets Samples

The results obtained in Table 4 and the plots in Figure 7 shows that the hydrogen content at an average increase from pure coal sample 1 pellet having a hydrogen percentage of 32.50% to pure sawdust biomass samples 7 pellets having hydrogen percentage of 74.68%. The hydrogen content was highest in samples 7 pellet and lowest in the samples 2 pellet, this suggest that the hydrogen content in sawdust biomass is high when compared to pure coal.

The results obtained in Figure 7 agreed with the suggestion of [8] that a lump of good coal should possess low hydrogen content, and the hydrogen content of bio- coal briquettes should be low, and this will enhance better combustion.

However, the range of hydrogen content observed in this study is higher than the range of values reported by [8] [10] [16] [12]. The higher hydrogen content observed in the sawdust coal pellets is due to the high content of hydrogen in the sawdust biomass (74.68%), and this may be attributed to hemicelluloses, cellulose and lignin content in the sawdust biomass.

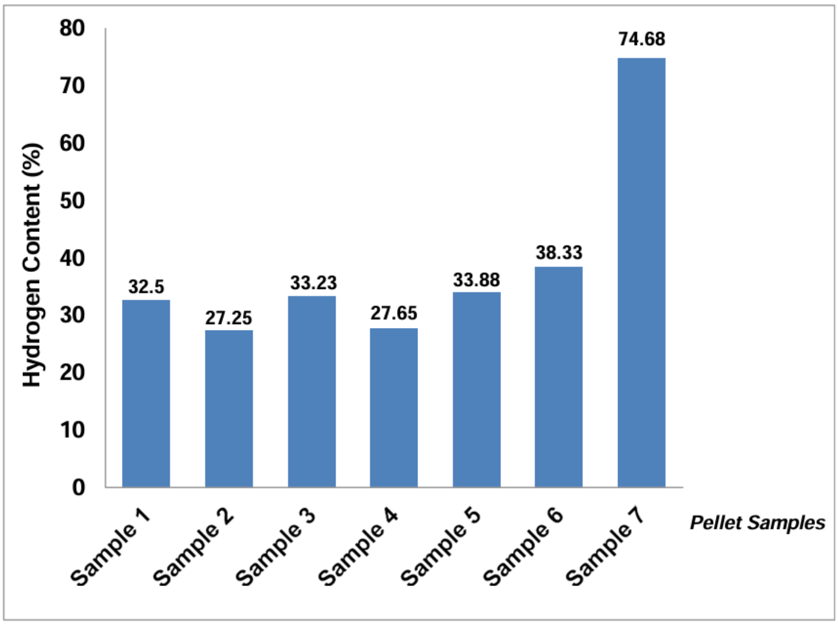

Figure 7: Hydrogen Composition of Pellets

3.8. The Combustion Analysis of Pellet Samples

The stoichiometric combustion equations of the pellet samples, their product of combustion and the amount of combustion product are shown in Table 5.

Table 5: Stoichiometric Combustion Equation of Pellets

Pellets	Stoichiometric Combustion Equation	Combustion Products (kmol)			
		CO_2	H_2O	SO_2	N_2
Sample 1	$C_{3.82}H_{32.50}O_{0.19}N_{0.08}S_{0.016}+11.89(O_2+\frac{79}{21}N_2)\rightarrow 3.82CO_2+16.25H_2O+0.01SO_2+44.79N_2$	3.82	16.25	0.016	44.79
Sample 2	$C_{2.79}H_{27.25}O_{0.29}N_{0.08}S_{0.02}+9.48(O_2+\frac{79}{21}N_2)\rightarrow 2.79CO_2+13.63H_2O+0.02SO_2+35.73N_2$	2.79	13.63	0.02	35.73
Sample 3	$C_{2.50}H_{33.23}O_{0.33}N_{0.07}S_{0.03}+10.68(O_2+\frac{79}{21}N_2)\rightarrow 2.50CO_2+16.62H_2O+0.03SO_2+50.23N_2$	2.50	16.62	0.03	40.23
Sample	$C_{2.26}H_{27.65}O_{0.38}N_{0.07}S_{0.02}+$	2.26	0.02	13.83	50.57

4	$13.45(O_2 + \frac{79}{21}N_2) \rightarrow 2.26CO_2 + 13.83H_2O + 0.02SO_2 + 50.57N_2$				
Sample 5	$C_{1.66}H_{33.38}O_{0.26}N_{0.10}S_{0.06} + 10.06(O_2 + \frac{79}{21}N_2) \rightarrow 1.66CO_2 + 16.94H_2O + 0.06SO_2 + 37.93N_2$	1.66	16.94	0.06	37.93
Sample 6	$C_{1.93}H_{38.33}O_{0.19}N_{0.02}S_{0.06} + 11.48(O_2 + \frac{79}{21}N_2) \rightarrow 1.93CO_2 + 19.17H_2O + 0.06SO_2 + 43.19N_2$	1.93	19.17	0.06	43.19
Sample 7	$C_{0.84}H_{74.68}O_{0.38}N_{0.02}S_{0.22} + 19.54(O_2 + \frac{79}{21}N_2) \rightarrow 0.84CO_2 + 37.34H_2O + 0.22SO_2 + 73.49N_2$	0.84	37.34	0.22	73.49

[10]

From Table 5, it is observed that the combustion of the pellet samples yields carbon dioxide (CO_2), water vapour (H_2O), sulphur dioxide (SO_2) and nitrogen (N_2) as the combustion products.

3.9. Pellet Emissions Analysis

The Percentage of emissions (in both wet and dry analysis) from the combustion of the pellet samples was calculated and obtained using equations 11 and 12 and the results are shown in Table 6 and Figure 8–9.

Table 6: Wet and Dry Emissions Analysis

Pellet Samples	**Percentage of Gases Emitted**						
	WET ANALYSIS				**DRY ANALYSIS**		
	CO_2	SO_2	N_2	H_2O	CO_2	SO_2	N_2
Sample 1	5.89	0.03	69.04	25.05	7.86	0.03	92.10
Sample 2	5.35	0.04	68.49	26.13	7.24	0.05	92.71
Sample 3	4.21	0.05	67.75	27.99	5.85	0.07	93.55
Sample 4	3.39	0.03	75.84	20.74	4.28	0.04	95.69
Sample 5	2.93	0.11	67.03	29.94	4.19	0.15	95.66
Sample 6	2.99	0.09	67.12	29.79	4.27	0.13	95.59
Sample 7	0.75	0.19	65.68	33.37	1.10	0.29	98.58

3.10. Pellets Emissions

The products of combustion (emissions) of the pellets sample 1 – 7 shown in Table 5 are carbon dioxide (Co_2), sulphur dioxide (SO_2), Nitrogen (N_2) and Water Vapour (H_2O). Each of the emissions from the pellet combustion is explained as follows.

Carbon Dioxide Emissions: It is noticeable that, carbon dioxide emissions were highest in pellet sample 1 and lowest in sample 7. The carbon dioxide emissions progressively decreases from sample 1 to sample 7 both in the wet and dry analysis as shown in Figure 8-9, while the range of the values of carbon dioxide emitted is (5.89% - 0.75%) for the wet analysis and (7.86% - 1.10%) for dry analysis. From the ultimate analysis results of the pellet samples, it was observed that pellet samples with the highest carbon content possessed the highest carbon dioxide emissions while pellet samples with the lowest carbon content possessed the lowest carbon dioxide emissions. The decrease in carbon dioxide emissions from pellet samples 1 – 7 as the sawdust biomass concentration increases by 10% in each of the pellet samples is coherent with the findings of [10] [31 - 35] which says that addition of biomass to coal reduces the emissions of carbon dioxide during combustion.

Sulphur Dioxide Emissions: The emissions of sulphur dioxide from the combustion of pellets samples 1 – 7 show that the amount of sulphur dioxide emitted was minimal in sample 1 and maximum in sample 7 both in the wet and dry analysis as shown in Figure 8–9. The progressive increase of the amount of sulphur dioxide emitted from samples 1 – 7 is similar to the trend of sulphur content increment from samples 1 – 7, as observed from ultimate analysis results shown in Figure 3 and Table 4. The range of sulphur dioxide emitted in the pellets samples are 0.03 – 0.19% (wet analysis) and 0.03 – 0.29% (dry analysis) which is slightly higher than the values (0.02 – 0.027%) reported by [10]. The increase in the amount of sulphur dioxide emitted as the percentage of sawdust biomass in the pellets increases, is due to the higher composition of sulphur in sawdust biomass.

Nitrogen Emissions: From emission analysis results in Table 6 and Figures 8 – 9, it was observed that the range of nitrogen emitted in the wet emission analysis is 65.68% - 75.84% and 88.58% - 92.10% in the dry analysis. It was also observed from the wet analysis that the emissions of nitrogen from the combustion of the pellets samples 1 – 7 follow the diminishing order with sample 1 having the highest emissions and sample 7 having the lowest; this is having strong agreement with the report of [36]. The decrease in Nitrogen emission as the sawdust content increases is attributed to the high content of Nitrogen in sawdust compared to coal. However, pellet sample 4 shows a deviation from the trend having the highest percentage of Nitrogen emission. This has shown that the addition of sawdust biomass to coal results to a decrease in the emissions of nitrogen, and this is in conformity with the findings of [17].

In the dry emission analysis, it was however observed that the nitrogen emission increases from pellet samples 1 – 7. The decreasing trend of nitrogen emissions observed in pellet samples 1 – 7 is in line with the report of [37 - 39] and this is due to the decreasing nitrogen content in the pellet samples, from 1 – 7 as observed in the ultimate analysis test in Figure 6.

Water Vapour Emissions: The range of water vapour emitted in pellet samples 1 – 7 is 20.74 – 33.37% on a wet analysis basis. From the plots of emission in Figure 8, it was observed that water vapour emission in the pellets increases across samples 1 to 7. The increment in water vapour emissions from samples 1 – 7 as the sawdust biomass concentration increases is due to the higher hydrogen content in the sawdust, is similar to the findings of [10] in their study of assessment of the compatibility of biomass – coal blends. The incremental trend of water vapour emissions as observed in Figure 8 is similar to the trend of hydrogen content obtained from the ultimate analysis test shown in Figure 7.

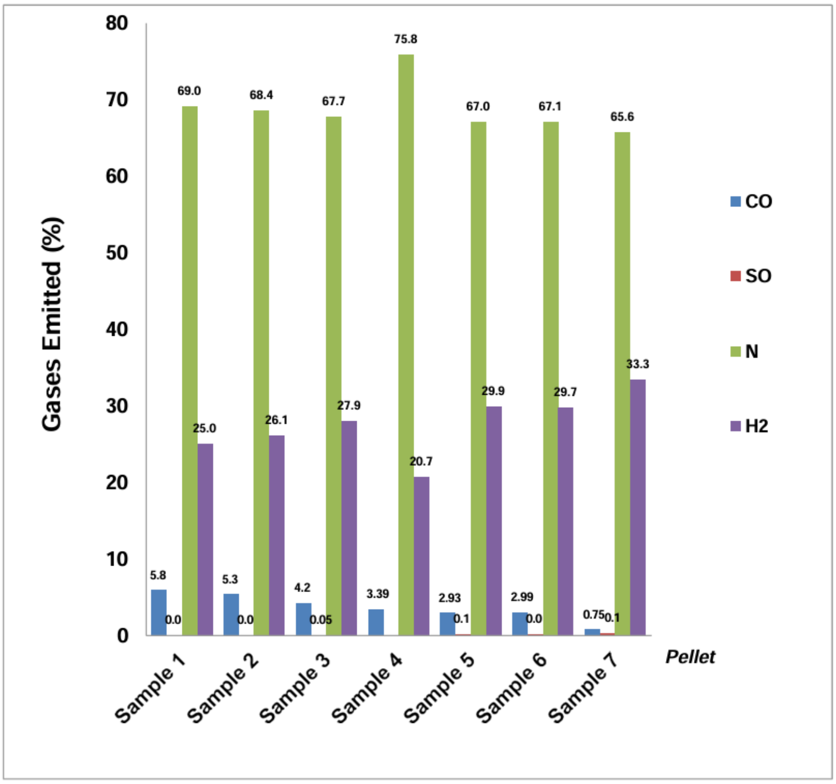

Figure 8: Sample 1-7 Analysis of Wet Emissions

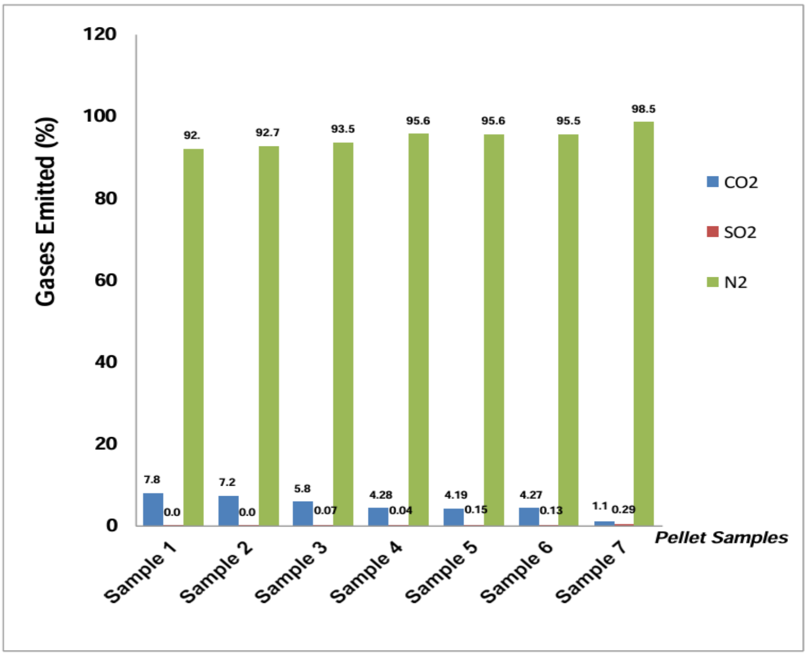

Figure 9: Sample 1-7 Analysis of Dry Emission

4.0. Conclusion

The study primarily focused on the utilization of sawdust biomass as an additive fuel to coal using resin as a binder. The results obtained from the calorimetry test indicated that sawdust coal blend is a good fuel for optimum thermal performance since the calorific values obtained are reasonably high for various heating applications. Ultimate and emission analysis results have revealed that the amount of carbon dioxide, sulphur dioxide, nitrogen and water vapour emitted during combustion is a function of the carbon, sulphur, nitrogen, and hydrogen composition of the sawdust-coal pellets and the sawdust-coal mixed ratio. Emission analysis results demonstrated that the addition of sawdust biomass to coal reduced the emissions of carbon dioxide (GHGs), which significantly reduces global warming (a target of Sustainable Development Goal No. 13). It is also revealed from the study that sulphur dioxide emission slightly increases as the sawdust composition in the pellet increases. Future research should optimise sawdust ratios and evaluate long term impacts on emissions.

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