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Performance evaluation of downdraft gasifiers under various conditions

Performance evaluation of downdraft gasifiers under various conditions

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Abstract. This research studied the effect of biomass types and moisture content on the performance of a downdraft gasifier. Sawdust, woodchip and bean chaff were used as test samples at three moisture contents (10, 20 and 30% w.b) which was determined with oven drying method and Pascal's manometric tube was prepared to measure the quantity of methane, hydrogen sulfide, carbon dioxide and carbon monoxide in the syngas. The gas obtained at 10% moisture content for the three biomass after gasification was analyzed and compared to standard values. Ash content, gasification time and temperature were measured using standard methods. The ash contents at 10, 20 and 30% moisture contents for wood chips, sawdust and bean chaff were 0.210, 0.457, 0.750kg, 0.202, 0.290, 0.651kg and 0.295, 0.228, 0.394kg respectively. The gas samples were taken at 10% moisture for analysis because it produced the lowest ash content**.** Gas produced at 10% moisture content showed that methane, CO_2 and H_2S contents for wood chips; sawdust and bean chaff were 60.85, 27.50, 0.44%; 62.33, 23.77, 0.87% and 63.94, 18.91, 0.58% respectively. The values of CO was insignificant. The moisture content of the biomass significantly ($p < 0.05$) affected the values of ash content, gasification time and temperature but the effects of biomass types were not significant. Ash content and gasification time increased with increase in moisture level with the least value of 0.210 kg and 61 minutes at 10% moisture content respectively. The gasification temperature decreased as moisture level increased and vice versa. Increase in moisture level increased the ash content and gasification time. The higher the gasification temperature, the lower the time. Gasifier efficiency was also affected by moisture content and biomass types. The best gasifier efficiency was observed at 10% moisture content with 60, 57 and 75% for sawdust, woodchips and bean chaff respectively.

1. Introduction

In recent times, waste no longer carries the common notion as people in ancient times thought it as substances that have exhausted their use. Waste management is been practiced across different regions and countries because waste has a huge negative impact on the natural environment through environmental pollution; a predominant challenge facing human populace in Sub Saharan Africa [1-4]. Presently, one of these common wastes that have gotten a lot of attention is agricultural waste. Diverse researches are been conducted to put agricultural waste into proper use, most of which considers these waste as biomass to generate useful products such as biogas [5-14]. Moreover, fossil fuels are not considered to be renewable or eco-friendly as they contribute to the level of pollution in the environment which has effects on the ecosystem. Energy is essential for the sustenance of humans in the world; modern-day power for business development is essentially based on fossil fuels which is coupled with different human activities have been proven to be responsible for the warming of the climate system. Developing countries like Nigeria face added dilemmas regarding environmental protection due to their heavy dependency on biomass and fossil fuel [15].

Biomass gasification occurs as a thermochemical process to produce a gaseous fuel from a carbonaceous feedstock, which includes but not limited to eucalyptus wood, rice straw, rice husk, pine wood, sugar cane, corn stalk, corn cob, coconut shell, olive husk, poplar and so on [16]. During the Second World War, the use of wood gasifier peaked when almost a million gasifier were used all over the world, mainly for vehicles operating on domestic solid fuels instead of gasoline. The gas obtained from coal gasification is called producer gas. The producer gas is the moisture of hydrogen and carbon II oxide prepared by passing a stream of air through red hot coke, the oxygen in the air oxidize the coke of carbon II oxide with the liberation of a lot of heat but the Nitrogen is unchanged. The heat generated is then used to pyrolyse or thermally breaks down the rest of the material into volatile gases. Gasifiers are the main devices used in the gasification process; a process which involves the generation of syngas (consisting C0, H_2, CO_2, N_2, tar, ashes and small particulates) from biomass [17]. Biomass gasification mainly involves a process whereby agricultural residues or biomass are subjected to partial combustion at a temperature up to 10000^o C in order for the biomass to undergo pyrolysis and reduction, thereby releasing its gaseous constituents as hydrogen, carbon dioxide and methane. Biomass gasification has been in existence over a long period of time, and the process has gained some level of attention and improvement over the years.

There are four major types of commonly utilized gasifiers, namely, downdraft, updraft, fluidized bed and entrained bed gasifier [18]. The updraft and downdraft type of gasifiers are classified based on the exit point of the gases; in the updraft type of gasifier, the producer gas is collected at the top of the gasifier, while in the downdraft types, the producer gas is collected at the bottom of the gasifier. The widely most deployed gasification technique in small-scale application is the downdraft gasifier, which was reported to be produced by about 75% of gasifier manufacturers in Europe [19,20]. According to FAO in 1986, the downdraft types of gasifier have been reported to produce cleaner gas as compared to the updraft gasifier. The major areas in gasifier design that needs improvement and where attention needs to be directed to the area of gas cleaning systems which aids the removal of impurities in the gases generated from the gasifier before using the gas to run an internal combustion engine.

Gasification process depends on the different factors such as air supply organization [21], size of the biomass particle [22], fuel chemical composition [23] and other factors. Furthermore, various biomass properties do have a different influence on the gasification process especially the fuel moisture content. The fuel moisture content can (a) promote temperature in the gasifier [23], (b) its growth can decrease the activity of boudouard reaction and aid the decrease of CO content in the produced gas, (c) its growth can, however, favor H_2 content increase in the syngas [24]. Another property of biomass is water vapor; this reacts with carbon and CO to produce H_2. This process is described through supercritical water and gas shift reactions, however, H_2 amount in the syngas go down can be found too [25-28]. This makes the inclusion of the description of used gasification technology and possible operation condition very vital.

This research focused on the effect of gasification parameters like moisture content of the biomass and also biomass types on the gasification process and the quality of the gas that will be generated at different moisture content levels. A downdraft gasifier designed at the Federal University of Agriculture, Abeokuta was considered in this research work (Reference "designing a small scale downdraft gasifier for biomass gasification"), since it has established it that it produced cleaner gas as compared to the updraft gasifier by FAO in 1986. The design, construction and testing were tailored after downdraft gasifier. Attention was given to the effect of biomass moisture content (wet basis) and biomass types on gasification time, gasification temperature, ash content and its overall effects on the efficiency of the gasifier.

2. Materials and Methodology

2.1. Description of the Gasifier used

2.1.1 Testing and Evaluation. The biomass used for testing the development gasifier are been chaff, saw dust, and wood chips based on their availability within and outside research area. An average mass of one kilogram of each biomass was used as test weight for all the experimental runs. The factors considered before and after the experiment runs are shown in table 1.

Table 1. Factors considered before and after the experiment runs

Input		Output	
i.	Percentage moisture content	i.	Oxidation temperature
ii.	Different biomass	ii.	Ash content
		iii.	Time of gasification
		iv.	Lower Heating Value
		v.	Gas Components
		vi.	Efficiency

2.1.2. Moisture Content: The moisture content of the biomass from the field was determined by the gravimetric method using the oven drying method. The moisture content was determined in wet basis, then moisture content dry basis was derived from it in order to determine the volume of water needed to vary the moisture content of the biomass.

A. Initial Moisture Content of Saw Dust
Formula for moisture contents:

$$\text{MCW basis (\%)} = \frac{weight\,of\ moisture}{weight\,of\ wet\,sample} * 100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

A 1kg sample of biomass was placed inside the oven and temperature was set to maximum of 40^0C, and the sample was dried to bone weight.

W_1 = Weight of Biomass before drying = 1kg
W_2 = Weight of Biomass after drying = 0.80 kg
W_3 = Weight of Water present = **M_1- M_2**= 1- 0.80 = 0.200

$$\text{Moisture Content Wet Basis} = \frac{W3}{W1} * 100\%$$

$$MC_{wb} = \frac{0.20}{1.00} * 100\%$$

MC_{wb} = 20%

Moisture Content Dry basis (MC_{db})

$$\text{MCdb} = \frac{MCwb}{100 - MCwb} * 100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

$$MC_{bd} = \frac{20}{100 - 20} * 100\% \quad , \qquad MC_{db} = 25\ \%$$

To derive the Mass of dry matter in the sample:

$$MC_{db} = \frac{Weight\,of\ moisture}{Weight\,of\ Dry\,matter} * 100\%$$

$$25 = \frac{0.200}{Weight\,of\ Dry\,matter} * 100\%$$

Weight of Dry matter = $\frac{200*100}{25}$

Weight of Dry matter = 0.80 gram.

The Lower Heating Value of the solid biomass (KJ/Kg): This was obtained from tables of standard values. This is needed to calculate the efficiency of the gasifier.

2.1.3 Measuring Equipment and Safety Precaution. Mercury-in-glass thermometer**,** thermocouple**,** weighing scale**,** stop watch and drying oven were the different equipment used for measurements.

- Gasification Temperature (◦C): The temperature of the biomass before the gasification was measured with the use of mercury-in –Glass thermometer, and the temperature at the gasification zone was measure with the use of thermocouple.
- Ash content (Kg): The amount of ash left after gasification was collected and measured with aid of weighing scale.
- Gasification Time (hr.): The time required to completely gasify 1kg of biomass samples were monitored with the aid of stop watch.

Various types of hazards are hazard are associated with the gasification process, such as toxic hazards, fire hazards, environmental hazards and explosion hazards. Producer gas consists of carbon monoxide, which is slightly toxic as it combines with hemoglobin in the blood, preventing oxygen absorption and dizziness. Fortunately, there is less chance of gas hescape during operation as gasification system works under suction. However, situation is quite different during starting and closing installations. To avoid the trapping of gas, it is recommended to install the gasifier plant in the open air or well ventilated areas. To avoid explosion hazards, Air leakage into cold gasifier still containing gas which can ignite.

Table 2. Types of risk identified and the precautions taken

Risk Identified	Precaution taken
High surface temperature	Insulation of hot parts system
Inhaling poisonous gas	Use of nose cover
Backfiring from nozzles	Installation of nozzle covers

2.1.4. Gasifier Testing Procedures. The developed gasifier was loaded with the tested materials and evaluated as discussed. The following procedures were following to test the gasifier after completing the fabrication and assembly.

- The prepared sample was fed into the reactor from the top.
- The ignition port was opened after the sample has been fed into the reactor chamber
- The initial temperature of the system (reactor + biomass) were recorded with the aid of temperature measuring instrument.
- Fire was introduced through the ignition port into the reactor to provide partial combustion for the biomass.
- The blower was activated to suck air into the system and it was left to operate for at least 15 minutes in order to gain appreciable temperature increases.
- After 15 minutes the ignition port and the reactor upper lid were closed to provide air- tight environment.
- The temperature at the oxidation zone was closely monitored in order to see the temperature at which gasification will occur; Gasification is expected to occur at 600- 900◦ C according to

established literatures. The temperature was monitored and recorded with the use of thermocouple.

- The Ash content was collected at the bottom of the reactor after the gasification was complete and weighted in order to know how efficient the system is. The mass of the ash was recorded.
- The Tar content also was collected at the bottom of the cyclone unit but little tar content was observed and this confirms that the biomass was properly gasified.
- Bio-gas was collected at the exit point of the filtering section. The sample collected was subjected to ignition and it ignites in less than 3 seconds meaning the gas higher combustible constituents.
- The testing of the gasifier took about 120 minutes for 1kg of the biomass to gasify completely.
- The gasification time, Gasification temperature and ash content were recorded for different levels of moisture content as presented below in the tables.

2.1.5. Determination of biogas fractions using Pascal Manometric Glass tube. Thirty (30) cm^3 of the gas was trapped into the pascal manometry glass tube via the gas regulator. The Pascal manometric glass is already filled with known volume of fractionating reagents mixture which consists of 1M magnesium percolate, 1M sodium hydroxide, 1M barium sulphate and 1M nitric acid. The fractionation uses the redox principle in which the reduction oxidation process will precipitate the fractions of the gases. The % of the gas fractions was gotten using the formula below:

- $\%CH_4 = \frac{a * 76.08}{Volume\ of\ gas\ used}$ where a is the volume of CH_4 gas trap$_p$ed.
- $\%CO_2 = \frac{b * 44.01}{Volume\ of\ gas\ used}$ where b is the volume of CO_2 gas trapped
- $\%H_2S = \frac{c * 43.06}{Volume\ of\ gas\ used}$ Where c is the volume of H_2S gas trapped

Figure 1. Pascal manometric tube used for gas analysis.

2.1.6. Gasification Performance Evaluation

The overall performance of gasification experiment carried out in this downdraft gasifier will be evaluated based on the lower heating value (LHV) of producer gas; the cold gas efficiency (CGE) is a measure of gasifier performance.

- It can be defined as the ratio between the flow of energy in the gas and the energy in the gas and the energy contained within the fuel.
- It is called cold gas efficiency as it does not take into account that the product gas exiting the gasifier is hot.
- The higher the CGE, the better the fuel conversion.

$$\text{Cold Gas Efficiency} = \frac{LHVgas * Vgas}{LHVfuel * Mfuel} * 100\% \quad \text{……………………..} \quad (3)$$

Where: η_{CG} = cold gas efficiency %

LHV_{gas}= lower heating value of the product gas ($MJ/m^3{}_n$)

V_{gas} = normal volume flow of gas ($m^3{}_n/s$)

LHV_{fuel} = lower heating value of the gasifier solid fuel (MJ/kg)

M_{fuel} = solid fuel flow (kg/s)

2.1.7. Experimental Model and Statistical Analysis. A two-way analysis of variance method (with interaction) was used to analyze the data obtained from the experiment using statistical package for social science (SPSS). The methodology was chosen because it fits the form of data to be collected – two factors. The first factor is the Biomass with three levels; wood chips, saw dust and bean chaff. The second factor is the Moisture content with three levels; 10%, 20% and 30% moisture content level. The experiment was replicated twice to aid the use of the analysis of variance method. The main idea is to determine if percentage of moisture content present in a biomass and the biomass types have any significant effect on three measures of gasification; Ash content, Gasification time, Gasification temperature, and to also determine if there is any interaction effect among the dependent variables. Specifically, the three basic hypotheses considered for each of the measures are as follows:

H_0: The biomasses have no significant effect on the gasification measure.

H_0: The moisture content has no significant effect on the gasification measure.

H_0: The interaction between the biomasses and moisture content has no significant effect on the gasification measure.

These hypotheses are rejected if the probability value is significantly less than 0.05 (i.e. p-value < 0.05).

3. Result and Discussion

The completed and assembled downdraft gasifier was loaded with the biomass materials (Saw dust, Wood chips and Bean Chaff). The test was conducted by varying the moisture content of the various biomass materials between 10, 20 and 30% wet basis. The amount of ash left, gasification time and gasification temperature were measured.

3.1. Ash Content at Various Moisture Content levels

IOP Conf. Series: Earth and Environmental Science **445** (2020) 012057 doi:10.1088/1755-1315/445/1/012057

The results presented in Table 3 shows the amount of ash left at various moisture content levels (10, 20 and 30%) when various biomass were used. The initial temperature of the biomass before the gasification was 36^{o} C. Up to the temperature of 200^{o} C only water was driven off the biomass. The pyrolysis took place between 280 to 500^{o} C, tar and gases containing carbon dioxide were observed and collected. Light tars, were also formed when the oxidation temperature was between 500 to 700^{o} C. Table 3 shows the average values of ash content produced from sawdust, wood chips and bean chaff at moisture levels of 10, 20 and 30%. The mass of ash collected after gasifying 1kg each of the biomass.

Table 3. Ash content (kg) obtained after gasification of various biomass used at specified moisture content

Moisture Content %	Saw Dust	Wood chips	Bean chaff
10	± 0.210	± 0.202	± 0.295
20	± 0.457	± 0.290	± 0.228
30	± 0.750	± 0.651	± 0.394

Other statistics: *Standard Deviation(s) = 0.1985, Variance s^2 = 0.0394, Standard error of the mean = 0.0662*

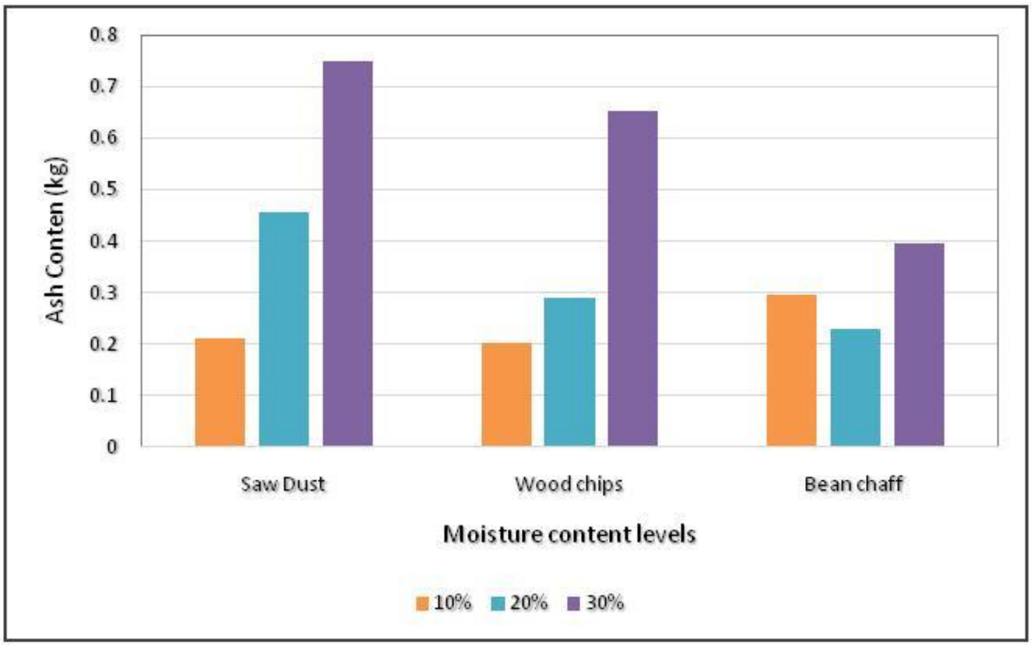

Figure 2. The Graphical representation of the variation in the amount of ash left at various moisture content.

It can observed from Figure 3 that the least ash content was obtained with wood chips at 10% moisture content while the highest ash content was at recorded at sawdust of 30% moisture content. The lower the ash content the better the bio-gas quality and the higher the volume of gas that will be generated. As observed from table 3, increases in moisture content of the saw dust leads to increase in amount of ash generated which affects the efficiency of the gasifier. The wood chips has the least ash content at 10% moisture content while the highest ash content was at 30% moisture content for wood chips, as observed from Table 3, increase in moisture content from 10 – 30% also leads to an increase in the amount of ash generated. However, for the Bean chaff, the least ash content was recorded at 20% moisture content while the highest ash content occurs at 30% moisture content. An increase in moisture of bean chaff from 10-20% leads to a decrease in ash content, but the ash content increases at 30%.

IOP Conf. Series: Earth and Environmental Science **445** (2020) 012057 doi:10.1088/1755-1315/445/1/012057

Table 4 shows the two way ANOVA table where it was revealed that there was no significant different between the ash content obtained for the three biomass types. However, there is a significant different in the ash content with respect to the moisture content. This implies that the ash content was significantly affected by the moisture content rather than biomass types (at P-value < 0.05). The interaction of the biomasses and the moisture content has significant effect on the ash content output.

Table 4. ANOVA table for biomass versus moisture content on ash content

Source	SS	DF	MS	F-statistics	P-value
Corrected Model	224	8	0.28	22.550	0.000
Intercept	1.747	1	1.747	1410.046	0.000
Biomass	0.000	2	0.000	.135	0.876
Moisture	0.179	2	0.090	72.278	0.000
Interaction	0.044	4	0.011	8.894	0.003
Error	0.011	9	0.001		
Total	1.982	18			
Corrected Total	0.235	17			

a. R Squared = .952 (Adjusted R Squared = .910)

SS = Sum of Square, DF = Degree of Freedom, MS = Mean of Squares

3.2. Effect of Moisture Content and Biomass Types on Gasification Time

The gasification time is the time it takes for complete biomass gasification to occur. The average gasification time for different biomass types at various moisture levels are as presented in table 5.

Table 5. Average Gasification time (minutes) obtained after gasification of various biomass used at specified moisture content

Moisture Content %	Saw Dust	Wood chips	Bean chaff
10	± 62	± 67	± 61
20	± 71	± 106	± 55
30	± 95	± 123	± 89

Other Statistics: *Standard Deviation(s) = 23.4041, Variance,* s^2 *= 547.75, Standard error of the Mean = 7.801*

We can infer from Table 5 and visualize from Figure 4 that the wood chips with 30% moisture content level has the highest average gasification time (123 minutes), while the saw dust with 10% moisture content has the lowest average gasification time (62 minutes). We can infer from this progression that the higher the moisture the longer it takes the biomass to gasify. It will take a longer time for drying to occur due to the amount of water present in the biomass. The woods chips as shown above in the chart have the highest average gasification time at 30% moisture level. The wood chips at 30% has the highest average gasification time among the three biomass used for testing. The higher the moisture content, the higher the average gasification time. The bean chaff has its lowest gasification time at moisture content of 20% as it does not follow the progression of saw dust and wood chips. The grain size and bulk density which is lower helps the bean chaff to burn faster.

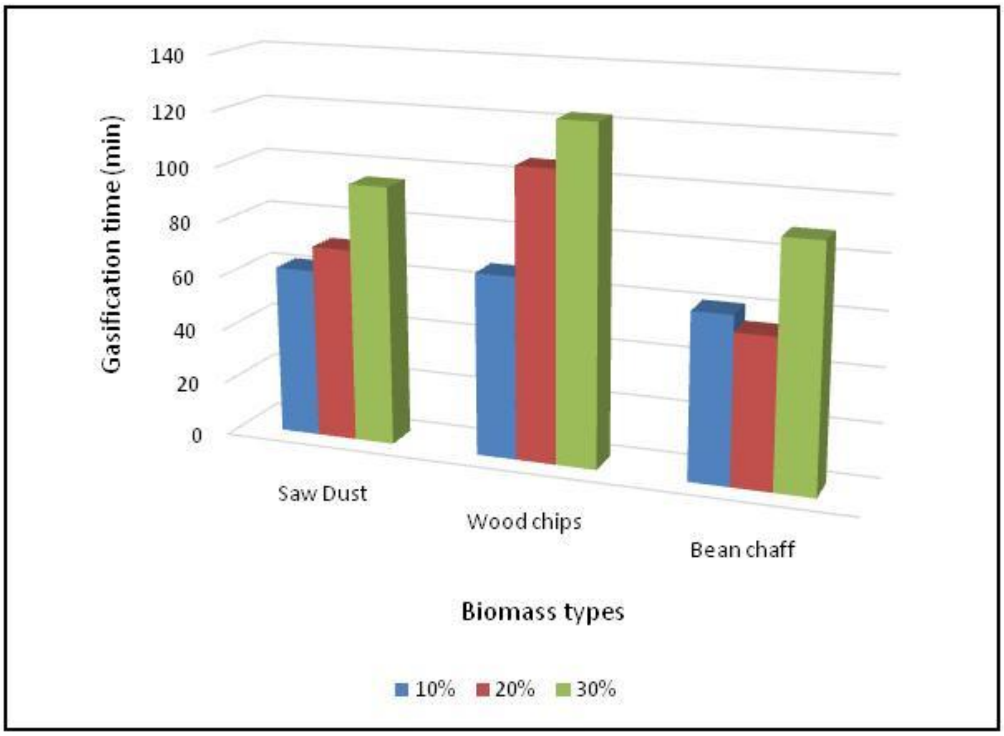

Figure 3. The Graphical representation of the variation in the amount of ash left at various moisture content.

Table 6 shows the two way ANOVA table where it was revealed that there was a significant different in the gasification time with respect to the moisture content and the biomasses used. This implies that the gasification time was significantly affected by the moisture content and the biomasses (at P-value < 0.05). However, there was no significant effect from the interaction of both on the gasification time. A pairwise comparison shows that, the beans chaff and saw dust were not significant different from each other but significantly different from the wood chips effect.

Table 6. ANOVA table for biomass versus moisture content on Gasification Time

Source	SS	DF	MS	F-statistics	P-value
Corrected Model	8703.000[a]	8	1087.875	9.737	.001
Intercept	117612.500	1	117612.500	1052.723	.000
Biomass	2985.333	2	1492.667	13.361	.002
Moisture	4634.333	2	2317.167	20.740	.000
Interaction	1083.333	4	270.833	2.424	.124
Error	1005.500	9	111.722		
Total	127321.000	18			
Corrected Total	9708.500	17			

a. R Squared = .896 (Adjusted R Squared = .804)
SS = Sum of Square, DF = Degree of Freedom, MS = Mean of Squares

3.3. Effect of moisture content and biomass types on Gasification temperatures

Table 7. Gasification temperatures (degree Celsius) obtained after gasification of various biomasses

Moisture Content%	Saw Dust	Wood chips	Bean Chaff
10	± 725	± 787	± 857

20	± 650	± 695	± 780
30	± 645	± 650	± 540

Other Statistics: Standard Deviation(s) = 99.136, Variance (s^2)= 08727.844, Standard error of the Mean = 33.045

Gasification temperature is another factor observed during the experimentation. Table 7 shows the average oxidation temperatures for different biomass at the moisture content levels of 10%, 20% and 30%. As shown in the Figure 5, the average oxidation temperature for saw dust was at the highest level at moisture content 10%. The average oxidation temperature for 20 and 30% moisture level are similar with little temperature difference of 5%. The Temperature reduces as the moisture level increases.

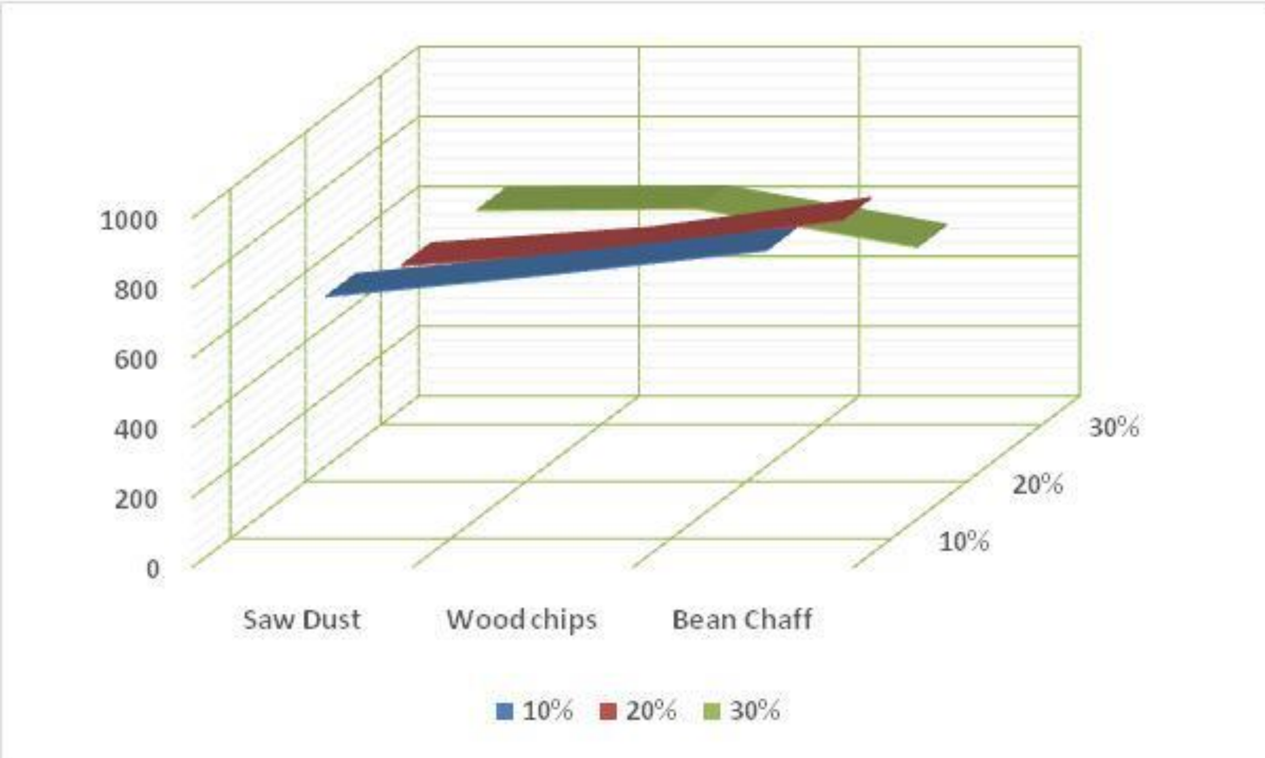

Figure 4. Surface representation of the various oxidation temperatures at various moisture content levels

Also, for the wood chips the average Oxidation temperature is on the lowest level at 30% moisture content and highest at 30% moisture content. The higher the moisture content, the lower the oxidation temperature, more energy goes into the drying out of the moisture from the biomass. The bean chaff recorded the highest average oxidation temperature at moisture content of 10% and this is the highest values among the three biomasses used for the experimentation. The lowest oxidation temperature among wood chips saw dust and bean shaft was recorded at 30% moisture level for bean chaff. The higher the moisture level the lower the oxidation temperature. The bean chaff has the highest oxidation temperature at 10% moisture content followed by wood chips and saw dust recorded the lowest oxidation temperature at 10%. The same trend was observed at 20% moisture content, the beans chaff has the highest oxidation temperature and lowest oxidation temperature for saw dust occurs at 10% moisture level.

Table 8. ANOVA table for biomass versus moisture content on Gasification Temperature

Source	SS	DF	MS	F-statistics	P-value
Corrected Model	145432.000[a]	8	18179.000	7.831	.003
Intercept	8899980.500	1	8899980.500	3833.903	.000
Biomass	8700.333	2	4350.167	1.874	.209

Moisture	95114.333	2	47557.167	20.487	.000
Interaction	41617.333	4	10404.333	4.482	.029
Error	20892.500	9	2321.389		
Total	9066305.000	18			
Corrected Total	166324.500	17			

a. R Squared = .874 (Adjusted R Squared = .763)
SS = Sum of Square, DF = Degree of Freedom, MS = Mean of Squares

From Table 8, the two way ANOVA result shows a significant different between the gasification temperature obtained for the three levels of moisture content and its interaction with the biomasses. However, there was no significant different in the gasification temperature with respect to the biomasses. This implies that the gasification temperature was significantly affected by the moisture content rather than the three biomasses (at P-value < 0.05).

3.4. Component of the Gas Produced

The gas samples obtained during the course of experimentation was trapped into a plastic contained and sealed properly. The sample was taken to the laboratory for chemical analysis and the results obtained are as showed below. The laboratory method used is briefly described below and the data obtained as presented in the Table 9. Two replicates of the laboratory analysis were carried out. The Pascal manometric glass tube method was used to determine the gas component and the percentage proportion. The different biogas composition as analyzed from the laboratory is as presented in Table 9. The composition consist of Methane gas (CH_4), Hydrogen Sulphide, Carbon-dioxide, Carbon mono-oxide and Hydrogen. The methane has the highest percentage composition out of all the gaseous constituents tested.

Table 9. Component of gas obtained for various biomasses

Gas component (%) at 10% MC	Saw Dust	Wood chips	Beans chaff
CH_4	± 62.33	± 60.85	± 63.94
CO_2	±23.77	± 27.50	± 18.91
H_2S	± 0.87	± 0.44	± 0.58
CO	± 0.58	± 0.35	± 0.41
H_2	± 12.24	± 10.86	± 16.16

The different biogas composition as analyzed from the laboratory is as presented in table 9. The composition consist of Methane gas (CH_4), Hydrogen Sulphide, Carbon-dioxide, Carbon mono-oxide and Hydrogen. Methane has the highest percentage composition out of all the gaseous constituents tested.

4. Conclusion

This study focused on the effect of three biomasses at three moisture content levels on gasification process and the quality of the gas that will be generated at different moisture content levels. The moisture content was varied on the selected biomass types and the effect of the variation of biomass moisture content on parameters like gasification time, gasification temperature and amount of ash were studied. The effect of the moisture content was significantly observed on the three gasification parameters considered.Heat loss was experienced during the experiment, thus, lagging of the spacing between the internal cylinder and external cylinder of the reactor chamber to minimize the heat loss. Biomass feeding mechanism should also be looked into in the future research work so as to ensure proper feeding of the biomass into the system.

Conflict of Interest

Authors declare that there are no conflicts of interest whatsoever. All authors agrees to this submission

Acknowledgements

The authors appreciates the efforts of our laboratory staff who contributed to the success of this research

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