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Investigation of the Combustion Properties of Bio-Coal Briquette Blends of *Prosopis Africana* Pods

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Abstract:

This study investigated the properties of bio-coal briquettes made by blending coal with Prosopis Africana pods in order to determine the optimum biomass composition. The briquettes were produced using a hydraulic press at 10 MPa applied to coal: biomass compositions of 100:0, 80:20, 60:40, 40:60, 20:80 and 0:100% by weight of mixture and particle size of 600 µm. Cassava starch and Calcium Hydroxide acted as binder and desulphurization agent respectively. The physical, mechanical and combustion characteristics of the briquette samples produced were determined based on ASTM standards. Results revealed that bio-coal briquettes from produced Prosopis Africana pods can serve as an alternative energy source for heating and cooking applications in Nigeria. The results of analysing data from the physical, ultimate and proximate properties of the produced briquettes indicated that the optimum biomass composition for producing briquettes from coal and Prosopis Africana pods is 40% as its taps into the superior combustion characteristics of both the coal sample and biomass sample.

Keywords: *Bio-coal briquettes, Biomass composition, Blends, Combustion properties, Proposis Africana.*

Introduction

Energy is fundamental to the quality of human life since human activities are totally dependent on its supply. It is a key ingredient in all sectors of modern economies. Due to population increase and economic development, energy demand will increase significantly in the future. How then can this huge energy requirement be satisfied in an environmentally friendly way?

The Nigerian energy industry is probably one of the most inefficient in meeting the needs of its customers. The use of kerosene and gas for cooking and domestic heating is very expensive and the common man in Nigeria cannot afford it. For decades, most people in rural Nigeria have relied solely on firewood for their energy needs. Continual exploitation of fuel wood used in domestic heating applications would lead to deforestation, which has environmental implications.

This has drawn attention to the need for an urgent transition to a more sustainable energy system that would be affordable and eco-

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friendly. Many research are on-going on the prospects of using agricultural residue and other biomass for the production of solid fuels called briquettes, which would serve as substitutes to the depleting non-renewable energy sources (Efomah and Gbabo, 2015). To improve the quality of biomass briquettes, biomass is blended with other materials with high fixed carbon content such as coal. Recent studies has reported that combination of coal and biomass (bio-coal briquette) increased the burning properties. During combustion the low ignition temperature of the biomass simultaneously combusts with the coal and the combined combustion of both gives a favorable ignition and combustion properties that emits less smoke (Anggraeni et al., 2021; Usaka et al., 2019; Onuegbu et al., 2012).

Previous research works on the use of coal and biomass wastes such as sawdust (Adekunle et al., 2015), groundnut shell and maize cob (Onuegbu et al., 2012), cassava stalk (Ikelle et al., 2017), melon shell (Oyelaran and Tudunwada, 2015), rice husk (Ikelle et al., 2014), sesame seed stalk, (Guusu et al., 2021) have shown tremendous potentials in using these materials for the production of industrial and domestic fuels. However, the production of bio-coal briquette using *Prosopis Africana* waste has not been reported in literature. The main purpose of this study is to investigate the properties of bio-coal briquette that will be produced using *Prosopis Africana* waste at different biomass concentrations in order to determine the optimum biomass composition using sub-bituminous coal.

Materials and Method

This study was conducted in Joseph Sarwuan Tarka University Makurdi, in Makurdi Local Government Area of Benue State Nigeria. Makurdi is the capital of the Benue state of Nigeria. The materials/ equipment used for this study includes; Okaba coal sample, Prosopis Africana pods, hydraulic press, mild steel mould, stop watch, cassava starch, hydraulic press, digital weighing balance, water, briquette stove, milling machine, platinum crucible, oven, 600μm standard sieve, cooking pot, thermometer, muffle furnace, meter rule and venier caliper.

Sample Collection and Preparation

The coal sample used in this experimental study was obtained from Okaba deposit (Sub-bituminous Coal) in Kogi State, Nigeria. The biomass sample used in this experimental study is the pods of *Prosopis Africana* which was collected at local farms, markets and dump sites in Makurdi local government in Benue State, Nigeria. The collected coal and biomass samples were screened of impurities and sun dried to reduce the moisture content after which they were pulverized to obtain particle size reduction. The pulverized coal and biomass samples were passed through laboratory test sieves to achieve a uniform particle size of 0.600 mm.

Briquette Samples Preparation

The pulverized coal sample was blended at different biomass composition of 0%, 20%, 40%, 60%, 80%, and 100 %. The binder used in this experimental study was cassava starch, while calcium hydroxide acted as the desulphurizing agent. For each concentration, 5% calcium hydroxide based on the entire mass of coal was added as desulphurizing agent and 20% cassava starch based on the entire mass of mixture was used as binder for all samples (Kaliyan and Morey 2009; Guusu, 2021; Adekunle, 2015). The choice of cassava starch binder was due to its easy availability and cost effectiveness. Literature studies recommended composition of 20% or more for biological binders.

The briquettes were formed in a cylindrical mold with an inner diameter of 47.33 mm, a height of 83.26 mm. The different concentrations were loaded into the cylindrical mold and were compressed at pressure value of 10 MPa using a manually operated hydraulic press at room temperature. The formed briquettes were extruded and labeled. Table 1 shows the nomenclature of the samples.

Table 1. Briquette Samples Percentage Composition of Coal and Biomass

Briquette Sample	Coal Composition (%)	Biomass Composition (%)
A	100	0
B	80	20
C	60	40
D	40	60
E	20	80
F	0	100

Proximate analysis

Proximate analysis which involves the determination of moisture content, volatile matter, fixed carbon and ash content of the briquette samples was determined based on the American Society of Testing and Materials (ASTM) specifications using muffle furnace and platinum crucible.

Moisture content

2g of the briquette sample was kept in oven at 105 ºC for one hour. Then the oven dried sample was weighed, and moisture content of sample calculated by using following formula:

$$MC = \frac{W_2 - W_3}{W_2 - W_1} \times 100 \quad (1)$$

W_1 = Weight of crucible

W_2 = Weight of crucible and sample

W_3 = Weight of crucible and sample, after drying

Volatile matter

2g of briquette sample in a crucible was placed in the oven until a constant weight was obtained after which the briquettes were kept in the furnace at a temperature of 550°C for 10 minutes and weighed after cooling. The volatile matter was determined using the formula below:

$$VM = \frac{B - C}{B} \times 100 \quad (2)$$

B = the weight of oven dried sample.

C = the weight of sample after 10 minutes in the furnace at 550°C.

Ash content

To determine the ash content, 2g of the briquette sample was weighed in a crucible and placed in the furnace for 4hra to obtain the ash weight. The ash content (AC) was calculated as:

$$AC = \frac{weight\ of\ ash}{original\ weight\ of\ sample} \times 100 \quad (3)$$

Fixed carbon

The fixed carbon (FC) was calculated by subtracting the sum of the moisture content (MC), volatile matter (VM) and ash content (AC) from 100.

$$PFC = 100 - (MC + VM + AC) \quad (4)$$

Ultimate analysis

Ultimate analysis which involves the determination of carbon and hydrogen, nitrogen, Sulphur and ash in the briquette sample was also determined based on the American Society of Testing and Materials (ASTM) standards at Pedagogic consulting, Ayodele Fanoiki Street, Lagos. Percentage carbon and hydrogen were determined using a platinum crucible and a furnace. 2g of sample was weighed into platinum crucible and placed in a Leibig – Pregled chamber containing magnesium percolate and sodium hydroxide. The sample was burnt off to produce carbon oxide hydroxide and water. The CO_2 was absorbed by sodium hydroxide while water was absorbed by magnesium percolate. The amount of water and carbon dioxide were calculated by difference.

$$\%\ C = \frac{a \times 0.2727}{Wt\ of\ sample} \times 100 \quad (5)$$

$$\% H = \frac{b \times 0.1117}{Wt\ of\ sample} \times 100 \quad (6)$$

Where $a = quantity\ of\ CO_2\ b = quantity\ of\ H_2O$

The percentage nitrogen was analyzed by the Kjeldahl method. This consists of three techniques of analysis namely Digestion, Distillation and Titration. 0.5g of each finely ground dried sample was weighed carefully into the Kjeldahl digestion tubes to ensure that all sample material got to bottom of the tubes. To this were added 1 Kjeldahl catalyst tablet and 10ml of conc. H_2SO_4. These were set in the appropriate hole of the Digestion Block Heaters in a fume cupboard. The digestion was left on for 4 hours, after which a clear colourless solution was left in the tube. The digest was cooled and carefully transfer into 100ml volumetric flask, thoroughly rinsing the digestion tube with distilled water and the flask was made up to mark with distilled water.

The distillation was done with Markham Distillation Apparatus which allows volatile substances such as ammonia to be steam distilled with complete collection of the distillate. The apparatus was steamed out for about ten minutes. The steam generator is then removed from the heat source to allow the developing vacuum to remove condensed water. The steam generator is then placed on the heat source (i.e., heating mantle) and each component of the apparatus was fixed up approximately.

5ml portion of the digest above was pipette into the body of the apparatus via the small funnel aperture. To this was added 5ml of 40% (W/V) NaOH through the same opening with the 5ml pipette. The mixture was steam-distilled for 2 minutes into 50ml conical flask containing 10ml of 2% Boric Acid plus mixed indicator solution placed at the receiving tip of the condenser. The Boric Acid plus indicator solution changes colour from red to green showing that all the ammonia liberated have been trapped. The green colour solution obtained was then titrated against 0.01N HCL contained in a 50ml Burette.

At the end point or equivalent point, the green colour turns to wine colour which indicates that all the Nitrogen trapped as Ammonium Borate $(NH_4)_2BO_3$ have been removed as Ammonium chloride (NH_4Cl).

The percentage nitrogen in this analysis was calculated using the formula:

$$\% N = \frac{(VH_2SO_4 \times NH_2SO_4) - (VBK \times NNaOH) - (VNaOH \times NNaOH)}{1.4007 \times W} \quad (7)$$

VH_2SO_4 = mL standard H_2SO_4 pipetted into flask for sample,

VNaOH = mL standard NaOH used to titrate sample,

NH_2SO_4 = Normality of H_2SO_4,

NNaOH = Normality of NaOH,

VBK = mL standard NaOH used to titrate 1ml standard H_2SO_4 minus B,

B = mL standard NaOH used to titrate reagent blank distilled into H_2SO_4

1.4007 = milliequivalent weight of nitrogen x100

W = sample weight.

For percentage Sulphur content, 1 g of the pulverized sample was mixed with 3 g of a mixture of magnesium oxide and anhydrous sodium carbonate in ratio 2:1. The mixture was heated to 400℃ for two hours in a muffle furnace, after which it was cooled and digested in water. Barium chloride was added to precipitate the sulphate as barium sulphate. The Barium sulphate precipitate was filtered, and the amount of Sulphur was determined using equation below.

$$\% Sulphur = \frac{weight\ of\ BaSO_4\ ppt \times 0.1373}{weight\ of\ sample} \times 100\% \quad (8)$$

The percentage oxygen content of the briquettes was determined using the formula.

$$\%\ O = 100\% - (C + S + N + H + ash)\%$$

Where C, H, S, N, O and ash are the carbon, hydrogen, Sulphur, nitrogen, oxygen and ash content of the briquettes respectively.

Calorific Value Determination

Calorific value was determined using a Gallenkamp Ballistic Bomb Calorimeter in accordance with American Society of Testing and Materials (ASTM) standards at Pedagogic consulting, Ayodele Fanoiki Street, Lagos. 0.25g of each briquette sample was weighed into the steel capsule. A 10cm cotton thread was attached to the thermocouple to touch the capsule. The bomb was closed and charged in with oxygen up to 30 atm. The bomb was fixed up by depression the ignite switch to burn the sample in an excess of oxygen. The maximum temperature rise in the bomb was measured with the thermocouple and galvanometer system. The rise in temperature was compared with that obtained for 0.25g of Benzoic value of each sample was determined by the following stepwise calculations:

Calculations

Mass of Benzoic Acid $= W_1$

Calorific value of 1gm Benzoic Acid $= 6.32\ kcal/g$

Heat released from Benzoic Acid $= 6.32 \times W_1\ kcal$

Galvonometer deflection without sample $= T_1$

Galvonometer deflection of Benzoic Acid $= T_2 - T_1$

$$\text{Calibration constant} = \frac{6.32 \times W_1}{T_2 - T_1} = y$$

The standardizing is repeated five times and average value calculated for y.

Mass of sample $= 0.25g$

Galvonometer deflection with sample $= T_3$

Galvonometer deflection of sample $= T_3 - T_1$

Heat released from sample$= (T_3 - T_1)y\ kcal$

$$\text{Calorific value of sample} = \frac{(T_3 - T_1)y}{0.25}\ kcal/g \quad (9)$$

Performance Test

The water boiling test using the briquette samples was carried out at the metallurgy and materials laboratory, Mechanical Engineering, Joseph Sarwuan Tarka University Makurdi. The test was done to obtain and compare ignition time, burning rate and water boiling time of each briquette samples that was produced. Each briquette sample was ignited at the base with a cigarette lighter in a drought free place. The time required for the flame to ignite the briquette was recorded as the ignition time using stopwatch. Water boiling test was carried out to compare the cooking efficiency of the briquettes. It measured the time taken for each set of briquettes to boil an equal volume of water under similar conditions.100g of each briquette sample was used to boil 100cm^3 of water using small stainless cup and domestic briquette stove. During this test, the burning rate of the briquettes was determined as the ratio of the mass of the briquette (in grams) burned to the total time (in minute) taken.

Results and Discussion

The result obtained for the various analyses are presented in Table 2 to 4. Moisture content refers to the quantity of water contained in the briquette. Moisture content is a very important property which can greatly affect the burning characteristics of briquette. Low moisture content is desired because less amount of heat energy is wasted in moisture liberation during combustion (Mambo *et al.*, 2017). Figure 1 presents the effect of varying biomass content on the moisture content of the briquette samples. These results revealed that the moisture content values ranged from 5.21 – 8.42 % with the moisture content values increasing with increase in biomass content. According to literature findings, for optimum performance and quality, the range of moisture content is 6 – 8%. At this range of moisture content, the briquettes are strong, free of cracks and the briquetting process is smooth. But at moisture content greater than 10%, the briquettes are poor and weak (Huko *et al.*, 2015). Moisture content values reported in literature includes; 2.35 – 5.72 % for cassava stalk bio-coal briquette, 2.78 – 6.95 % for rice husk bio-coal briquette, 1.03 – 7.11 % for sesame seed stalk bio-coal briquette, 5.87 – 7.36 % for sawdust bio-coal briquette, 6.00 – 10.00 for groundnut shell bio-coal briquette and 7.00 – 8.00 for elephant grass bio-coal briquette.

Ash is the non-combustible component of remaining after a briquette sample is completely burnt. Figure 1 presents the effect of varying biomass content on the moisture content of the briquette samples. The ash content values ranged from 1.81 – 4.31% with the ash content values decreasing with increase in biomass content. These values compare favorably with values of 23.15 - 27.60 % for cassava stalk bio-coal briquette, 16.82 – 22.06 % for rice husk bio-coal briquette, 4.70 - 18.24 % for sesame seed stalk bio-coal briquette, 19.76 – 45.77 % for groundnut shell bio-coal briquette, 6.93 – 18.27 % for melon shell bio-coal briquette, 3.12 – 16.98 % for corn cob bio-coal briquette, and 5.18 – 18.22 % for elephant grass bio-coal briquette. Typically, coal has higher ash content than the biomass. Therefore, increasing the biomass composition will result in a decrease in the ash content, coupled with the fact that $Ca(OH)_2$ was used as desulphurizer. These findings are consistent with several bio-coal briquette studies such as Onuegbu *et al.*, (2010); Adekunle, (2015); Oyelaran & Tudunwada, (2015); Ikelle & Ogah (2017); Estiaty *et al.,* (2018).

Volatile matter values of the briquette samples produced range from 28.97 – 65.87%. The amount of volatile matter indicates whether fuel would produce smoke or not when burning, low volatile matter values are desired in solid fuels, typically biomass exhibits high volatile matter values (Efomah and Gbabo, 2015). For this study, it was observed that the volatile matter values increased with increase in biomass content as seen in Table 2. Fixed carbon is the solid combustible residue that remains after a briquette sample is heated to expel moisture and volatile matter. For this study, the fixed carbon values range from 23.90 – 61.52%. It was observed that, the fixed carbon values decreased with increase in biomass content.

Table 2. Proximate Analysis Result of Briquette Samples

Sample	Moisture Content (%)	Volatile Matter (%)	Ash Content (%)	Fixed Carbon (%)
A	5.21	28.97	4.31	61.52
B	5.58	34.48	4.05	55.88
C	6.04	38.81	3.77	51.38
D	6.70	50.38	3.15	39.78
E	7.13	55.09	2.57	35.21
F	8.42	65.87	1.81	23.9

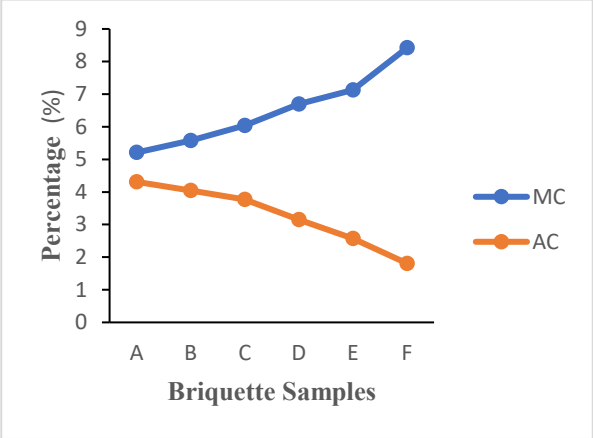


Figure 1. Moisture and Ash Content of the Briquette Samples

The percentage carbon values for this study ranged from 10.50 – 78.20% and its value decreased with increase in biomass content as shown in Table 3. This can be attributed to the effect of the lower carbon content of the biomass (10.50%). The percentage hydrogen values for this study ranged from 2.13 – 7.50% and its value decreased with increase in biomass content as shown in Table 3. This can be attributed to the effect of the lower hydrogen content of the biomass (2.13%). The percentage nitrogen values for this study ranged from 3.60 – 13.20% and its value increased with increase in biomass content as shown in Table 3. This can be attributed to the effect of the higher nitrogen content of the biomass compared to coal. The percentage Sulphur values for this study ranged from 0.20 – 0.80% and its value decreased with increase in biomass content shown in Figure 2. This can be attributed to the effect of the lower Sulphur content of the biomass compared to coal. Lower Sulphur content is desirable. These findings are consistent with several bio-coal briquette studies such as Guusu et al., (2021); Adekunle et al., (2015), Ikelle et al., (2014) and Oyelaran and Tudunwada (2015) .Percentage Sulphur values reported by Oyelaran and Tudunwada (2015) for melon shell bio-coal briquette varied between 0.34 – 0.72 %, sawdust bio-coal briquette varied between 0.4 – 0.6 % (Adekunle et al., 2015), elephant grass bio-coal briquette varied between 0.2 - 0.82 % (Onuegbu et al., 2010), rice husk bio-coal briquette varied between 3.45 – 6.21 % (Ikelle et al., 2014) and sesame seed stalk bio-coal briquette varied between 0.36 – 0.42 % (Guusu et al., 2021). The percentage oxygen values for this study ranged from 9.90 – 73.97% and its value increased with increase in biomass content shown in Table 3. This can be attributed to the effect of the higher oxygen content of the biomass compared to coal.

Table 3. Ultimate Analysis Result of Briquette Samples

Sample	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Sulphur (%)	Oxygen (%)
A	78.20	7.50	3.60	0.80	9.90
B	66.50	6.30	5.40	0.70	21.10
C	53.70	5.40	7.60	0.60	32.70
D	40.20	4.10	9.20	0.50	46.00
E	28.70	3.50	11.10	0.40	56.30
F	10.50	2.13	13.20	0.20	73.97

Calorific value determines the energy content of the briquette samples, and its values depends on the briquette's chemical composition and moisture content (Oyelaran & Tudunwada, 2015). The calorific value for the briquette samples as shown in Table 4 reveals that the briquettes can produce enough heat required for household cooking and small-scale industrial cottage applications as the values range from 16.25 to 23.25 MJ/kg. Calorific values reported by Adekunle et al., (2015) for sawdust bio-coal briquette varied between 17.68 – 33.30 MJ/kg,

rice husk bio-coal briquette varied between 9.00 – 16.40 MJ/kg (Ikelle et al., 2014), elephant grass bio-coal briquette varied between 15.98 – 20.39 MJ/kg (Onuegbu et al., 2010), corn cob bio-coal briquette varied between 8.25 – 15.69 MJ/kg (Ikelle and Ogah, 2014), cassava stalk bio-coal briquette varied between 22.50 – 25.40 MJ/kg (Ikelle et al., 2017), groundnut shell bio-coal briquette varied between 8.85 – 14.85 MJ/kg (Oji and Monday, 2017) and sesame seed stalk bio-coal briquette varied between 19.98 – 24.17 MJ/kg (Guusu et al., 2021). Results also revealed that the calorific value of the briquette samples decreased with increase in biomass content as shown in Figure 3. This is because of the lower calorific value of the biomass compared to coal.

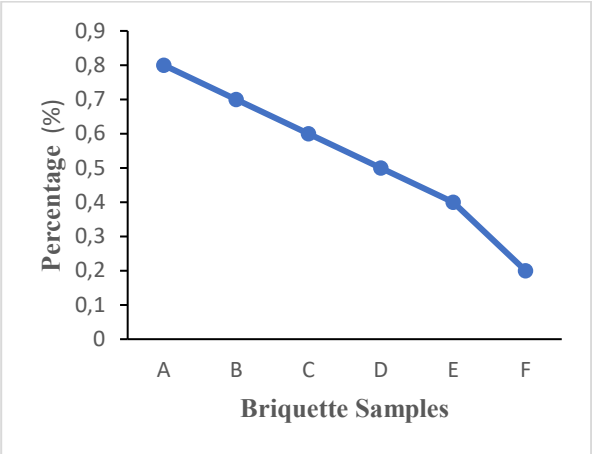


Figure 2. Percentage Sulphur of the Briquette Samples

Table 4. Combustion Properties of Briquette Samples

Sample	Ignition Time (sec)	Burning Rate (g/min)	Water Boiling time (min)	Calorific Value (MJ/kg)
A	217	1.39	8.99	23.25
B	191	1.85	8.08	21.12
C	168	2.49	7.55	18.90
D	149	2.66	6.13	18.27
E	127	3.12	5.58	17.02
F	103	3.56	5.38	16.25

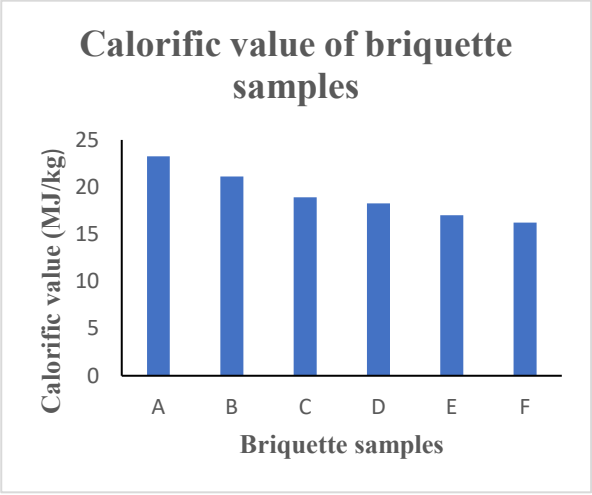


Figure 3. Calorific Value of Briquette Samples

A combustible material should be easily ignitable particularly for household purpose, thus; lower ignition time values are preferred. Ignition time was taken as the average time taken to achieve steady glowing flame. From table 4, ignition time values range from 60.00 to 240.00 seconds with the value decreasing with increase in biomass content due to its high volatile matter. Ignition time values reported by Ikelle et al., (2014) for rice husk bio-coal briquette varied between 23.33 – 46.22 seconds, elephant grass bio-coal briquette varied between 19.20 – 186 seconds (Onuegbu et al., 2010), corn cob bio-coal briquette varied between 27.20 – 37.00 seconds (Ikelle and Ogah, 2014), cassava stalk bio-coal briquette varied between 21.19 – 46.22 seconds (Ikelle et al., 2017), melon shell bio-coal briquette varied between 32.00 – 68.00 seconds (Oyelaran and Tudunwada, 2015) and sesame seed stalk bio-coal briquette varied between 52 – 114 seconds (Guusu et al., 2021).

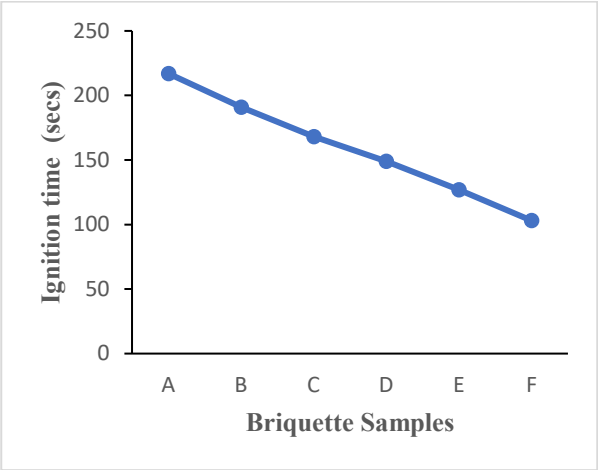


Figure 4. Ignition Time of Briquette Samples

Burning rate refers to the amount of briquette mass that is consumed per unit time during combustion (the rate at which the briquette releases its energy). It is dependent on the chemical composition and geometry of the material (Adekunle, 2015). In this study, burning rate values range from 1.08 g/min to 5.85 g/min with its value increasing with increase in biomass content as shown in Figure 16. This increase is due to the high volatile matter possessed by the biomass.

Experimental results showed that the time required for briquette samples to boil an equal volume of water ranged from 4.25 to 10.97 minutes with its value decreasing with increase in biomass content as shown in Figure 18. 44. Adekunle, (2015) explained that boiling time is dependent on two factors: burning rate (how fast the fuel burns) and calorific value (how much heat is released). Water boiling time values reported by Ikelle et al., (2014) for rice husk bio-coal briquette varied between 1.42 – 4.12 minutes, elephant grass bio-coal briquette varied between 1.57 – 3.65 seconds (Onuegbu et al., 2010), corn cob bio-coal briquette varied between 1.63 – 4.57 minutes (Ikelle and Ogah, 2014), cassava stalk bio-coal briquette varied between 1.56 – 4.94 minutes (Ikelle et al., 2017), groundnut shell bio-coal briquette varied between 8.00 – 12.00 minutes (Oji and Monday, 2017) and sesame seed stalk bio-coal briquette varied between 6.15 – 6.38 minutes (Guusu et al., 2021).

Conclusion

This experimental study focused on the effect of variable biomass composition on the properties of bio-coal briquette produced *Prosopis Africana* pods. Results revealed that bio-coal briquettes from produced *Prosopis Africana* pods can serve as an alternative energy source, which can be used for heating and cooking applications in Nigeria. Results showed that increase in biomass composition increased the moisture content, volatile matter, burning rate and reduced the density, ignition time, ash content, Sulphur content, water boiling time and calorific value of the briquette samples. Based on this study, bio-coal briquette produced from biomass composition of 40% had overall superior combustion characteristics.

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