Performance Evaluation of Bio-Coal Briquette Produced From Soybean Stalks

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ABSTRACT
The performance evaluation of bio-coal briquettes of various compositions using coal and soybean stalks was carried out. Cassava starch was used as binding agent while calcium hydroxide was used as a desulphurizing agent. The samples of coal and soybean stalks were pulverized separately and blended in proportions of 100:0, 80:20, 60:40, 40:60, 20:80, 0:100 % by weight respectively, and densified at 10MPa and 60s dwell time in molds to produce the briquettes with the first and last compositions being controls. The physical properties, combustion analysis, proximate and ultimate analyses were carried to ascertain the composition of the bio-coal briquettes with the best performance. The results showed that briquette with coal to soybean stalks composition of 60:40% had an average energy value of about 21 MJ/kg which is sufficient to produce heat required for household cooking and small-scale industrial applications. It also had better ignition time, burning time and water boiling test, and would potentially have less adverse effect on the environment. It therefore have good potentials for deployment as eco-friendly alternative fuel for domestic heating application and small industries. Furthermore, the adoption of the production of this fuel for massive application will be a great opportunity for implementation of United Nation's waste-to-wealth drive while greatly impacting on disposal strategies.
Keywords: Bio-coal, Briquette, Soybean stalk, Calorific value, Proximate analysis, Performance evaluation
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INTRODUCTION

Energy is extremely vital to economic growth and development, national and regional environmental protection. These concerns that lead to sustainable development based on equity, empowerment, environmental harmony and economic efficiency can be tackled through the effective production and optimization of energy in a sound environmental manner. Production of renewable sources of energy is natural over a given period of time. They are widely available and accessible even in huge quantity and the cleanest source of energy obtainable on this planet. One if the most important sources of renewable energy Biomass. Non-renewable energy sources like nuclear, coal, , oil and natural gas are available in limited or finite supply and cannot be restored within a short period of time. They are rapidly depleting. They are however not ecologically friendly [1-3]. There is need for alternate sources of energy due to increasing global energy demand, and continuous growth in population. Biomass is plant or animal based organic material, which includes dedicated energy crops, agricultural crops and trees, wood residues, food, feed and fiber crop residues, agricultural waste, aquatic plants, algae, forestry and, processing by-products and other non-fossil organic matter [4-6].

Over 140 billion metric tons of biomass is generated globally, every year from agriculture [7-10]. Enormous amount of energy and raw materials equivalent of approximately 50 billion tons of oil are produced from this bulk of biomass materials. Fossil fuel can be substantially replaced by agricultural biomass waste, if converted to energy it can reduce emissions of greenhouse gases and provide renewable energy to some 1.6 billion people in developing countries, which still lack access to electricity [11]. Organic biomass materials waste are important resource exist in form of residual stalks, straws, leaves, roots, husks, nut or seed shells, waste wood and animal husbandry wastes. Widely available, renewable, and virtually free, [12].

Supply of efficient, adequate, reliable energy to both residential and industrial consumers is a major problem facing Nigeria today. This has Unfavorably impacted the social and economic life of the citizenry. Firewood, which is a biomass serves as a main source of cooking fuel to the bulk of households in Nigeria (still about 80%). It is regrettable that Exploitation and supply sources are becoming thinner, further contributing to the three environmental challenges: desertification, erosion and deforestation [13-16]. The need to consider alternative sources of energy for domestic and industrial use in the country is extremely important due decreasing availability of fuel wood, coupled with the ever-rising prices of kerosene and cooking gas in Nigeria which draws attention especially among the dominant rural populace.

Extensive annual pollution of the environment in Nigeria are due to deposition of huge quantities of agro-residues that are burnt or allowed to decompose or used uneconomically. Amongst the major residues are groundnut shells, cotton, rice husk, , corn and sorghum stalks. Also available in huge quantity is sawdust, a milling residue. A wide spectrum of health effects ranging from eye irritation to death is associated with the direct burning of loose biomass which also results to very low thermal efficiency and widespread atmospheric pollution, which is apart from the problems of storage, handling, and transportation [17, 18]. Due to these setbacks associated with burning of biomass, it becomes imperative to develop strategies of converting biomass to secondary fuels with better combustion characteristics than the parent materials [18].

One of the abundant fossil fuel resources that occurs in several areas in Nigeria with direct combustion posing adverse effects on the environment is Coal. This ranges from bituminous to lignite. Coal are of different varieties and their classifications are extremely important in deciding their suitable applications. A rebirth of interest in coal and how it can be used without its harmful environmental impact and its accompanying health hazards was enacted due to quest by nations to produce efficient and reliable energy for manufacturing and domestic uses. [19, 20]. One option to be used in reducing the energy crisis in Nigeria is to explore the indigenous coal reserves, which are in abundance but poorly harnessed. Forest resources and oil reserves currently being depleted, and the need for sustainable energy system has shifted the focus of researchers to a more convenient environmentally-friendly solid fuel known as bio-coal briquettes.

Briquettes are institutional and household fuel resource produced by densification of raw waste organic materials by compressing into moulds which is then dried for some days before being used for heating or cooking. A type of solid fuel produced by compressing pulverized coal, biomass, binder, and sulphur fixation agent is called bio-coal briquette is [21-23]. Instead of being released to the environment as sulphur (IV) oxide, the presence of a sulphur fixation agent (desulfurizing agent) ensures that most of the sulphur content in the coal is fixed into the ash [10]. Ikelle *et al*. [21] stated that during burning, the co-combustion of the coal and the biomass gives better combustion yield and reduces emissions of pollutant. Bio-coal briquettes emit less dust and soot, have promising ignition and better thermal efficiency. The process around this is that, since the component of the biomass briquette ignites at low temperature compare to the coal, this ensures that the volatile matter in the coal which would have otherwise been released as smoke at low combustion temperature combusts completely. The complete combustion of the volatiles materials reduces emission and is part of the total heat released by the fuel as well [23, 24].

The need to develop an alternative energy resource cannot be over emphasized and this is as a result of increased energy consumption. The conflict between the claims for development and creation of an environment which can also be an effective counter to decreasing supply and further improvement in energy mix and effectiveness are resolved the advent of Bio-coal briquettes. The biomass and coal deposits in Nigeria not being currently utilized could be transformed to wealth through its blend to produce bio-coal briquette. Several bio-coal briquetting studies have been carried out on different feedstock of agro-residue in Nigeria, such as spear grass, rice husk, maize comb, groundnut shell, melon shell, elephant grass but the use of soybean stalks for bio-coal briquetting [10, 16, 22, 24].

About 1.2 million tons of soybean is produced annually in Nigeria produces making it a significant stakeholder among the producers of the product on the African continent. Soybean are mostly produced in the middle belt with Benue State accounting for over 70% of the production in Nigeria [25-27].

Consequently, it is important that intensive efforts are made to address local energy problems in Nigeria with the use of bio-coal briquettes in order to extremely reduce the use of fuel wood while finding an effective way of utilizing Nigeria's massive agricultural wastes and the coal deposits in an environmentally friendly way. Pollution problems can be alleviated through the use of raw coal and disposed biomass waste, while reducing dependence on fuel wood and fossil fuel for domestic heating applications by providing an eco-friendly alternative [28-30].

This study will help provide an alternative energy source thereby diversifying the sources of energy in Nigeria, especially in the rural areas, thus creating an energy mix that will accelerate the country's drive towards sustainable development. The production of this bio-coal briquettes utilizes Soybean stalks which are agricultural wastes thereby eliminating waste disposal problem (converting waste to wealth), and also provide the impetus for tapping into the abundant underdeveloped coal reserves in the country. Also, the study will give additional understanding of the variables that will impact the quality, durability and combustion characteristics of bio-coal briquettes. Ultimately, the gathering and treatment of agricultural wastes and commercial production of briquettes could provide the ambience for the Federal Government of Nigeria to engage the teaming population of the youths in these productive activities.

MATERIALS AND METHOD

Briquette production followed the method used by Ikelle *et al*. [21] and Usaka *et al*. [31]. Soybean stalks were collected from farm waste dump sites at Tyodugh, near Joseph Sarwuan Tarka University, Makurdi, Nigeria. The stalks were sun-dried for seven days and pounded in a mortar with a pestle after which they were milled using an electric milling machine. The pulverized samples were then sieved to obtain materials of particle size 1 mm in diameter using an electrically operated sieve shaker (Jinling, Model: 8902-1205-0030). Sub-bituminous coal samples were obtained from Okaba mines in Kogi State, Nigeria. The samples were crushed using a metallic mortar and pestle then grounded to obtaine fine particle sizes of 1 mm using electric milling machine and sieved using standard sieve to obtained 1 mm particle sizes using the sieve shaker. The starch used as binder was bought from a cassava processing plant along Gboko road in Makurdi. It was also sieved to obtain 1 mm particle sizes.

Bio-coal briquettes of different compositions were formulated by blending the coal with Soya beans stalks at ratios of 80:20, 60:40, 40:60, and 20:80. Coal (100:0) and soybeans stalks (0:100) briquettes were separately produced as the controls. About 5 % of calcium hydroxide based on the coal composition in each sample was used as a sulphur fixation agent while 20 % by mass of the starch was used as a binder. This was scooped and hand fed into a cylindrical mold of dimensions 50 × 40 mm. A hydraulic briquette press was used to compact the briquette samples to a pressure of 10 MPa and a dwell time was 60 seconds which was maintained throughout the production. A summary of the production process of the briquettes is shown in Figure 1.

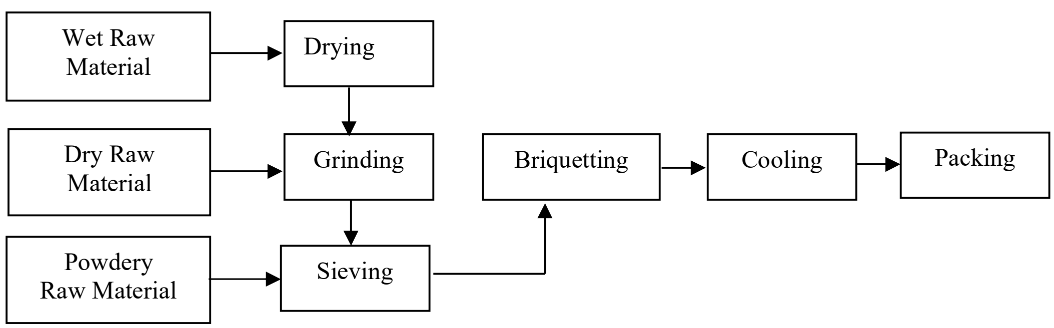

Figure 1: Flow diagram of the Briquette production process

Physical Properties of the Briquettes

An important physical property of a solid fuel is density. In order to make transportation, storage and handling easier, high density briquettes are required. ASTM B311-13 standard was used to determine the bulk density of the briquette. A cylindrically shaped container of 1000 ml (1000 cm^3) volume was used. The container was weighed empty to determine its mass and then it was filled with the sample and weighed again. The bulk density was determined by dividing the mass of the material by the volume of the container. The bulk density was calculated by using the formula:

$$Bulk\ density = \frac{Mass\ of\ briquette\ sample\ (g)}{Volume\ of\ measuring\ cylinder\ (cm^3)} \qquad (2)$$

The level of abrasion was determined using a vibrating sorting machine (Sieve shaker, Jinling, Model: 8902-12050030) with 4×4 mm sieve. The material extracted from the briquettes consisted of 3 pieces with a total weight of around 100-110 g, and the sorting duration was for 5 minutes. The mass of particles falling under the sieve was determined after vibration, and based on these masses, the abrasion was determined using equation 3.

$$A - \frac{m_l}{m_i} \times 100\ (\%) \qquad (3)$$

where A = abrasion (%), m_l = mass of briquettes loss (g), m_i = initial mass of briquettes (g).

Impact resistance index of the briquettes was determined in accordance with ASTM D440-86. Five drops were set as the standard. The briquettes were released from a vertical height of 1.8 m, and allowed to freely fall and impact on a concrete floor. After five drops, the broken pieces of briquettes were collected and weighed using an electronic balance with accuracy of 0.01 g. Only the number of pieces which weighed 5 % or more of the initial weight was recorded for the purpose of calculating the impact resistance index. Impact Resistance Index (IRI) was then computed using equation 4.

$$IRI = \frac{N}{n} \times 100\% \qquad (4)$$

where N =number of drops and n = the number of pieces that weighed 5 % or more of the initial weight of briquette after N drops. Porosity of the briquettes was obtained by first weighing each of the samples (w_1), and submerging them in separate beakers containing 250 ml of water for 5 minutes. The briquettes were then removed from the water and weighed (w_2). The porosity of the briquette was determined based on the amount of water each absorbed. Porosity index was calculated as the ratio of the mass of water absorbed by the samples into the mass of the sample immersed in water.

$$PI - \frac{w_2 - w_1}{w_1} \qquad (5)$$

Compressive strength of briquettes was determined in accordance with ASTM 1037-93 using an Instron Universal Strength testing machine with load cell capacity of 25 kN. The cross-head speed was 0.305 mm/min. A sample of briquette to be tested was placed horizontally in the compression test fixture and a load was applied at a constant rate of 0.305 mm/min until the briquette failed by cracking. The compressive strength in cleft was then computed using equation 6.

$$Compressive\ strength, \sigma = \frac{3F}{l_1 \times l_2 \times l_3} (N/mm^2) \qquad (6)$$

where $l_1,\ l_2\ and\ l_3$ are lengths of briquettes at points one, two and three, respectively (mm)

Combustion Analysis

The combustion analysis was carried out to determine the combustion characteristics of the briquette fuel. The gross calorific value of the samples of the bio-coal was determined in accordance with ASTM Standard E711-87-2012. This was done using an adiabatic bomb calorimeter. About 0.4 g of each sample was burnt in the bomb calorimeter until complete combustion was obtained. The difference between the maximum and minimum temperatures obtained was used to compute the gross calorific values of the biomass materials using equation 7.

$$Q = \frac{(C_{water} + C_{cal})}{W_f} (T_2 \quad T_1) \qquad (7)$$

where Q = Calorific value in species $\left(\frac{kJ}{kg}\right)$, W_f = Weight of the bio coal material sample (kg), C_{cal} = Heat capacity of the bomb calorimeter $(kJ/kg°C)$, $T_2 - T_1$= Rise in temperature $(°C)$, C_{water} = Heat capacity of water $(kJ/kg°C)$.

To ascertain the ignition time, the samples were ignited at the edge of their bases with a Bunsen burner. The time taken for each briquette to ignite was recorded as the ignition time using a stopwatch [21].

This is the time taken for each briquette sample to burn completely to ashes. Subtracting the time it turned to ashes completely from the ignition time gives the burning time [32-34].

$$Burning\ time - Ashing\ time - Ignition\ time \qquad (13)$$

The cooking efficiency of the briquettes were compared using a water boiling test . It measures the time taken for each set of briquettes to boil an equal volume of water under similar conditions. During the process, 100 g of each briquette sample was used to boil 250 ml of water using small stainless cups and a domestic briquette stove [21, 35, 36].

Proximate Analysis

This is a standardized procedure for knowing the bulk components that make up a fuel. The ASTM–D 5142-09 [37] specification was used to determine moisture content, volatile matter, ash content and fixed carbon of the coal used.

A portion 2 g each of the samples was weighed out in a wash glass. The samples were placed in an oven for 2 hours at 105 ºC and up to constant weight loss. The moisture content was determined according to ASTM standard. The loss in weight represents the moisture content.

$$\%MC = \frac{W_1 - W_2}{W_1} \times 100 \qquad (14)$$

where $W_1 = Initial\ weight,\ W_2 = Weight\ after\ drying$

The ash content of the briquettes was also determined using ASTM standard procedures. A portion 2 g were placed in a pre-weighed porcelain crucible and transferred into a preheated muffle furnace set at a temperature of 600 ºC for 1 hour after which the crucible and its contents were transferred to a desiccator and allowed to cool. The crucible and its content were reweighed and the new weight noted. The residual sample in the crucible was heated without lid in the muffle furnace at 700 ± 50°C for one and half hour. The crucible was then taken out, cooled first in air then in desiccators and then it is weighed. This process continues till constant weight is obtained. The residue represents the ash content in percentage.

$$\% AC = \frac{W_2}{W_1} \times 100 \qquad (15)$$

where W_1 = original weight of dry sample, W_2 = weight of ash after cooling.

The volatile matter of the Soybean stalks/Coal briquettes was also determined. A portion 2 g of the sample was heated to about 920 ºC for 10 minutes in a partially closed crucible in a muffle furnace. The crucible and its content were retrieved and cooled first in air then in desiccators. The difference in weight was recorded, the loss in weight represents the percentage volatile matter.

$$\% VM = \frac{W_1 - W_2}{W_1} X\, 100 \qquad (16)$$

where W_1 = Original weight of the sample, W_2 = Weight of sample after cooling.

Percentage fixed carbon (PFC) was determined using the formula according to ASTM standard to be

$$FC = 100 - (\%VM + \%AC + \%MC) \qquad (17)$$

where VM = Volatile matter, AC = Ash content, MC = Moisture content.

Ultimate Analysis

Estimation of important chemical elements that make up biomass, namely carbon, hydrogen, oxygen, nitrogen and sulphur were determined through an ultimate analysis. These properties were determined in accordance with ASTM-D 4239-08 [38] and ASTM-D 5373-08 [39] standards. The oxygen was obtained by subtracting the percentage of ash, carbon, hydrogen, nitrogen and sulphur from 100.

2 g of sample was weighed into platinum crucible and placed in a Leibig – Pregle 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.

$$\% C = \frac{0.2727a}{wt\ of\ sample\ 1} \times 100 \qquad (18)$$

$$\% H = \frac{0.2727b}{wt\ of\ sample\ 1} \times 100 \qquad (19)$$

where a = quantity of CO_2, b = quantity of H_2O.

Sulphur content was determined using ASTM-D 4239-08 standard. 1g weight of the briquette sample was put into a porcelain crucible and mixed with 3.00 g of Eschka mixture. The mixture was then covered with 1.00 g of Eschka mixture. The crucibles were then put in a cold muffle furnace and the gradually heated to 800°C for 60 minutes. Digestion was carried out in hot water for 45 minutes with intermittent stirring. The solution in each beaker was then decanted through a No. 540 Watman filter paper into a 400 ml beaker. 3 drops of methyl orange indicator were added drop wise until the colour turned just neutral. Then, 1 ml of hydrochloric acid was added, after which 25 ml of potassium sulphate solution was also added. The sample was thereafter heated to boiling and 10 ml of 10% barium chloride solution was gradually added while stirring. The solution was boiled for 30 minutes and filtered with No. 42 Watman filter paper after it has cooled down. The trapped residue was washed thoroughly with hot water. The total sulphur content was the calculated using equation 20.

$$\% S = \frac{A - B \times 13.738}{C} \qquad (20)$$

where A = mass of barium sulphate from the Sample, B = mass of barium sulphate from the blank, C = mass of sample.

The percentage oxygen content of the briquette sample was determined by difference as indicated in equation 21.

$$\% O = 100 - \%(C + S + N + ASH) \qquad (21)$$

where C, H, S, N, O and ASH are the carbon, hydrogen, sulphur, nitrogen, oxygen and ash content of the bio-coal briquettes respectively. The % Nitrogen was analyzed by the Kjeldahl method.

The samples were analyzed chemically according to the methods of analysis described by the Association of official Analytical Chemist (A.O.A.C., 18th Edition, 2005). 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 of it got to bottom of the tubes. To this were added 1 Kjeldahl catalyst tablet and 10 ml of concentrated 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 colorless solution was left in the tube. The digest was cooled and carefully transferred into 100 ml 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 10 minutes. The steam generator was then removed from the heat source to allow the developing vacuum to remove condensed water. The steam generator was 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 pipetted into the body of the apparatus via the small funnel aperture. To this was added 5 ml of 40% (W/V) NaOH through the same opening with the 5 ml pipette. The mixture was steam-distilled for 2 minutes into 50 ml 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 50 ml 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:

$$\% N = \frac{(VH_2SO_4 \times NH_2SO_4) - (VBK \times NNaOH) - (VNaOH \times NNaOH)}{1.4007 \times W} \qquad (22)$$

where 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,`NaOH = 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 = milli-equivalent weight of nitrogen ×100, and W = sample weight.

RESULTS AND DISCUSSION

Effect of Composition Ratio on the Physical Properties of the Briquettes

The effect of composition ratio on the physical properties of the briquettes are shown in Figures 2 to 6. For these Figures, 1 to 6 on the horizontal axis represent samples with coal:soybean stalks compositions of 100:0, 80:20, 60:40, 40:60, 20:80 and 0:100 % by weight respectively. Bulk density is a value which gives the weight per volume of solid fuel briquettes, and can help determine their heat content. Figure 2 shows the impact of composition ratio on bulk density of the briquettes. High bulk density is therefore a desirable value [33, 40, 41]. The bulk density of the briquettes ranged between 0.416 g/cm^3 (0:100) and 0.994 g/cm^3 (100:0). As seen in Figure 2 decreasing composition of soybean stalks, decreases the bulk density. The mathematical regression equation for bulk density depends on merging composition of the briquettes with R^2 values of 0.9428. The findings of this work agree with those of Guusu *et al*. [42] in their investigation of the performance of bio-coal briquettes made sesame seed stalks.

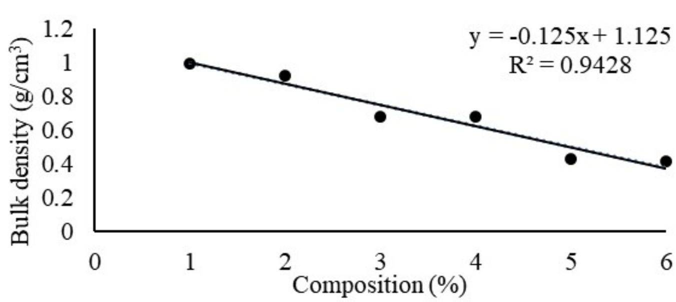

Fig. 2: Effect of Composition Ratio on Bulk Density of the Briquettes

Figure 3 shows the effect of compressive strength composition and ratio on of the briquettes. Compressive strength is the highest crushing weight a briquette can hold before cracking or breaking. The lowest acceptable compressive strength in industry is 0.38 MPa [43-46]. All ratios of the solid fuel briquettes exceeded this standard during compressive strength testing shown in Fig. 3, and hence would not break easily during transport or storage. The compressive strength of the briquettes increased depending on decreasing ratios of soybean stalks from 0.867 MPa to 2.2.07 MPa. The 80:20 ratio of bio-coal briquettes had the highest compressive strength (2.07 MPa). When the strength is increased, the atmospheric humidity in the briquettes is decreased and briquettes durability is increased. The mathematical regression equation for compressive strength depends on blending composition of the briquettes with the R^2 values of 0.99. The findings of this study on compressive strength compared favorably with those of some studies in the literature [17, 42, 47, 48].

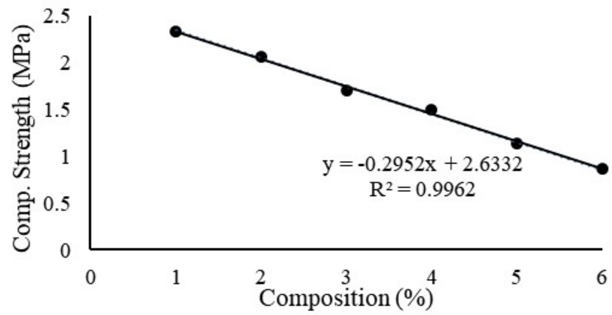

Fig. 3: Effect of Composition on Compressive Strength of the Briquettes

Figure 4 shows the effect of composition ratio on abrasion of the briquettes. Durability is a measure of resistance to shock or abrasion of the compacted fuels due to handling and transportation. . The percentage abrasion of various samples is presented in the Figure. It can be seen that the abrasion resistance of briquettes increased with decreasing percentage of soybean stalks, the range being 2.92% and 5.49%. There was a significance decrease in the values of abrasion resistance. This agrees with the assertion of Ikelle *et al*. [21] in their Study on the Combustion Properties of Bio-Coal Briquette Blends of Cassava Stalk. It further shows the need to obtain better durability and optimal blend of coal and the biomass. [49-51].

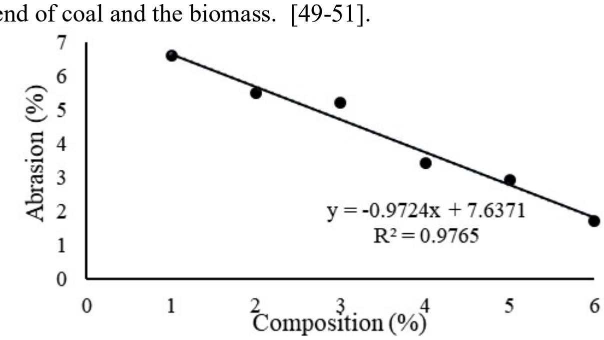

Fig. 4: Effect of Composition Ratio on Abrasion of the Briquettes

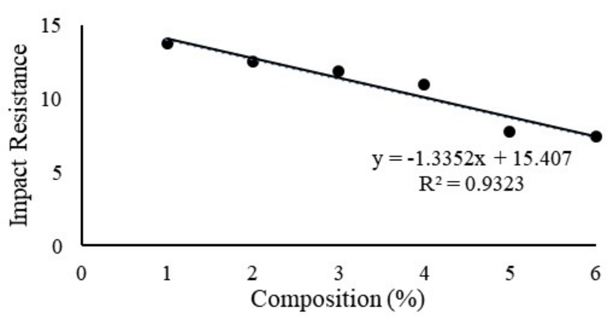

Fig. 5: Effect of Composition Ratio on Impact Resistance of the Briquettes

Impact resistance index of a briquette is a measure of the ability of the briquette to withstand shock load [51, 52]. The impact resistance index of various samples is presented in Figure 5. The impact resistance of the briquettes decreases with increasing percentage of soybean stalks with R^2 values of 0.93. The findings of this study compared favorably with that of Mitchual *et al*. [52] in their study in relating compacting Pressure and Mixing Proportion of Briquettes Produced from Maize Cobs and Sawdus Physico-Mechanical Properties. Hence, the percentage of the biomass must be managed in a way that does not alter the impact resistance [2, 8, 33, 50].

Porosity has influence in transportation and storage. The Porosity of the briquettes are presented in Figure 6. High porosity would result in high compressibility due to plenty of void space. Low porosity of the briquettes which indicates that the void space is less and the briquettes within the given volume is more would result in low compressibility. The result for porosity index showed that briquettes of biomass in which the particles are more adhered to each other will have a lower porosity index values than those with loose particles. Coal dust particles, has less coarse particles than soyabeans stalk as such the briquettes from their mixture will have pores that will improve the passage of oxygen needed for combustion to take place. The higher the porosity, the higher the rate of penetration of oxidant and outflow of combustion and pyrolysis products during combustion, and the higher will be the burning rate of the briquettes [9, 18, 23, 31].

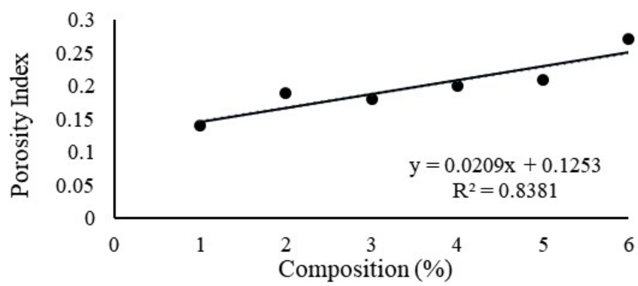

Fig. 6: Effect of Composition Ratio on Porosity Index of the Briquettes

Effect of Composition ratio on Combustion Properties of the Briquettes

Calorific value (CV) is the quantity of heat expended on complete combustion of 1 kg of bio-coal at the reference state of products of combustion according to ASTM [43]. This is the most significant combustion property for defining the suitability of a bio-coal briquette as a fuel. It gives an indication of the quantity of fuel required to generate a specific amount of heat energy. Figure 7 shows that calorific value decreased with increasing ratios of biomass from 100:0% (24 MJ/kg) to 0:100% (18 MJ/kg). Though the calorific value of the bio-coal decreased with increase in soybean stalks concentration, they are still comparable with net calorific value of kerosene put at 37 MJ/kg and wood at 14.6 MJ/kg used for domestic heat applications. The decrease in calorific value may be due to the blending of biomass and the addition of calcium hydroxide, a non-combustible substance and the starch used as binder which does not contribute to the total heat value released [4, 19, 34, 36].

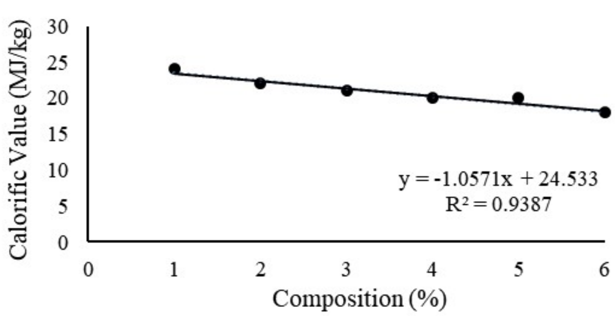

Fig. 7: Effect of Composition Ratio on Calorific Value of the Briquettes

Ignition time is the average time required to ignite the composite briquettes. It is affected by the amount of volatile matter and the surface area of the briquettes exposed to the airflow. The results of ignition time in Figure 8 showed that the ignition time of the briquettes decreases with increase in biomass concentration. This can be explained from the fact that the biomass contains more volatile matter than the coal Therefore, increasing its concentration in the briquette will definitely increase the ignitibility of the briquette. The briquette samples with 100:0 % coal: soybean stalks took the longest time to ignite (91.33 seconds). However, the ignition time dropped progressively with the incorporation of the biomass. The blending of coal and soybean stalks produced briquettes that ignited very fast, thereby solving the slow ignitability problem of coal briquettes. The result of the ignition time tallies with several findings in literature [10, 11, 13, 24].

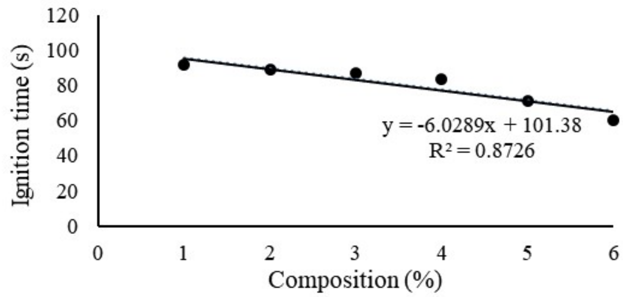

Fig. 8: Effect of Composition Ratio on Ignition Time of the Briquettes

. The burning rate has a significant effect on briquette application. The burning time which is the duration taken to bring a certain amount of water to boiling is influenced by volatile matter, porosity and biomass of the fuel. The performance for the produced briquettes is shown in Figure 9. Briquettes with high burning rates imply that more briquettes will be required in combustion as they burn off readily.

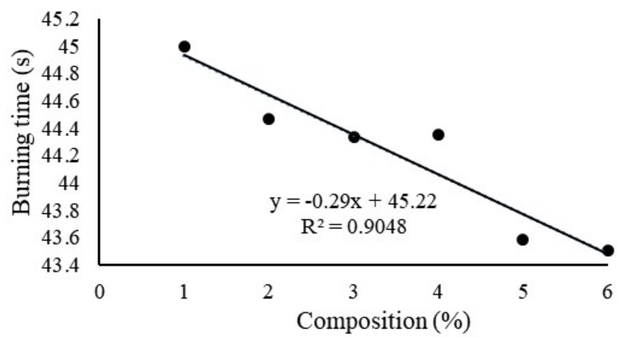

Fig. 9: Effect of Composition Ratio on Burning Time of the Briquettes

The differences in burning time for briquettes of 100% coal and the briquettes of 60% coal and 40% soybean stalks were not much, therefore blending will not only make the briquettes ignite faster but will allow for longer cooking time. Among the factors that control the burning rate of a material are chemical composition and geometry (bulk, packing, orientation) of the material. Biomass contains more volatile matter than the coal and it is more porous which allows for easy infiltration of oxygen and out flow of combustion products [24]. Therefore, increasing the proportion of the biomass is expected to increase the burning rate of the briquettes. The result of the ignition time is agreement with those obtained from some studies [18, 35, 42]. The burning time result revealed that increase in biomass content decreased burning time from 44.47 minutes (80:20%) to 43.58 minutes (20:80%) with R^2 values of 0.9048. This result agrees with several works and underscores the need to strike a useful balance in terms of composition [12, 17, 33, 36].

The results in Figure 10 indicated that biomass reduces the time required for the briquettes to boil a specific quantity of water. Water boiling tests was carried out to compare the cooking efficiency of the bio-coal briquettes of varied biomass composition with a coal briquette. It measures the time required to stimulate cooking as well as other fuel characteristics of the briquettes such as the burning rate and the specific fuel consumption during the boiling phase. The experimental results showed that the time required for briquette samples to boil an equal volume of water ranged from 9.33 to 19.33 minutes with its value decreasing with increase in biomass content as shown in Figure 10. For this study, there was no variation of particle size, pressure or geometry of the briquettes. Adekunle [30] explained that boiling time is dependent on two factors: burning rate (how fast the fuel burns) and calorific value (how much heat is released). Boiling time values in this study compares reasonably with 17 – 30 minutes for waste paper and groundnut shell briquette [10], 8 – 25 minutes for maize cob and groundnut shell bio-coal briquettes [24].

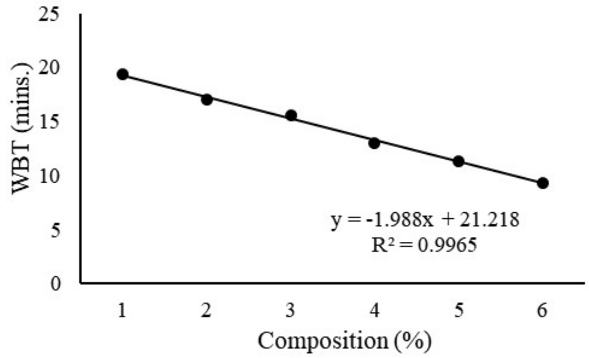

Fig. 10: Effect of Composition Ratio on Water Boiling Time of the Briquettes

Proximate analysis

Figure 11 illustrates the moisture content of the briquettes increased with increasing proportions of soybean stalks. The moisture content of the briquettes ranged between 4.7 and 8.2%. The values are well within the range of moisture content reported in the above literatures. Moisture content is mainly affected by the feed stock species and its properties. Experiments show that when the moisture content of material is 6 ~ 14%, the adhesive effect is best and the briquettes produced have the best quality. When the moisture content is lower than 6% or higher than 14 %, particles of feed stock are not consistent and briquette is tended to fall into pieces. The proximate analysis show that moisture content values increased with the amount of soybean stalks, and the samples with 100% of this component had the highest value. This is because soybean stalk is coarser than coal. The results also showed that the briquetting of coal and soybean stalks reduces the moisture content of the briquettes. For a composition of 60:40 % and 40:60 % coal:soybean stalks, the results of 7.42 and 7.48 % is considered efficient. The tolerance level of moisture content for briquettes is between 7 and 12% depending on the nature of the feed [17, 42, 50]. The moisture content of the briquette above tolerance level lowers its thermal efficiency as well as its burning rate. Consequently, more energy will be used to exhume the moisture. The briquettes in this study remain solid for a long period of time before losing their shape due to the low moisture content [2, 31, 41].

Ash content of bio-briquette of 100:0% has lowest ash content of 6.02%, while 0:100% briquettes has a highest value of 6.419%. The low ash content in this study as observed Figures 11 reflects the high specific heat of combustion/heating value which is an indication that the briquette does not contain high mineral (non-combustible) matters. As posited by Sotannde *et al.* [49], ash content normally causes an increase in the combustion remnant, thereby lowering the heating effect. The low ash content as observed in this study corroborates the findings of Akowuah *et al.* [3], Adetogun *et al.* [40] and Sotannde *et al.* [49] who reported low ash contents of 2.6%, 1.06% to 1.23% and 3.50% to 5.75% respectively. Lower ash content is an indication of good quality briquette, as the ash content of briquettes produced in this study is around the acceptable 4 ± 2 % tolerance level of ash content for fuel [21]. Higher ash content in a fuel usually leads to higher dust emissions, air pollution, and affects the combustion volume and efficiency of combustion. The low ash content of the briquettes is a reflection of high specific heat of combustion/heating value which is an indication that the briquettes do not contain high mineral (non-combustible) matters [48].

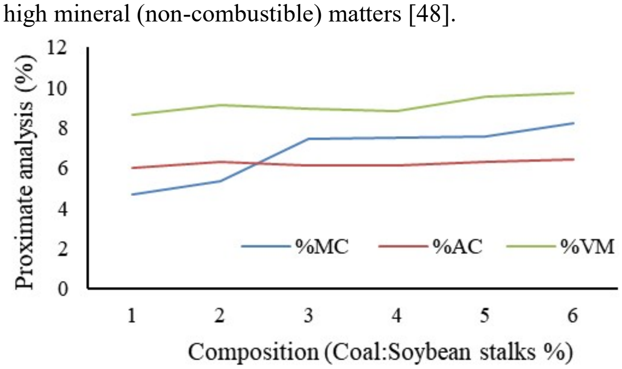

Fig. 11: Effect of Composition Ratio on Percentage Moisture content, Ash content and Volatile matter of the Briquettes

Volatile matter is a mixture of short- and long-chain hydrocarbons such as combustible or incombustible gases or combination of both released during burning [50-52]. These gases strongly affect the combustion behavior of briquettes [11]. Lower volatile matter is an indication that the briquettes might not be easy to ignite, but once ignited they will burn smoothly, while high volatile matter results in high combustibility at low ash content [6]. Volatile matter contains the composition of methane, hydrocarbons, hydrogen and carbon monoxide, and incombustible gases like carbon dioxide and nitrogen, that means volatile matter could demonstrate high ease of ignition bio-briquettes or vice versa. The particles of soya beans stalk are less bonded to each than coal particles, 100% soybean stalks briquettes generated more volatile matter upon heating than 100% coal briquettes. To reduce the volatile matter and make the briquettes more suitable for combustion, the composition of coal and soybean stalks were varied to produce briquettes with optimum quality. This agrees with the findings of Onukak *et al.* [9].

Essentially, the fixed carbon of a fuel is the percentage of carbon available for char combustion. Fixed carbon gives an indication of the proportion of char that remains after volatile matter is distilled off. It gives a rough estimate of the heating value of a fuel and acts as the main heat generator during burning [3]. The percentage of fixed carbon content in briquettes is a critical factor that influences the calorific value of fuel.

The fixed carbon content of briquettes produced as shown in Figures 12 (77.07% to 78.96%) is close to the high values obtained by Sotannde *et al.* [49], ranging between 85.25% and 85.95%. They reported that it is expected that the high fixed carbon and smokeless flame will enhance the heat value and combustion duration of briquette. A good quality and efficient fuel briquette is dependent on lower volatile matter and ash content with a higher fixed carbon content [16]. The results of this study strongly agrees with this observation.

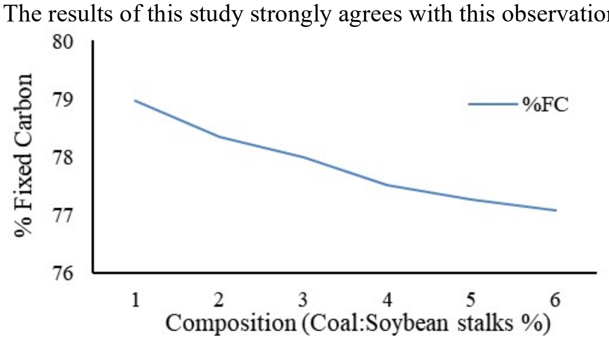

Fig. 12: Effect of Composition on Fixed Carbon of the Briquettes

Ultimate Analysis

Figures 13 and 14 show the ultimate analysis of the raw materials. It can be seen that the carbon contents are high in all the compositions with 52.13% (100:0 %) to 45.89% (0:100 %). The higher the carbon content, the higher is the calorific value and the better the quality of the bio-coal briquette [19]. The carbon contents of the bio-coal briquettes are adequately high for them to be good fuel for domestic heat applications. The composition of the ash-free organic component of bio-coal is relatively uniform. The major components are carbon 52.13% to 45.89%; oxygen 41.2% to 42.96% and hydrogen 4.59% to 5.21%. The results also showed a small proportion of nitrogen (0.52% to 0.92%) and sulphur (0.03% to 0.15%). Since the Sulphur and Nitrogen in the bio-coal briquettes are low (all below 1%), it will be better as fuel because it will emit less sulphur dioxide and nitrogen to the atmosphere which pose adverse health challenges. These results are consistent with findings of Ikelle *et al*. [21] and Guusu *et al*. [42], respectively.

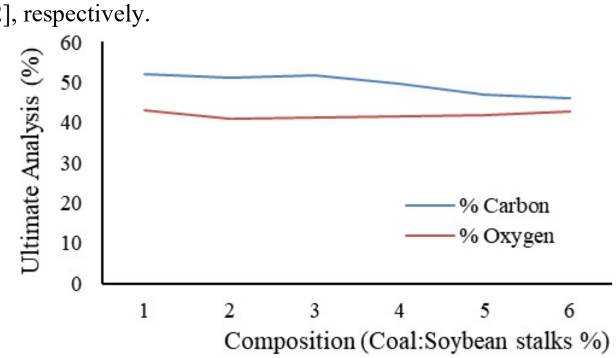

Fig. 13: Effect of Composition Ratio on Percentage Carbon and Oxygen of the Briquettes

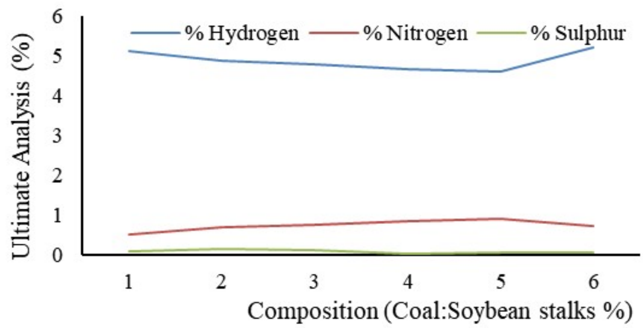

Fig. 14: Effect of Composition Ratio on Percentage Hydrogen, Nitrogen and Sulphur of the Briquettes

CONCLUSION AND RECOMMENDATION

This work examined the physical, proximate, and ultimate and combustion characteristics of briquettes produced from coal and soybean stalks. Based on the findings, the sample with 60% coal and 40% soybean stalks yielded satisfactory characteristics of solid fuels and would make good bio-coal briquettes. Though the general performance of all the blends points to the potentials of bio-coal utilization, this sample stood out in all the parameters investigated. They will potentially be durable, have negligible adverse impact on the environment and paramountly, better combination characteristics if implemented as an option for rural home heating and small scale industrial applications. Moreover, it will provide a good waste to wealth outlet while directly contributing to environmental cleanliness. Based on the findings of this work, further work will be carried out focusing only on solutions and methods to improve the water resistance properties of bio-coal briquettes will be useful for taking into consideration of alternative fuel. Also, the investigation of the combustion behavior of the hybrid fossil fuel-biomass briquettes in various reactors (for example, for household heating), free combustion as well as controlled combustion and emissions resulting from free combustion (especially SO_2 emissions) will be the right decision.

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