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Investigation of some Properties of Bio-coal Briquettes Produced using Beniseed (*Sesame seed*) Stalks as Biomass

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Authors' contributions

This work was carried out in collaboration among all authors. Author HIG designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors JSI and AOE managed the analyses of the study. Author AOE managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

This study evaluated the properties of bio-coal briquettes made by blending coal with beniseed (*sesame seed*) stalks in order to determine the optimum composition. The briquettes were produced using a hydraulic compression machine at 5, 10 and 15 bar 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 sizes of 212, 300 and 600 µm. The physical, ultimate and proximate properties of the briquettes were then measured and analyzed. The results indicated that the optimum composition for producing the briquettes lies between 60:40% and 40:60%. These ranges of composition of briquettes had the lowest ignition time of 57.6s, highest percentage volatile matter of 42.7% and low percentage sulphur content of 0.38%. Furthermore, the 40:60% briquettes had the highest mean calorific value of 26.67 MJ/kg. These indicate good potentials for briquettes using coal and beniseed stalks as an alternative energy source while contributing to a friendly environment and wealth generation.

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1. INTRODUCTION

Energy is one of the crucial inputs for socio-economic development. Energy is not the only prime agent for the generation of wealth but a significant factor in economic development and the driving force for industrialization of any society [1]. Energy availability, supply and consumption are very important indicators of technological and socio-economic development of any nation, playing a vital role in synergizing the three pillars of sustainability (economy, social and environment). Sustainable energy development involves exploitation, processing and utilization of energy resources to meets human needs in an environmentally friendly way [2,3].

Sustainable development of energy sources is very important for developing countries like Nigeria. The ever-increasing consumption of fossil fuels resulting in overdependence, and rapid depletion of reserves are of serious concern in the country. Rising prices of Kerosene and cooking gas, and seasonal and potential future shortages lead to concerns about energy supply security required to sustain economic growth and household utilization. This has led to continual need to consider alternative sources of energy for domestic and industrial use in the country. A challenging task facing Nigeria, like other developing countries, is finding a means of expanding its energy services especially to the rural households while addressing the health and environmental consequences of over dependence on fuelwood for cooking [4]. About 80% of Nigerians living in the rural or semi-urban areas depend solely on fuel wood for their energy needs. About 90% of the total wood demand from the forest goes into fuel wood. Annual fuel wood consumption in Nigeria reached about 43 10^9 kg before 2010 and it is rapidly increasing [5].

Annually, Nigeria produces agro-residues that are burnt or allowed to decompose or used inefficiently causing significant pollution of the environment. Apart from the problems of transportation, storage and handling, the direct burning of loose biomass is associated with very low thermal efficiency and air pollution, resulting in a wide spectrum of adverse health effects ranging from eye irritation to death from respiratory complications [6].

Nigeria still relies heavily on traditional sources of energy to meet its domestic energy demand resulting in health and environmental implications. Among the available energy resources in Nigeria, coal and coal derivatives (smokeless coal briquettes, bio-coal briquettes, and biomass briquettes) have been shown to have high potential for use as suitable alternative to coal/fuel wood in industrial boilers and brick kilns for thermal application and domestic purposes [7,8].

Briquettes are flammable materials formed by compression or densification of matter in solid form to improve handling and enhance volumetric calorific value to be used as fuel [9-13]. Common types of briquettes in use are coal briquettes, charcoal briquettes, and biomass briquettes. Recent studies have shown that blending coal and biomass gives bio-coal briquettes which have better combustion properties and less harmful emissions compared to raw coal briquettes and fuelwood [7,14-22]. A bio-coal briquette is agglomerated by compacting pulverized coal, biomass, binder and a desulphurizer [23,24]. The high pressure involved in the process ensures that the coal and the biomass bind together which eases transportation and storage. The presence of a desulphurizer ensures that most of the sulphur content of the coal is fixed into the ash instead of being liberated into the atmosphere as sulphur (IV) oxide.

In Nigeria, several bio-coal briquette studies have been carried out using agro-residue such as rice husk, maize cob, groundnut shell, melon shell, spear grass, elephant grass, sawdust, etc. but non-existent on the use of beniseed stalk [7,14,15,17,25]. Nigeria is the seventh largest producer in Africa, producing about 300,000 tons of beniseed with the largest producing states being Jigawa, Nassarawa, Benue and Taraba [26]. Nigerian farmers on the average generate about 2 tons/hectare of beniseed stalks post-harvest, and with an average of about 330000 hectares cultivated annually, Nigeria has the potential of generating 660000 tons of beniseed stalk annually. Beniseed stalk has average calorific value of 4152 kcal/kg (17.39 MJ/kg) [27], while Okaba coal has heating value of 25.74 MJ/kg [28-30]. Blending beniseed stalk with coal is expected to improve the calorific value of the briquettes.

In this study, the combustion characteristics of bio-coal briquettes made from beniseed stalks at different concentrations with Okaba coal in order to determine the optimum biomass composition and also evaluate the performance were examined. The main objective was to investigate some properties of the bio-coal briquettes. Specifically, the study determined the optimum conditions for producing the briquettes and the influence of processing and material variables such as particle size, composition and compression pressure on the physical, mechanical and combustion characteristics of the briquettes. The scope of this study was limited to the collection of coal samples from the Okaba coal mine site in Kogi State and beniseed stalks from local farms around Makurdi, blending of the coal and biomass to produce briquettes at different compositions as well as carrying out the evaluation of physical, mechanical and combustion characteristics of the briquettes. The study provided better understanding of the variables that would influence the quality, durability and combustion characteristics of the bio-coal briquettes. It is hope that the results will contribute towards the reduction of the dependence on fuel wood and petroleum derivatives for domestic heating applications, contribute to solid waste reduction by converting the biomass to household fuel and by extension, contribute to the protection of forest reserves, mitigate health hazards faced from use of smoky fuels for domestic application.

2. MATERIALS AND METHODS

Most of the equipment was obtained from the Metallurgy and Materials Laboratory at Federal University of Agriculture, Makurdi and National Center for Energy Research and Development, Nsukka. The coal samples used were obtained from Okaba deposit (Sub-bituminous Coal) in Kogi State, Nigeria. The samples were sun-dried for 7 days to reduce the moisture content to about 15% and increase grindability. The beniseed stalks used were collected from local farms around Makurdi, Benue State, Nigeria. The biomass sample was screened of impurities and then sun-dried for 7 days to reduce the moisture content also to about 15%. The samples were then weighed each day of drying until a constant weight was achieved, and then crushed, pulverized and screened to particle sizes of 212, 300 and 600 μm. The binder used was cassava starch, while calcium hydroxide was the desulphurizing agent used with both obtained from the open market.

Preparatory for briquetting, the pulverized coal samples were blended with the biomass at different composition ratios of 0, 20, 40, 60, 80 and 100%. For each concentration, 5% calcium hydroxide based on the entire mass of coal was added as desulphurizing agent and 10% cassava starch based on the entire mass of mixture was used as binder for all the samples according to the method used by Adekunle [16]. The mixture at different concentrations were loaded into a mold measuring 40×40×40 mm and compressed using a hydraulic compression machine. The bio-coal, biomass and coal briquettes were produced separately under briquetting pressures of 5, 10 and 15 MPa exerted using a hydraulic press and then placed in an open space for drying to enhance solidification. The drying was continued until the briquettes attained a constant weight. 54 samples were selected for the study depending on the composition of coal, composition of biomass, particle size and compaction pressure. Fig. 1 shows samples of the briquettes produced. The samples are shown based on the parameters in Table 1. For convenience however, mean values of the properties were systematically computed in two ways to obtain 18 and 6 samples for analysis as shown in Tables 2 and 3 respectively.

The physical and mechanical properties of the samples were then measured beginning with the bulk density. Density is an important physical property of a solid fuel. High density briquettes are desirable in order to make transportation, storage and handling easier. The bulk density of the briquette samples produced was determined using the geometric measurement method [31]. The length (l), width (w) and height (h) of the cube briquettes were measured using a meter rule and Vernier calipers to calculate Volume ($v = lwh$), the mass (m) of the sample was measured and then bulk density (BD) determined using the equation 1.

$$BD = m / lwh \qquad (1)$$

Fig. 1. Samples of the Briquettes produced

Table 1. Samples prepared for the study

Sample	Composition Coal:Biomass (%)	Particle Size (µm)	Compaction Pressure (MPa)	Sample	Composition Coal: Biomass (%)	Particle Size (µm)	Compaction Pressure (MPa)
A15	100:0	212	5	D15	40:60	212	5
A110		212	10	D110		212	10
A115		300	15	D115		300	15
A25		300	5	D25		300	5
A210		300	10	D210		300	10
A215		600	15	D215		600	15
A35		600	5	D35		600	5
A310		600	10	D310		600	10
A315		212	15	D315		212	15
B15	80:20	212	5	E15	20:80	212	5
B110		212	10	E110		212	10
B115		300	15	E115		300	15
B25		300	5	E25		300	5
B210		300	10	E210		300	10
B215		600	15	E215		600	15
B35		600	5	E35		600	5
B310		600	10	E310		600	10
B315		212	15	E315		212	15
C15	60:40	212	5	F15	0:100	212	5
C110		212	10	F110		212	10
C115		300	15	F115		300	15
C25		300	5	F25		300	5
C210		300	10	F210		300	10
C215		600	15	F215		600	15
C35		600	5	F35		600	5
C310		600	10	F310		600	10
C315		212	15	F315		212	15

Table 2. Coding of Samples for mean properties

Code	Mean of samples
A212	A15, A110 and A115
A300	A25, A210 and A215
A600	A35, A310 and A315
B212	B15, B110 and B115
B300	B25, B210 and B215
B600	B35, B310 and B315
C212	C15, C110 and C115
C300	C25, C210 and C215
C600	C35, C310 and C315
D212	D15, D110 and D115
D300	D25, D210 and D215
D600	D35, D310 and D315
E212	E15, E110 and E115
E300	E25, E210 and E215
E600	E35, E310 and E315
F212	F15, F110 and F115
F300	F25, F210 and F215
F600	F35, F310 and F315

The abrasion test is a method of testing the quality and durability of a solid fuel. The abrasion resistance index was determined using a method adopted by Lunguleasa [32]. In this method, 3 briquettes were subjected to vibration in a 3 mm sieve for a period of 5 minutes after weighing on an electronic balance, with an accuracy of two decimal places. During this period briquettes were agitated over the grid, and the friction that occurs between them and the sieve and the side walls causes generation of dust particle due to abrasion. After 5 mins, the device was stopped and the quantity of dust obtained was weighed and recorded with respect to the original mass of briquette. The set-up is shown in Fig. 2. In this way, the degree of durability for wooden briquettes is obtained which is a performance indicator for quality of briquettes. A smaller index indicates better durability. To determine this indicator equation 2 was used.

$$A = (m_1 / m_i) \times 100\% \qquad (2)$$

where A = abrasion (%), m_1= mass of briquettes loss (g) and m_i= initial mass of briquettes (g).

Table 3. Coding for samples for mean properties based on composition of biomass

Code	Mean of all samples produced with
A0:100	0% composition of beniseed stalk.
B20:80	20% composition of beniseed stalk.
C40:60	40% composition of beniseed stalk.
D60:40	60% composition of beniseed stalk.
E80:20	80% composition of beniseed stalk.
F100:0	100% composition of beniseed stalk.

Fig. 2. Set up for abrasion resistance index determination

The Compressive strength of the 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 Proximate Analysis of the samples was conducted starting with the moisture content. The percentage moisture content on dry basis, MC, was determined using standard CEN/TS 14774. 3 g of briquette sample was oven dried at 105°C until a constant mass was obtained. The change in weight D after 16–18 hours was then used to determine the sample's MC using equation 3.

$$MC = (D / E) \times 100\% \quad (3)$$

where MC is the percentage moisture content, D is change in weight, and E is the initial weight before drying.

The percentage ash content AC was determined using standard CEN/TS 14775. 2 g of the briquette was heated in a furnace at 450°C for 1 hour and weighed after cooling to get the weight of the ash (C). The AC was determined using equation 4.

$$PAC = (C / A) \times 100 \quad (4)$$

where PAC is the percentage ash content, C is the weight after cooling, and A is the weight of the oven-dried sample.

Water resistance was done according to a method used by Rotimi and Davis [33]. In this method, for each biomass composition one briquette sample was selected for different particle sizes and pressure variations. One briquette was immersed in a clear container of tap water at 27ºC for 120 s. The percentage of water gain was calculated using equation 5.

$$\text{Percentage water gained} = ((w_1 - w_2) / w_1) \times 100 \quad (5)$$

Water Resistance Capacity = 100 - % water gained, where, w_1 = initial weight of briquette and w_2 = final weight of briquette.

The percentage volatile matter was determined by keeping 2 g of fragmented briquettes in an oven for a period of 2 hours at a temperature of 110ºC to obtain a constant weight (w_1) after the fragmented briquettes were cooled, it was then kept in a crucible and placed in a furnace for 10 minutes at 550ºC to obtain weight (w_2) [34]. The percentage volatile matter was determined using equation 6.

$$VM = ((w_1 - w_2) / w_1) \times 100 \quad (6)$$

where w_1 is weight after oven drying, w_2 is the weight after heating in furnace for 10 minutes.

The percentage fixed carbon (FC) was computed by subtracting the sum of VM, AC and MC from 100 as shown in equation 7.

$$\text{Fixed Carbon} = 100\% - (VM – AC – MC) \quad (7)$$

Simple water boiling tests using the briquette samples were carried out in the Metallurgy and materials laboratory, University of Agriculture, Makurdi. Briquettes weighing about 150 g were stacked into an energy efficient stove and about 6 to 7 (20 g approximately) dried wood sticks were placed on the pan below and sprinkled with about 10 ml of kerosene to initiate the combustion. It was then lit. Once the briquettes were seen to burn independently after starting the fire, the ignition time was recorded and the pan holding the wood sticks was withdrawn. The briquettes were then allowed to assume steady state combustion. 100 ml of water was put in a pre-weighed stainless-steel pot and the initial temperature of the water was recorded using a mercury thermometer before placing it on the burning stove. The test was conducted at atmospheric pressure. The subsequent changes in temperature up to boiling point were recorded at 2-minute intervals using the thermometer inserted in the opened pot. At the boiling point, the pot was removed from the stove and the fire was immediately put off with the aid of dry sand. The time taken for each set of briquettes to boil 100 ml of water was recorded.

The calorific values of the samples were determined using the Association of official Analytical Chemists (AOAC), 2002 method. This was done with bomb calorimeter (model XRY-1A, made in China). The procedure is outlined below. The outside canister was filled with water which was stirred to obtain an average temperature before the experiment. 3000 g or 3 l of distilled water were then put into the inner canister and their combined weight measured. Each time the bomb was removed from the inner canister, distilled water was added to compensate for the loss due to bomb removal. This is achieved by placing the inner canister bucket on a balance and adding water gradually until the weight reaches the standard (bucket + 3 l of water). The sample to be evaluated is then put in a mold (and compress if it is in powder form) and then weighed in grams.

Two ends of the ignition thread are then fixed on two electrodes and made to have good contact with the sample. 10 ml of distilled water was then put into the oxygen bomb and screw down the cover, and oxygen filled into the bomb at a pressure of 2.8 - 3.0 MPa. The oxygen bomb was then placed onto the clamp in the inner canister. The necessary connections were then made and the temperature sensor inserted into the inner canister. The “power” and “stir” buttons were then put on. The water was allowed to stir for about 2 minutes or until the temperature stabilizes which is noted as the initial temperature of water (T_o).

The “fire” button was then activated and the instrument automatically measured and saved the required data. The required testing time to finish the experiment was about 31s, and the final temperature of the water (T_f) was noted. The stirring was then stopped and the temperature sensor removed and the lid opened. The bomb was removed and the oxygen released before opening the bomb. The length/mass of the unburned firing wire was then measured. If some of the sample remained not burnt, the experiment failed. The inner lining of oxygen bomb and crucible were then washed using 100 ml of distilled water. 2 drops of methyl red indicator were then added and titration with 0.0709M sodium carbonate (prepared by dissolving 3.76 g sodium carbonate in water and diluting to 1 liter) was carried out. The consumed volume, V of alkali was then recorded. Equation 8 was used to compute the energy.

$$\text{Energy (kJ / kg)} = E\Delta T - \Phi - V \quad (8)$$

where g = Weight of sample, E = Energy equivalent of the calorimeter per °C, ΔT = Change in temperature, Φ = Correction for heat of combustion of firing wire and V= Volume of alkali used during titration.

The ultimate analysis of the samples beginning with the carbon content was then carried out. The Walkey-Black, 1934 method was used to determine the carbon content. 1 g of the finely ground sample was weighed into a 500 ml conical flask. 10 ml of 1M potassium dichromate was poured into the flask and the mixture was swirled. 20 ml of concentrated H_2SO_4 was added and the flask was swirled again for 1 minute in a fume cupboard. The mixture was allowed to cool for 30 minutes after which 200 ml of distilled water, 1g NaF and 1 ml of diphenylamine indicator were added. The mixture was swirled and titrated with ferrous ammonium sulphate. The blank was also treated in the same way. Equation 9 was then used to compute the percentage carbon content.

$$\text{\% Carbon} = (B - T \times M \times 1.33 \times 0.003 \times 100) / g \quad (9)$$

where B = Titration volume (Blank), T = Titration volume (Sample) and M = Molarity of Fe solution.

The Nitrogen/Crude Protein Determination was done using the micro-Kjedahl method as described in Pearson (1976). This method involves the estimation of the total nitrogen in the waste and the conversion of the nitrogen to protein with the assumption that all the protein in the waste is present as nitrogen. Using a conversion factor of 6.25, the actual percentage of protein in the waste was calculated using equation 10.

$$\text{\% Crude Protein} = \text{\% Nitrogen} \times 6.25 \quad (10)$$

The digestion of the sample was carried out in a Micro-Kjedahl digestion flask (500 ml capacity), Model Fk 500/3I in conjunction with an Ohaus weighing balance (0.001 g accuracy, model AR3130). The reagents used were catalyst mixture (20 g potassium sulphate, 1 g copper sulphate and 0.1 g selenium powder), and concentrated tetraoxosulphate (VI) acid. 1 g of the ground sample was weighed into the Kjedahl digestion flask. 1g of the catalyst mixture was weighed and added into the flask. 15 ml of the acid was also added. Heating was carried out cautiously on a digestion rack in a fume cupboard until a greenish clear solution appeared. The digest was allowed to clear for about 30 minutes. It was further heated for another 30 minutes and allowed to cool. 10 ml of distilled water was added to avoid caking. The digest was then transferred with several washings into a 100 ml volumetric flask and made up to the mark with distilled water.

Distillation was carried out using a micro Kjedahl distillation unit (model 734205) 100 ml conical flask (Receiver flask). The reagents used were 40% NaOH, and Boric acid indicator solution. A 10 ml aliquot was collected from the digest and put in the flask. A 100 ml receiver flask containing 5 ml boric acid indicator solution was placed under the condenser of the distillation apparatus so that the tip was 2 cm inside the indicator. 10 ml of 40% NaOH solution was added to the digested sample through a funnel stop cork. The distillation commenced by closing the steam jet arm of the distillation apparatus. The distillate was collected in the receiver flask (35 ml). The titration was carried out with 0.01M standard HCl to first pink colour. The ammonia generated was collected in excess boric acid. After complete ammonia distillation, the ammonium borate solution is titrated with a standard HCl solution. The strong acid (HCl) displaces weak boric acid from its salt. 1 mole of ammonia is equivalent to 1 mole of ammonium borate which is equivalent to 1 mole of HCl. Knowing the amount of 0.01 M HCl used for the titration, the amount of ammonia bound to borate can be calculated. From this amount, the quantity of nitrogen in the sample can be calculated.

The Sulphur content was determined using the Eschka Method. 1 g of the pulverized sample was mixed with 3 g of a mixture of magnesium oxide and anhydrous sodium carbonate in the ratio of 2:1. The mixture was heated to 400ºC for 2 hours in a muffle furnace, and then cooled and digested in water. Barium chloride was then added to precipitate the sulphate as barium sulphate. The precipitate was then filtered and the amount of Sulphur then determined (ASTM 1992). The Sulphur content was computed using equation 11.

$$\text{Sulphur Content \%} = (\text{Ppt } (BaSO_4) \times 0.1373 \times 100) / \text{Weight of sample} \quad (11)$$

The experimental measurements for the gaseous elemental constituents were done following the technical standards EN ISO 16948 (2016) and ISO 16994 (2016), while O (%) content was calculated according to the technical standard EN ISO 16993 (2016) as adopted from Brunerová et al. [35]. All measurements were performed repeatedly until three proper results of each element were obtained.

3. RESULTS AND DISCUSSION

The bulk density of the briquettes shows a general decrease as the percentage composition of the biomass increases as shown Fig. 3, recalling that the sample F100:0 contains 100% biomass. This can be attributed to the effect of initial lower mean density of the biomass of 413.27 kg/m3. This agrees with the results of Bhagwanrao and Singaravelu [36]. Fig. 4 indicates that density decreases as the particle sizes increase for each of the coal:biomass compositions. This observation is in agreement with Bhagwanrao and Singaravelu [36] who noted that bulk density decreased with increased particle sizes. This reduction in density is related to the fact that bigger particles have more interparticle spacing and less materials get compacted into the mold.

Pressure on the other hand mostly caused increase in the density of the briquettes within each particle size subgroup as shown in Fig. 5. This can be attributed to the compaction of more materials into the mold as the pressure increased resulting in more mass in a briquette of constant geometry.

According to Eriksson and Prior [37], the best density for briquettes should be above 1000 kg/m3. Clearly none of the briquettes in this study meets this criterion as the maximum density obtained was an average of 942.61 kg/m3 at 0% biomass composition and the minimum of 541.03 kg/m3 at 100% biomass. The effect of having briquettes of lower density is that they burn faster and have lowered heating values compared to briquettes of higher density [38]. It can be seen that the blending of coal with biomass has significantly improved the bulk density of the briquette and thus improved handling and increased energy delivered per fuel volume.

The water resistance of the briquettes was done to determine its capability of resisting moisture absorption when exposed to rain and other wet environmental conditions. The results indicate an increase in the resistance to water absorption by the briquettes as the biomass concentration increased. This can be attributed to the increase in fiber-containing biomass.

The water absorption ranged between a minimum value of 75.50% and maximum value of 95.07%. Fig. 6 shows that the introduction of the biomass caused the water resistance to increase by over 13 to 89.26% and stayed within the 90% band as the composition increased from 20 to 100% beniseed stalk. This suggests that the stalks had effect on the water resistance of the briquettes produced and tend to agree with Oyedemi [39] who opined that the addition of fibrous material to the briquettes increases its resistance to water absorption.

The results also show that the water resistance is also improved with each subgroup as pressure increases and particle size increments tend to reduce the water resistance as shown in Fig. 7. This is in agreement with work done by Davies and Davies [40] on the Effect of Briquetting Process Variables on Hygroscopic Property of Water Hyacinth Briquettes. In this work they produced briquettes at varying binder concentration, particle size and compaction pressure of 3, 5, 7, and 9 MPa. After the water repellence analysis was done, the results showed that water resistance of the briquettes was highest at compaction pressure of 9 MPa.

The moisture content of the briquettes was found to range between 1.03 and 7.11% with the briquettes produced with 0% biomass having the lowest moisture content and the briquettes produced with 80% the stalk having the highest moisture content. It increased as the composition of the stalk increased from 0 to 80% and then declined at composition of 100% as seen in Fig. 8. This range of moisture content does not exactly lie in the optimum range suggested by Grover and Mishra [41] of between 6 to 8%. According to Ngusale et al. [42], 6 to 14% is also ideal for briquettes production. Both authors suggested that briquettes at moisture content below 5% develop cracks and are not a good characteristic of briquettes. This suggestion was seen in the briquettes produced with the stalk of composition 0 and 60% as they all had moisture content below 5%. Also, the briquettes with 100% stalk and particle size 600 μm developed cracks.

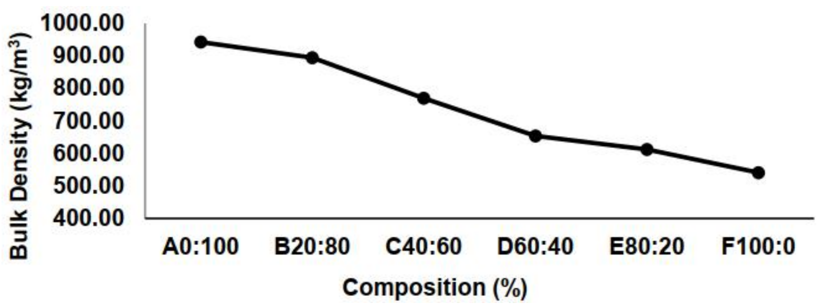

Fig. 3. Effect of composition on bulk density of the samples

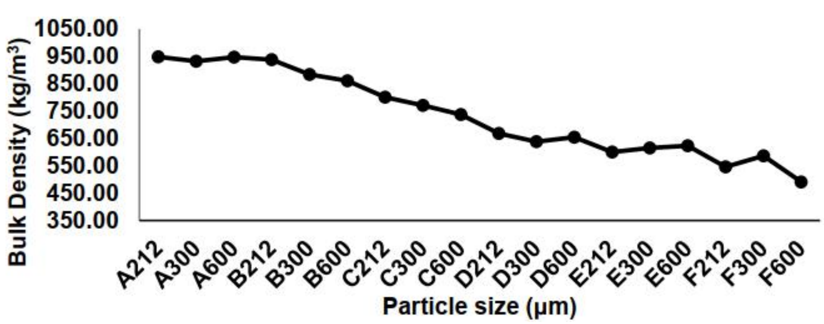

Fig. 4. Effect of particle size on the bulk density of the briquette samples

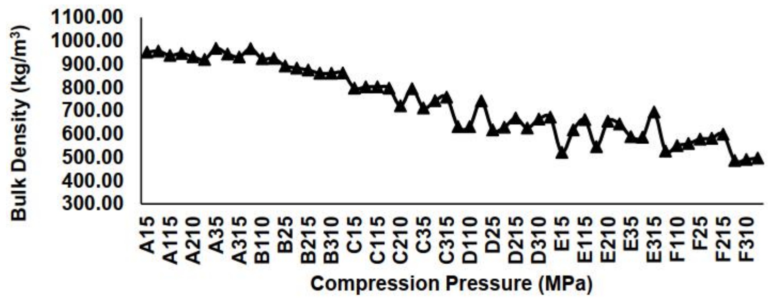

Fig. 5 Effect of compression pressure on the bulk density of the briquette samples

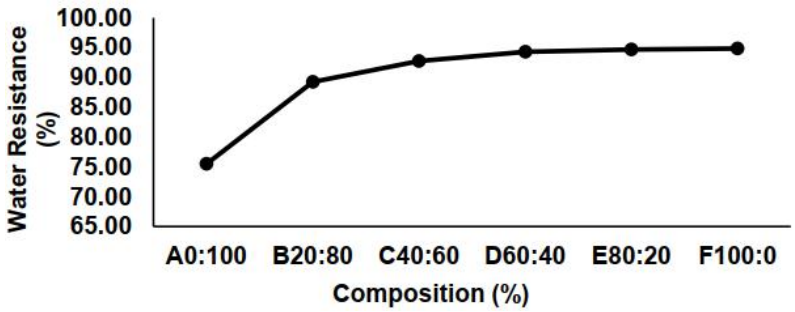

Fig. 6. Effect of composition on the water resistance of the briquette samples

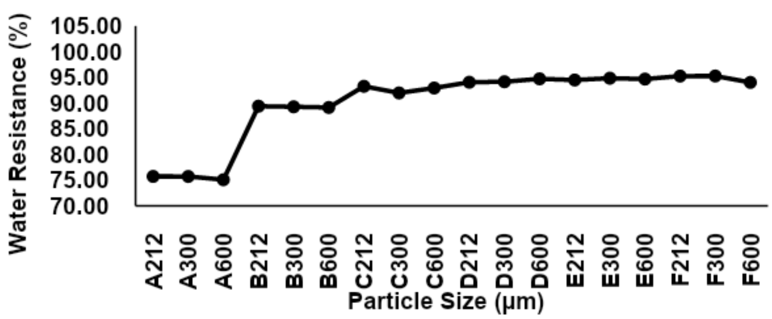

Fig. 7. Effect of particle size on the water resistance of the briquette samples

For all percentage composition of beniseed stalk, moisture content decreased with increase in particle size as seen in Fig. 9 this is also in agreement with results shown by Huko et al. [43] which is suggestive that briquettes with smaller grain or particle size tent to retain more moisture compared to briquettes with higher particle size due to the fact that smaller grain sized briquettes have more compact structure and releases moisture at a slower rate.

A very important relationship is the effect of moisture content on the calorific value of the briquettes. Fig. 10 shows that as the moisture content of the briquettes increased, there was drop in the calorific value of the briquettes. The calorific values have their lowest values (26.15 MJ/kg) at the points were the moisture content were highest (6.63%).

Although calorific values of briquettes are generally affected by many other factors such as density and type of biomass, it can be inferred that the moisture content has a significant effect on the calorific value of the produced bio-coal briquettes. Waweru and Chirchir [44] demonstrated in their research on the effect of the briquette particle sizes and moisture contents on combustion characteristics of composite briquettes that the calorific values of briquettes produced reduced by 24.80% when the moisture content of briquettes increased from 5 to 12%.

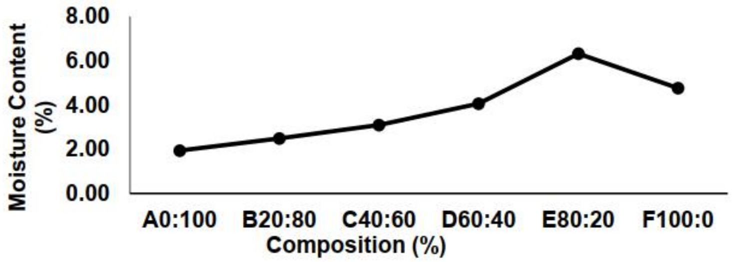

Fig. 8. Effect of composition on the moisture content of the briquette samples

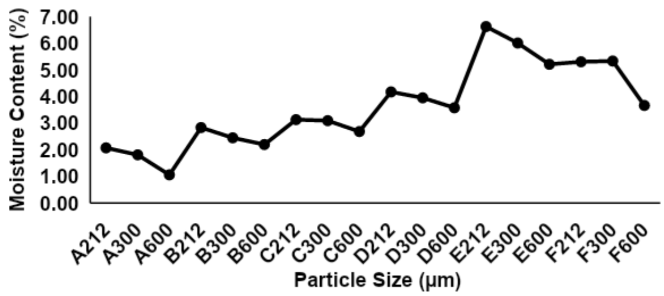

Fig. 9. Effect particle size on the moisture content of the briquette samples

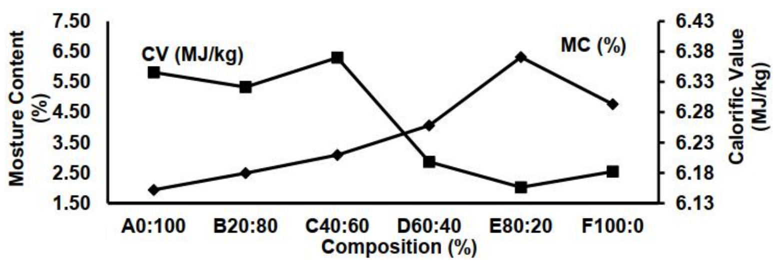

Fig. 10. Effect composition and moisture content on the calorific value of the briquette samples

In Fig. 11, the results of compressive strength of the briquettes show that briquettes made from beniseed stalk-coal blend of 20:80 and 80:20 had the highest compressive strength with percentage beniseed stalk at 80% showing the highest resistance to shear forces reaching an average compressive strength of about 5843 kN/m^2. Compressive strength is one of the most important characteristics of a briquette that determines the stability and durability of the briquette and how they respond to mechanical forces. It can be inferred that at these percentage combinations of the stalks and coal, briquettes produced can withstand high shear forces. In a related research, Yamen et al. [45] was able to show that briquettes produced at percentage compositions of coal between 0% and 30% and biomass at 70% to 100%, had increase in compressive strength.

The effect of compression pressure on compressive strength can be seen in all the briquettes. As the pressure increased, all the briquettes showed increased compressive strengths as shown in Fig. 12. Clearly, the compaction pressure of the briquettes samples increases the Compressive strength of the briquettes. This can be attributed to the increased cohesion force between particles of the mixture as the they are compacted at higher pressure.

Fig. 13 shows the relationship between compressive strength and particle size. The compressive strength of the briquettes produced reduced as the particle size increased. Bhattarai et al. [46] and Huko et al. [43] in separate researches were able to show that compressive strength is inversely proportional to particle size although these researches had no coal in the briquettes, the theory is basically the same as discussed by Grover and Mishra [41] where he suggested that finely divided solids easily attract free atoms or molecules from the surrounding atmosphere to form thin adsorption layers which are not freely movable by implication, can resist shear forces.

The durability of the briquettes is another very important handling characteristic. In this research work, most of samples show a durability index above 97.5% which is the minimum required durability index for briquettes solid fuels according to the European standards EN 14961 series. It can be seen from the analysis of effect of change in percentage composition of the stalk that at 40% and 60% compositions, the briquettes showed the highest average durability indices of 98.58% and 98.55% respectively and a gradual decline the percentage composition increases from 40 to 100% with the index at 100% stalk being 84.40% as shown in Fig. 14. The results above align with suggestions by Ajiboye et al. [47] who in their study involving the use of sawdust and charcoal briquettes with cassava starch as binder showed that the briquettes had higher durability when the raw materials were mixed at near equal proportions. They also opined that fine raw material particles increase the durability of the resultant briquettes which was confirm by the results of this work. The results in nearly all the briquettes groups, the durability of briquettes produced at particle size of 212 µm showed the highest durability as shown in the Fig. 15. The observations by Kaliyan and Morey [48] were also similar to this generally.

Calorific values of briquettes are generally affected by percentage fixed carbon, volatile matter, moisture content and other characteristics like the nature of the raw material, compacting pressure and particle size. Fig. 16 shows that the calorific values of the briquettes generally reduced with the increase in the composition of the briquettes and is highest at composition of 40% biomass. This might be due to interactions of Volatile matter, moisture content, ash content and fixed carbon and other experimental variations as mentioned above. Estialty et al. [49] produced bio-coal using "low-grade" coal and was able to show that as the composition of the biomass (corn cobs) increased, the calorific values of the briquettes reduced too. In other words, addition of coal to a biomass material in a briquetting process causes improvement in the calorific value of the briquette.

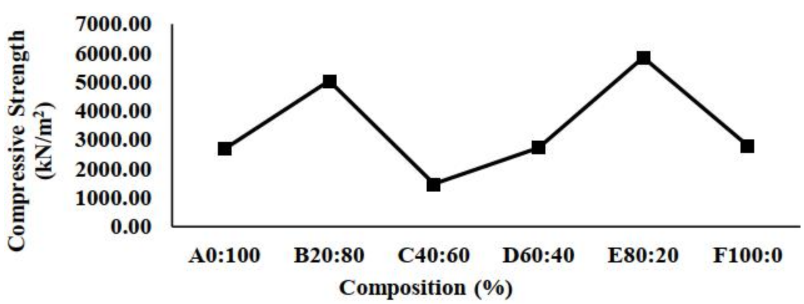

Fig. 11. Effect of composition on the compressive strength of the briquette samples

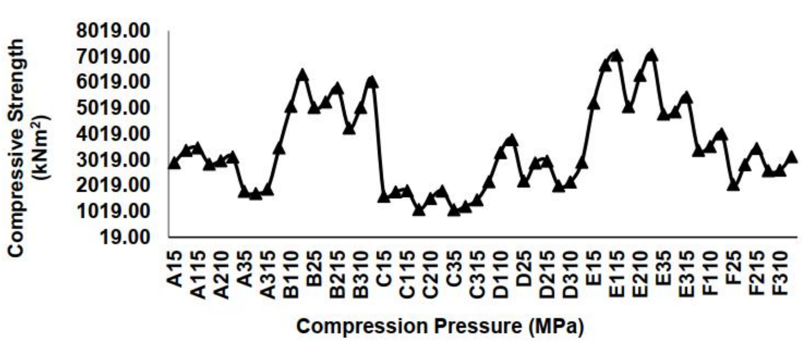

Fig. 12 Effect of compression pressure on the compressive strength on the briquette samples

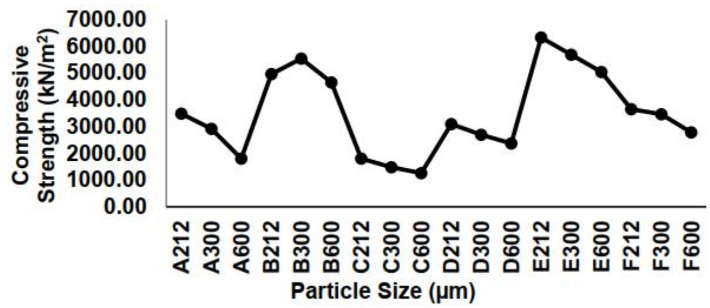

Fig. 13. Effect of particle size on the compressive strength of the briquette samples

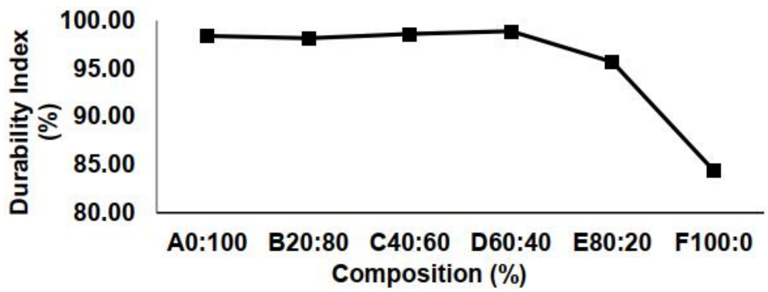

Fig. 14. Effect of composition on the durability index of the briquette samples

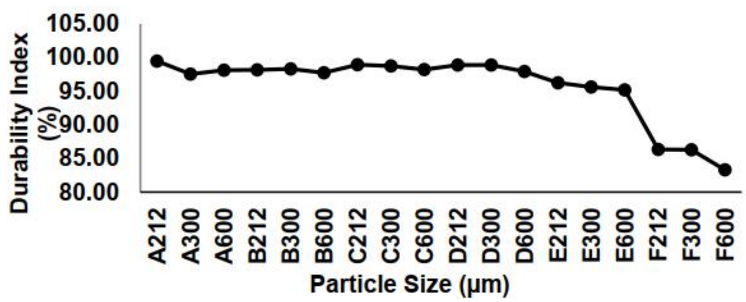

Fig. 15. Effect of particle size on the durability index of the briquette samples

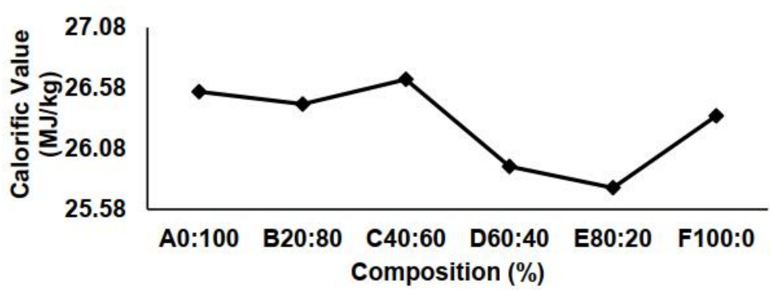

Fig. 16. Effect of composition on the calorific values of the briquette samples

The effect of changes in particle size can be seen in Fig. 17. The calorific values increased as the particle size increased within each percentage composition group. This agrees with Oyelaran et al. [50] who in his research showed that calorific values increase with increased particle size. According to him, the oxidation of the biomass during the grinding or milling process could be the cause of the decreased calorific values as the particles become smaller.

Also, Kumar and Pratt [51] in their research on determination of calorific values of biofuels observed that increased particle size increases the calorific values of bio-coal. This can be explained by the fact that smaller particle size has smaller inter-particular spaces resulting in slower flow of are between particle which in turn will cause slows combustion rate and less heat release per unit time.

The compression pressure also has effect on the calorific values of the briquettes as the pressure increased from 5 to 15 MPa, the calorific values also increased. This is shown in Fig. 18. Enemou et al. [52] and Altun et al. [53] both concluded that calorific values increased with increased compaction pressure and other factors like binder ratio and dwelling time. The result of calorific values of the briquettes in this study fulfill the minimum requirement of calorific value for making commercial briquette (>17.5 MJ/kg for all the samples), as stated by DIN 51731.

The volatile matter ranged from an average of 30.81% at 0% biomass and peaked at 50.98% at 100% biomass. It can be seen from Fig. 19 that as the percentage biomass increased, there was a general increase in percentage content of volatile matter of the bio-coal briquettes. This is in agreement with the results of Estialty et al. [49] where coconut biomass was blended with coal at different mesh sizes and found that the volatile matter of the resulting briquettes increased as the percentage biomass in the blend was increased. The increase volatile matter can be attributed to the high volatile matter of the biomass material. A similar trend can be observed in Fig. 20 indicating a general increase in percentage volatile matter with particle size.

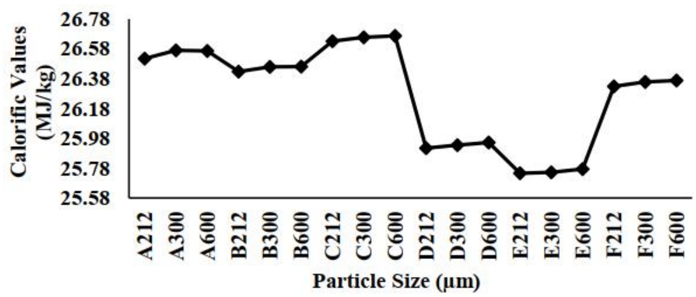

Fig. 17. Effect of particle size on the calorific values of the briquette samples

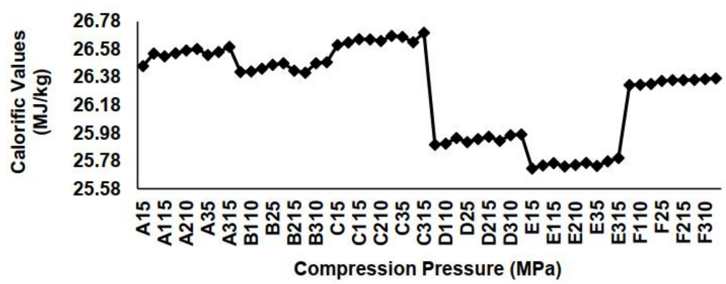

Fig. 18. Effect of compression pressure on the calorific values of the briquette samples

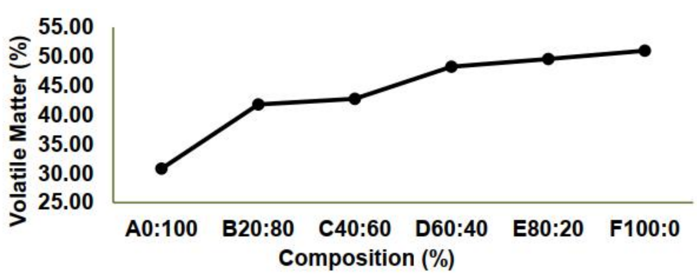

Fig. 19. Effect of composition on the volatile matter of the briquette samples

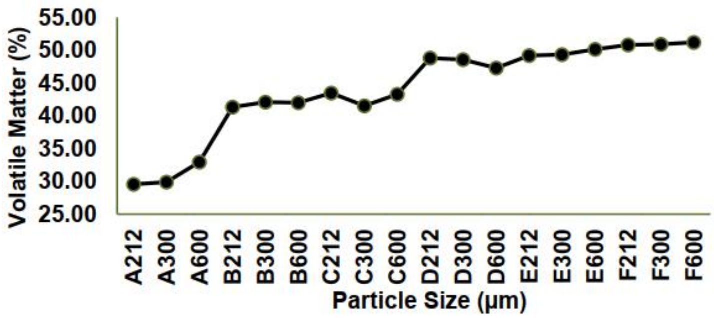

Fig. 20. Effect of particle size on the volatile matter of the briquette samples

According to Onukak et al. [54], volatile matter affects the calorific value of briquettes. Briquettes with low volatile matter have higher calorific values. A comparison between Fig. 17 and 19 agrees with these suggestions too. This is due to the fact that less energy is required to burn off volatile matter in these briquettes before the heat energy is released. Volatile matter is important characteristic of briquette needed for quick ignition of the briquettes. Briquettes with high biomass concentration had shorter ignition time due to high volatile matter. This is in agreement with Onuegbu et al. [55], who used Pennisetum purpureum and imperata cylindrica as biomass and blended with coal. The results showed a reduction in ignition time as the biomass increased and they attributed this to increase in volatile matter.

Ash content is an important characteristic of briquettes that measures how much unburnt material is left after the briquettes are burnt. The DIN 51731 recommend that the minimum ash content of briquettes should be 0.7%. Results of ash content in this study are as shown in Fig. 21. It decreased with increase in the concentration of biomass in the briquettes. The highest value was at biomass composition of 0% with value of 13.78% and the least at 100% with 5.18%, indicating that the addition of the stalk produced an increase in the ash content of the briquettes produced. Compared to observations by Faizal et al. [56] who suggested a maximum acceptable ash content for good quality briquettes should be 4%, the results for the present study were higher. This could be because the coal and biomass used in this work do not possess similar attributes to the ones used in their study and thus not expected to produce briquettes with ash content of 4% or less. However, the ash content of produced for the briquettes in this study is lower than for situations in which some other agricultural wastes were used in other researches. The 5.18% ash content is much lower than that for sawdust at 8.1%, paddy straw at 15.5%, forest waste at 7.0% and rice husk at 19.2% which have been recommended by different researchers to be of good quality [57].

Ash content did not generally change as the particle size or compression pressure changed. However, it generally decreased with increase in biomass content as shown in Fig. 21, showing some stability between the 40:60 and 60:40 compositions. This observation can be explained by the very definition of ash content itself being the measure of the mineral content and other inorganic matter in biomass that are left after combustion is completed Kimutai and Kimutai [58], and it is generally is comparable with results obtained by Huko et al.

The ignition time of the produced briquettes averaged between 1.96 min and 0.99 min with briquettes of 100% coal having the highest ignition time of 1.96 min and the briquettes of 80% biomass with the least ignition time of 0.99 min as shown in Fig. 22. Generally, ignition time reduced as the concentration of biomass increased. This can be attributed to the increase in volatile matter as the biomass increased. Falemara et al. [59] suggested that briquettes with high volatile matter will ignite quicker and burn faster releasing a higher specific heat of combustion compared to briquettes with lower volatile matter. Onuegbu et al. [55] in a similar research where spear grass and elephant grass were blended with coal at different concentrations to produce briquettes. In their results, it was found that for both biomass materials, ignition time decreased with increase in biomass concentration.

Fig. 23 shows the effect of particle size variation on the ignition time of the briquettes. As the size of the blended material particle increases from

212 to 600 µm at each biomass concentration, the ignition time decreased. This observation might be adduced to the fact that bigger particle sizes could have more pronounce pore spaces in between the particles than the finer particle sizes. Thus, increase the porosity of the briquettes which might cause reduction in time taken for the briquettes to be ignited. This imply an inverse relationship between ignition time and the studied particle sizes. This observation agrees with Davies and Abolude [60] in their publication in which they investigated the Ignition and Burning Rate of Water Hyacinth Briquettes. Water Hyacinth plant was ground to particle sizes of 0.5 mm, 1.6 mm and 4 mm and used to produce briquettes. The ignition time for briquettes at 4 mm was the least at 66.61± 3.88 s and the briquettes with 0.5 mm particle size showed the highest ignition time of 107.92 ± 2.92 s.

Fig. 24 shows the effect of composition change and effect of change in the particle size on the water boiling time (WBT) of the briquettes. The results of water boiling test show that the average time required to boil 100 g of water by each briquette sample decreased as the concentration of biomass increased up to concentration of 40% the stalks at a value of 21.12 mins then begin to rise and reaches the boiling time of 21.59 mins. This observation agrees with research findings of Onuegbu et al. [55], where biomass briquettes at 50% biomass (elephant and spear grass) actually boiled water faster than briquettes made from 100% biomass. They suggested that beyond 50% concentration biomass in a bio-coal briquette, the water-boiling-time reducing effect of the biomass on the burning briquettes will begin to reduce.

Fig. 25 shows the interaction between average water boiling time WBT and average calorific values of the briquettes. This partly further explains why the time to boil the water begin to rise beyond the concentration of 40% biomass composition. Beyond 40% stalk composition, the drop in calorific value is an indication that less heat is delivered per unit time and thus taking a longer time to boil 100 g of water. Briquettes with 40% stalks had the fastest average water boiling time of 21.12 mins also has the highest corresponding calorific value of 26.67 MJ/kg, while the slowest average water boiling time was with 0% stalks even though it has a comparatively high calorific value of 26.35 MJ/kg. This might be due to initial slow progression of the combustion of the briquettes owing to their low volatile matter content.

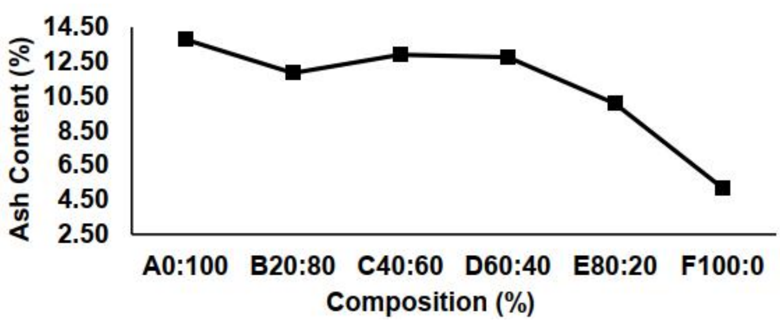

Fig. 21. Effect of composition on the ash content of the briquette samples

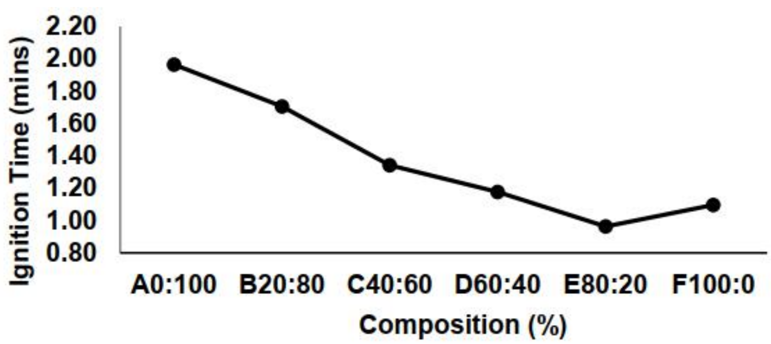

Fig. 22. Effect of composition on the ignition time of the briquette samples

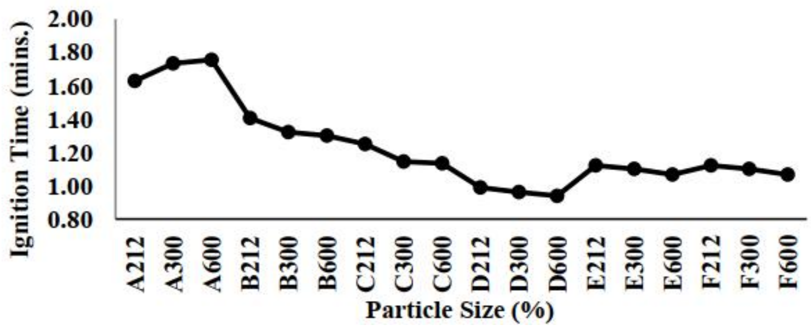

Fig. 23. Effect of particle size on the ignition time of the briquette samples

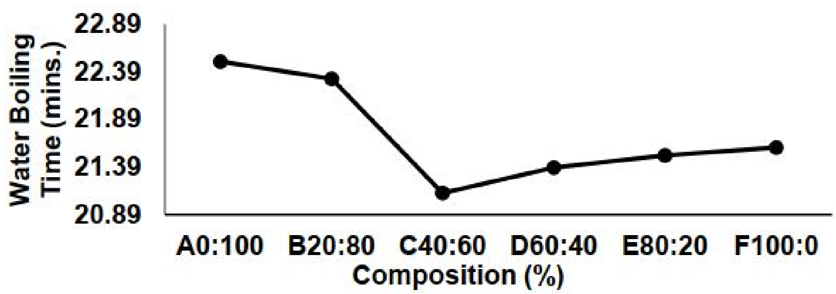

Fig. 24. Effect of composition on the water boiling time of the briquette samples

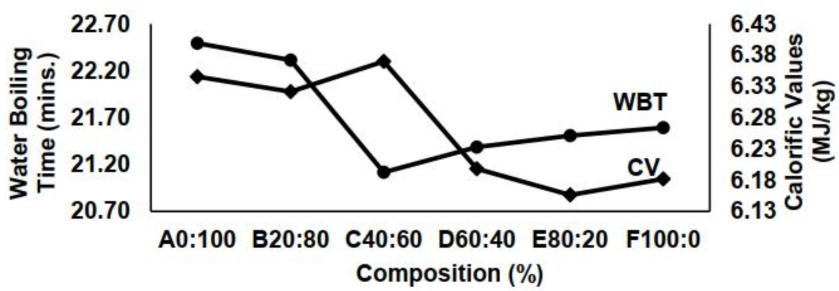

Fig. 25. Interaction of water boiling time with calorific value for the samples

Fig. 26 shows the effect of the change in particle size on the briquettes water boiling time. Within a given biomass concentration, briquettes with smaller particle sizes took longer time to boil water. This might be due to a similar observation by Davies and Abolude [60], suggesting that briquettes with smaller particle sizes will burn slower due to lower porosity resulting in lower infiltration rate of oxygen.

Figs. 27 to 30 show the effects of particle size and composition on Carbon, Oxygen, Nitrogen, Sulphur, and Hydrogen from the ultimate analysis of the briquettes. Similar trends were obtained for both cases. Clearly the change in biomass composition and particle sizes cause a change in the various elements contained in the briquettes. The key focus is in Figs. 28 and 30, which show the percentage Nitrogen and Sulphur because of the harmful emissions associated with NO_x and corrosion effect caused by SO_x gases. According to the Indian Bureau of Energy Efficiency (BEE), the acceptable range of Sulphur content of Biomass related fuels is 0.5% to 0.8%. Also, according to Alpha Resources LLC laboratory (ISO17034, ISO17025, ISO9001:2015) publication in 2018, the standard acceptable value for Nitrogen content in coal is 1.20% ± 0.18 dry basis measured according to ASTM D5373. Both Sulphur and Nitrogen in the briquettes produced in this work have maximum value of 0.42% and 0.84 respectively which is lower than 0.8% and 1.38% referenced in both standards [61,62].

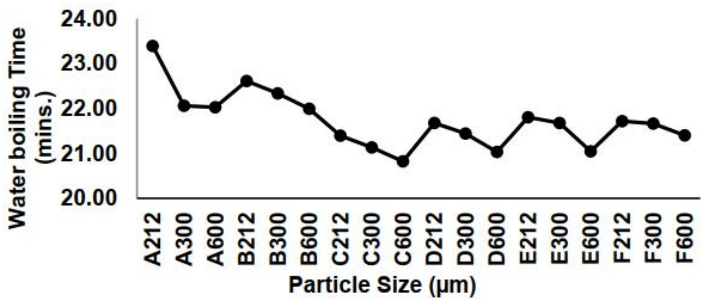

Fig. 26. Effect of particle size on the water boiling time of the briquette samples

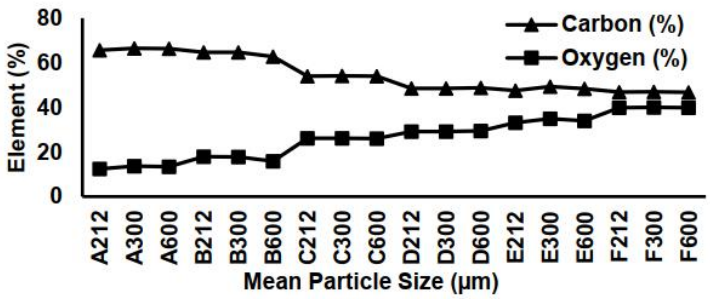

Fig. 27. Effect of mean particle size on carbon and oxygen

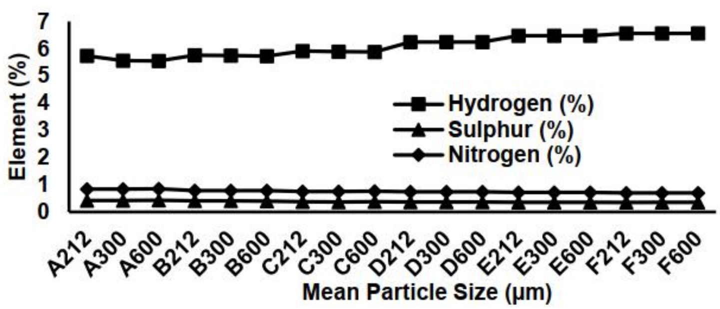

Fig. 28. Effect of mean particle size on hydrogen, sulphur and nitrogen

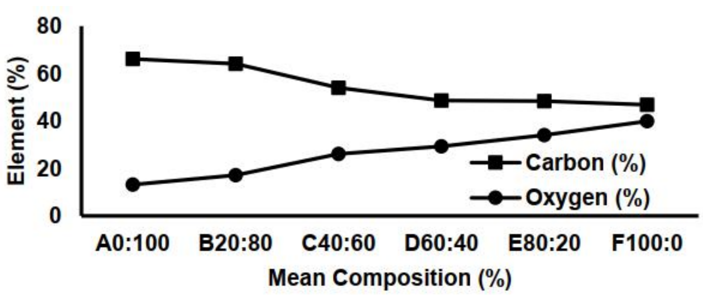

Fig. 29. Effect of composition on carbon and oxygen

Nitrogen with changes in particle size or composition. This can be attributed to the fact that at any given composition, the chemical components of the briquettes are same regardless of the particle size neither will the compaction pressure have changes in the chemical constituents of the briquettes [63,64].

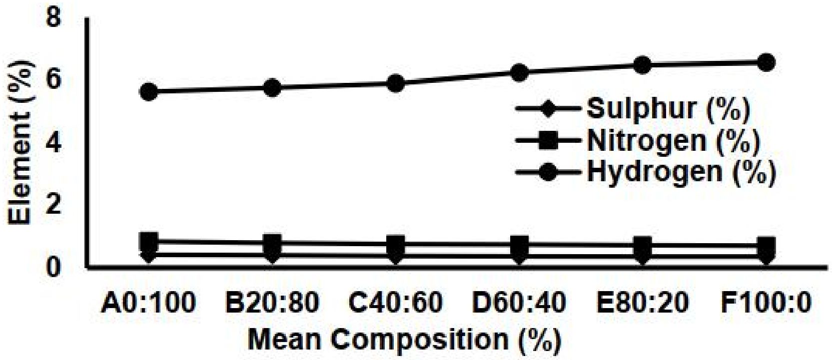

Fig. 30. Effect of composition on hydrogen, sulphur and nitrogen

Summarily, it was found from the study that D60:40 has the fastest ignition time of 57.6 s and A0:100 has the highest ignition time of 102.6 s. The next fastest ignition time are C40:60 and E80:20. The least average percentage volatiles are at composition A0:100 then followed by B20:80 and C40:60 with values 30.81%, 41.81% and 42.76% respectively. Percentage Sulphur has lowest value at F100:0 and E80:20 (0.36%) followed by D60:20 and C40:60 with values of 0.37% and 0.38% respectively. A0:100 has the least moisture content and followed by B20:80 and C40:60 with E80:20 having the highest percentage moisture content of 6.32%. The highest calorific value of 26.76 MJ/kg is at C40:60 composition followed by 26.35 MJ/kg and 26.32 MJ/kg at A0:100 and B20:80.

4. CONCLUSION

With the above deductions, it can be concluded that the optimum composition for producing briquettes from beniseed stalk and coal is between 40% and 60% stalks because at these concentrations, most of the major factors that determine a high-quality briquette had the best values. Generally, changes in particle size and compaction pressure had significant effects on the moisture content and water boiling time of the briquettes produced. Also, increased percentage of the stalks in the briquette caused increase in the percentage hydrogen, oxygen, water boiling time, moisture content and volatile matter, while causing a decrease in percentage Sulphur, nitrogen, carbon, fixed carbon ash content. It also influenced the ignition time, calorific values, durability index and bulk density. Hence, composition is the most important variable in the blending of biomass with coal for briquetting.

It hereby recommended that well organized awareness creation on the potentials of the briquettes as alternative energy source to wood fuel in the rural areas and training on how to use them by University of Agriculture, Makurdi in conjunction with the Benue State Government as well as other stakeholders be vigorously pursued. This will precipitate into the creation of a conducive environment for establishment of briquette making cottage industries in the rural areas by the State government. Furthermore, the revival of the mining of coal at the Orokam/Owukpa deposits in Ogbadibo Local Government Area of Benue State to serve as feedstock for briquette manufacture will be a step in the right direction, and organized cropping of beniseed and collection of the stalks be encouraged through an incentive-based initiative for the motivation of the farmers towards maximizing the availability of this component of the briquette. Further studies will be carried out to find adaptable technologies for large scale combustion of briquettes and other biomass fuel for conversion to energy.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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