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Investigating the Performance and Combustion Characteristics of Composite Bio-coal Briquette

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ABSTRACT

The awareness of the negative impact to environment due to deforestation, desertification and greenhouse emissions have led to finding alternative energy sources to traditional resources. In this work, briquettes of coal and banana waste (leave and pseudostem) were produced with calcium hydroxide as the desulphurizing agent while starch was used as the binder. Briquettes of varied biomass concentrations were produced by mixing the coal and banana leave and coal and banana pseudostem at various composition ratios by weight; (100: 0, 90:10, 80:20, 70:30, and 60:40). The briquettes were produced mechanically using a manual briquetting machine with pressure maintained at 7MPa. The results of the proximate analysis showed that the moisture content, volatile matter and ash content of the composites briquettes ranges between 6.74 and 9.36%, 25.25 to 39.78% and 6.25 to 8.75% respectively. The carbon content, porosity index, calorific value, ignition time, combustion rate and thermal efficiency of the composite briquettes ranges between 54.16 to 76.32%, 23.42 and 44.48%, 31.62 to 31.43 MJ/kg, 57.24 to 180.96 seconds, 0.035 to 0.083 g/min and 12.73 to 15.63% respectively. The higher calorific value and the lower volatile matter of the composite briquettes in compare with biomass briquettes make them more favorable as a solid fuel. However, the optimum biomass concentration for improving the cooking efficiency is at 35% banana waste.

1 Introduction

It is a known fact that fossil fuels play a key role in the global economic and political situations, their numerous challenges accounted for a shift to more sustainable energy sources [1]. Environmental, health and ecological problems is the major subject of concern associated with exploitation of these fuels. Reports by Intergovernmental Panel on Climate Change [2] revealed that, the world is experiencing severe consequences ranging from drought, melting of sea ice,

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diminishing of important plant and animal species, acid rain to overspread of diseases especially in the developing countries like Nigeria. The utilization of coal a fossil fuels is limited for both energy production and various coal conversion processes due the presence of sulphur. The quantity of sulphur dioxide emissions caused by the utilization of coals as a major fossil fuel leads to worldwide environmental problems [3]. Most biomass fuels have lower sulphur and nitrogen contents than coal, so in many cases NOx and SOx emissions can be decreased by biomass co-firing. For these reasons, biomass co-firing with coal has gained great interest in recent years. Of the alternative energy sources, biomass has a great potential as a result of being renewable in contrast to fossil fuels. Biomass can store some of the solar energy as a mass in its body by photosynthesis, and this energy is released during combustion of biomass [4]. However, transportation, storage, and utilization of the biomass are very difficult due to its uneven, fluffy, and dusty characteristics [5]. Therefore, direct combustion of biomass is not practical. Co–firing of biomass with coal has been an attractive way to increase the usage of biomass energy and to upgrade properties of low rank coals [6]. However, there is problem of density difference between coal and biomass which causes some difficulties during the co– firing process nevertheless this problem is been solved by densification of biomass into biomass–coal briquettes. The adoption of densification process, biomass materials can easily be adopted in direct combustion or co-firing with coal, gasification, and in other biomass-based conversions as a result of their uniform shape and sizes [7].

Coal is found nearly in every region of the world, especially in sedimentary rock basins, typically sandwiched as layers called beds or seams between layers of sandstone and shale [8]. The biggest reserves are located in the USA, Russia, China, and India. Its proven reserves have been estimated to be over 984 billion tons in the World [9]. In spite of the important geostrategic advantage of the coal in comparison with crude oil and natural gas, direct combustion of the low–grade coals generally causes lower efficiency and higher greenhouse gas emissions, and thus, requires higher operating costs. In view of the fact that all fossil fuels will eventually run out, it is essential to use them as efficiently as possible. For this reason, these coals should be upgraded into fuels that have acceptable energy efficiency and environmental security. Major techniques applied for enhancing coal properties have been blending, drying, cleaning (removal of minerals), chemical upgrading, and briquetting. These techniques provide removal of excess water and elimination of undesired organic and/or inorganic matters from the coal [10].

There are numerous sources of biomass energy that vary throughout the world. These sources are basically divided into four classes as energy crops, agricultural–based biomass, forestry– based biomass and wastes [11]. Agricultural residues of which the banana waste belongs, can be defined as a biomass energy source that contains agricultural crops and residues. Agricultural crops such as sugar cane, corn(maize), sorghum, wheat, and vegetable oil bearing crops (e.g. sunflower, rapeseed, and soybean) have been used to produce liquid fuels (biodiesel) [12]. However, exploitation of these crops as the energy source competes with the food industry. In contrast, agricultural residues are by–products of agricultural processes such as leaves, pseudostem, straws, husks, shells, and stalks. These residues can either be crop residues that remained in the field after harvest (banana leaves and pseudostem), or by–products of crop processing industry (rice husk, groundnut shell). These wastes are normally ploughed back into the soil, burnt, or grazed by stock if not used for energy. However, they can be utilized in the solid fuel production.

Briquetting is a densification process with the application of pressure to materials in order to obtain a compact, durable, and high quality fuel [7]. Briquetting processes involves drying, grinding, sieving, compacting, cooling, and packing as the need be. The reason for drying is to reduce the moisture content of raw material, the dried material is grinded and passed through a screen and then briquetted. The obtained briquettes are allowed to dry and stored. Briquetting process is one of the promising methods for producing a uniform, stable and durable fuel with the standard quality [13, 14]. The briquetting process helps to decrease the costs of handling, transportation, and storage. The volumetric calorific value of the briquette can also be increased due to increase in bulk density and decrease in moisture content [7, 15–17]. Furthermore, briquettes with the self–desulphurization and the self– denitrification characteristics can be obtained by adding some additives into briquette formulations like case of coal briquetting so as to reduce the sulphur content in the coal. For this reason, no extra apparatus is required for reduction in emissions, which results in reduction in operating and investment costs [18]. Pollution from total suspended particles is also prevented by briquetting process [19]. Briquetting process can be carried out at room temperature (cold briquetting) or at elevated temperatures (hot briquetting) with or without the use of binding material, (binder).. Briquettes can be produced from biomass materials in three different ways by one kind of biomass or mixtures of various biomass materials can be used in the biomass–based briquette production and biocoal (mixture of biomass and coal). Biocoal .briquette represents a type of solid fuel produced from coal and biomass with the application of pressure. During the briquetting process, biomass and coal particles adhere and interlace to each other. Therefore, these two materials do not separate from each other during storage, transportation and utilization [20]. During combustion process, coal acts as a stabilizer in the mixture of coal and biomass, whilst biomass reduces SO2, NOx and CO2 emissions owing to its low sulphur content, low nitrogen content, and CO2–neutral characteristic [21]. The, ignition and fuel properties of the coal can be improved with the addition of biomass by virtue of lower ignition temperature of biomass [20]. Moreover, rate of coal consumption can also be decreased [18].

Coal and biomass consist of same basic elements but in different proportions. This makes the combustion behaviours of both materials to be different. Biomass comprises almost four times more oxygen, less sulphur and nitrogen contents with higher volatile matter content and higher reactivity in comparison with coal. This makes it superior in ignitability and combustibility characteristics with higher burning rate compared to coal [22]. Biomass has lower bulk density compared to coal owing to its high moisture exceeding 50% [21]. This makes transportation, storage and handling of biomass materials to be more difficult and more expensive than that of coal [23]. Incorporating biomass from agricultural waste in coal briquetting formulations has proven to be an effective method to produce a better quality fuel. As rightly stated by Massaro et al., [24] that using materials which are abundant in waste streams and having desirable energy and binding characteristics to provide a briquetted fuel could be an economic and ecological viable substitute for conventional coal. Blesa et al., [25] wrote that this method not only saves high calorific value fuels and reduces waste disposal problems of mines, but also enables the formulation of clean solid fuel. The banana cultivation generates a significant amount of waste. The most significant residues are leaves, stalks and pseudostem because they are generated in greater amounts and occupy large volumes the waste which are left stay in the field after the harvest of banana.

The aim of this work is to investigate the performance and combustion characteristics of composite briquette produce from densification of the blend of coal and banana waste (banana leaves and pseudostem) using starch gel as binder and Ca (OH)2 as desulphurisation agent.

2 Materials and Methods

2.1 Materials and their sources

Sub-bituminous coal was obtained from Onyeama mine, Enugu, Enugu State, banana plant waste was obtained directly from a farm in Asin-Ekiti, Ekiti State, Cassava starch was bought from Ikole-Ekiti market, while, calcium hydroxide was bought from a chemical shop in Ogbomoso, all in Nigeria

2.2 Preparation of the Briquette Samples

The coal sample were milled preparatory to briquetting and labelled while the banana waste (banana leave and banana pseudostem) sample was screened of impurities like sand, metallic objects and chips of wood by passing through 2 mm sieve size. Twelve samples each from the blend with banana waste at various mixing proportions of briquettes of varied biomass concentrations were produced by mixing the coal and banana leave and coal and banana pseudostem at various composition ratios by weight; (100: 0, 95:5, 90:10, 85:15, 80:20, 75:25, 70:30, 65:35 and 60:40) The briquette samples and their composition are shown on Table 1. 5 % Ca (OH)2 based on the mass of the coal was added for desulphurization and 10 % cassava starch gel based on the entire mass of the mixture was used as binder for all the samples. The de-sulphurizing agent in the briquette reacts with the sulphur content of the coal to fix about 60-80% of it into the ash, while lime (CaO) as a desulphurizing agent captures up to 90-95% of the total sulphur in the coal leaving only 5-10% emitted as sulphur oxides Somchai et al., [26]. The samples were weighed using digital weighing balance with maximum load of 600 g and accuracy of 0.1 g. The different concentrations were loaded into the mould compartment of the manually operated hydraulic briquetting machine. A maximum of 12 briquettes were obtained at each operation of the machine under a total load of 60 N, while maintaining the pressure at 7 MPa throughout production. The samples were then sundried for 14 days before study. The briquettes were prepared for each experiment set and the arithmetic mean of the measurements was calculated.

2.3 Proximate Analysis, Carbon and Calorific Value Test

The moisture, volatile, and ash contents of the samples were determined through thermogravimetry process. The moisture was determined using standard method ASTM E871-82 [27] in a conventional oven. The volatile matter was determined using standard method ASTM E872 [28], and the ash was determined using standard method ASTM D 1102-84

[29]. The fixed carbon was determined through the difference of the sum of the others in relation to the total sample. Carbon content was determined by Liebig method while a bomb calorimeter (Leco AC-350 oxygen bomb calorimeter interfaced with a microcomputer) was used to determine the higher heating value (HHV), i.e. calorific value of the briquettes, according to the ASTM standard D5865 [30], all analyses were performed in triplicate.

2.4 Porosity Test

Porosity test is a measure of percentage of water absorbed by a briquette when immersed in water. Each briquette was immersed in 25 mm of water at 27°C for 30 seconds. The percent water gain was then calculated and recorded by using equation 1 [31, 32], was used to measure the porosity of briquettes.

$$Porosity = \frac{W_b - W_a}{W_b} \times 100 \tag{1}$$

Where

W_a= weight before immersion

W_b = weight after immersion

2.5 Determination of Ignition time

Ignition time was determined by burning 200 g of briquettes in charcoal stoves. Since end-point of lighting was subjective and dependent on some judgment according to what stage the ignition has been achieved, two similar charcoal stoves were ignited at the same time by placing equal amount of paraffin on the floor of the charcoal stoves and lit using a lighter. In this process, ignition time was taken as the average time taken to achieve steady glowing fire as recommended in literature [18, 33].

2.6 Determination of combustion rate

Burning time is obtained by observing the mass changes recorded on mechanical balance and also by using stop watch. It is the time for the biomass combustion to be completed. With known amount of total burnt briquette and burning time, average combustion rate can be calculated using equation 2 [18, 31].

$$Combustion\ rate = \frac{mass\, of\ fuel\, consumed\left(g\right)}{total\, time\, taken\left(min\right)} \tag{2}$$

2.7 Determination of Thermal efficiency (η)

Thermal efficiency (η) is the ratio of the work done by heating and evaporating water to the energy of the fuel consumed. This is given as in equation 3 [34, 32]

$$\eta = \frac{M_w C_w \left(T_f - T_i\right) + M_e L}{M_f H_f} \tag{3}$$

The numerator gives the net heat supplied to the water while the denominator gives the net heat liberated by the fuel, where η is the thermal fuel efficiency of the energy, Mw is the mass of water in the pot (kg), Cw is the specific heat of water (kJ/kgK), Ti is the initial temperature of water (K), Tf is the boiling temperature of the water (K), Me is the mass of water evaporated (kg), L is the latent heat of evaporation (kg), Mf is the mass of fuel burnt (kg), Hf is the calorific value of the fuel (kJ/kg).

3 Results

3.1 3.1 Result of Proximate analysis of raw materials

The proximate analysis of the raw materials is shown in Table 1. The result shows that Onyeama coal has mean lower moisture content (6.05%) while, pseudostem have the highest with 10.15%. The coal sample also possess the lowest volatile matter content of 25.83%, banana leave 70.12% while banana pseudostem have the highest volatile content of 70.92%. The ash content shows that coal has the least of 5.55% while banana leave and pseudostem have 10.16 and 9.54% respectively. However, the coal sample has higher mean fixed carbon content of 64.47% as compared to 14.73 and 10.35% for banana leave and pseudostem respectively. The coal sample also has higher calorific value of 31.92 MJ/kg compared to banana leave and pseudostem which possess 18.32 and 15.27 MJ/kg respectively.

Table 1 Result of Proximate analysis of raw materials

Parameter	Coal	Banana leaves	Banana pseudostem
Moisture content (%)	6.05±0.14	7.52±0.23	10.15±0.33
Volatile matter (%)	25.83±0.32	70.12±1.17	70.92±1.19
Ash content (%)	5.55±0.11	10.16±0.11	9.54±0.10
Fixed carbon (%)	64.47±1.15	14.73±0.19	10.35±0.21
Calorific Value (MJ/kg)	31.92±0.47	18.32±0.44	15.27±0.39

3.2 Result of Proximate analysis of briquettes

Moisture is an undesired property and effort is made to keep it at barest minimum. Moisture reduces the combustion of coal, since water cannot burn. It also reduces the flame temperature. From Figure 1, it can be seen that the moisture content of the briquettes produced ranges between 6.74 and 9.36. The optimal briquette moisture content should lie between 5 and 10%, a range for which moisture content did not significantly affect the physical properties of the briquettes. Wilaipon, [18], wrote that for successful densification it is required that the waste presents moisture content between 5 and 10% and particle size can be varied from 1 to 10 mm. Low moisture content of briquettes also helps in their storage (prevents rotting and decomposition). Volatile matter determines whether a material will burn with good flame and whether it will produce smoke, a material with high volatility will produce more smoke. Material with high volatile matter can easily be ignited and would burn with long smoky flames.

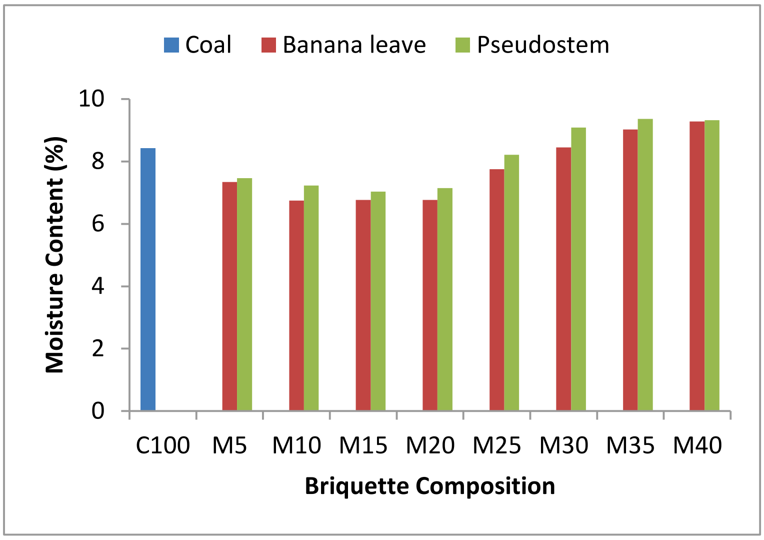

Fig. 1 - Moisture content of briquettes

From Figure 2, the volatile matter increased relatively from the 100% coal briquettes to M40 bi-coal composite briquettes The 100% coal briquette has 25.12% while for the bi-coal composite briquettes ranges between 25.25 and 39.78%, this is quite lower than the 70.92 and 75.12% for pseudostem and banana leave. The bio-coal briquettes are therefore expected to generate less smoke and burn with high flame since they have less volatile matters than 100 % banana leave and pseudostem. Ash is the inorganic residue that remains after the combustion of material. It is made up of oxides of elements that did not burn. Ash reduces handling and burning capacity and affects the combustion efficiency. It also forms part of the incombustible, hence it is undesirable. Figure 3 show that the 100% coal briquette has the least ash content of 5.72% as compared to between 6.25 and 8.75% for bio-coal composite briquettes. From the figure it can be seen that the ash content increases progressively from the 100% coal briquettes to M40 bio-coal briquettes. The progressive increase may be due to the addition of biomass, binder and desulphurizer which fixed some of the sulphur to ash.

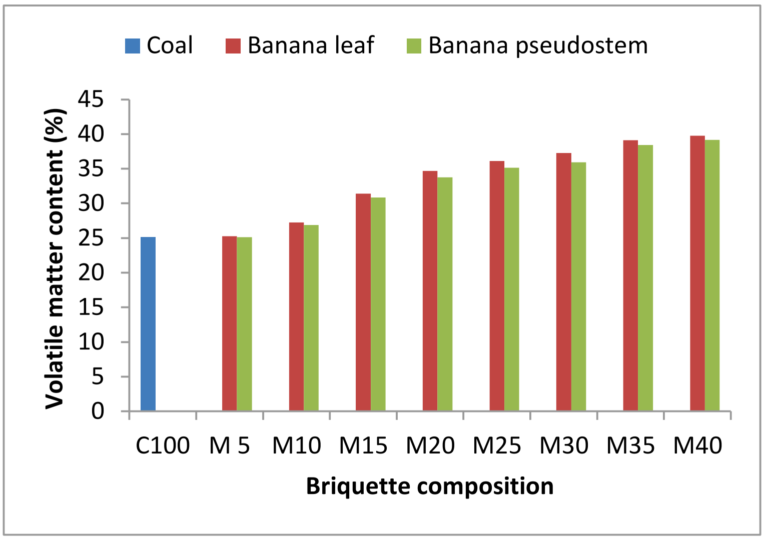

Fig. 2- Volatile matter content of briquettes

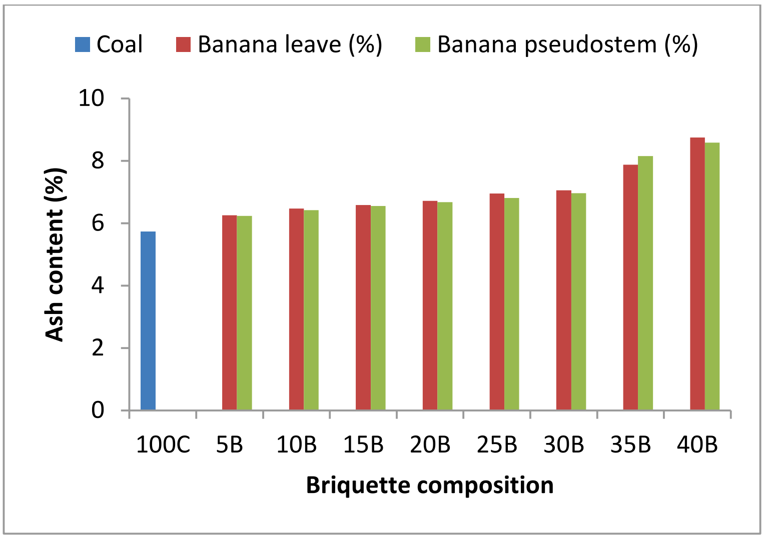

Fig.3 - Ash content of briquettes

3.3 Effect of biomass on the calorific value of bio-coal briquettes

The calorific value (CV) of a fuel is an expression of the energy content, or heat value, released when a unit value of it is burnt in air [35, 36]. It is the amount of heat in, or work obtainable from, a unit amount of the energy resource. It is an important parameter, which determines the quality of an energy source. The results in Figure 4 show that there was a progressive decrease in the calorific value as the biomass increases, since coal has higher calorific value than the biomass as seen in the results of the proximate analysis of the materials. It is obvious that decreasing the coal contents and increasing the biomass will result in a decrease in the calorific value As seen from the figure the calorific value of the bio-coal briquettes decreased with increase in biomass concentration the value ranges between 21.62 and 31.43 MJ/kg. This values are substantially higher compared to 15.5 MJ/kg reported by Abdullah et al., [37] for banana pseudostem, 19.4 MJ/kg for palm oil wastes (EFB) reported by Abdullah et al.,[38], and are also higher than calorific value of banana leaves of 17.1 MJ/kg reported by Sellin et al.[39]. The calorific value of the briquettes is also within the acceptable range for commercial briquette (>17.5 MJ/kg) DIN 51731 [37].

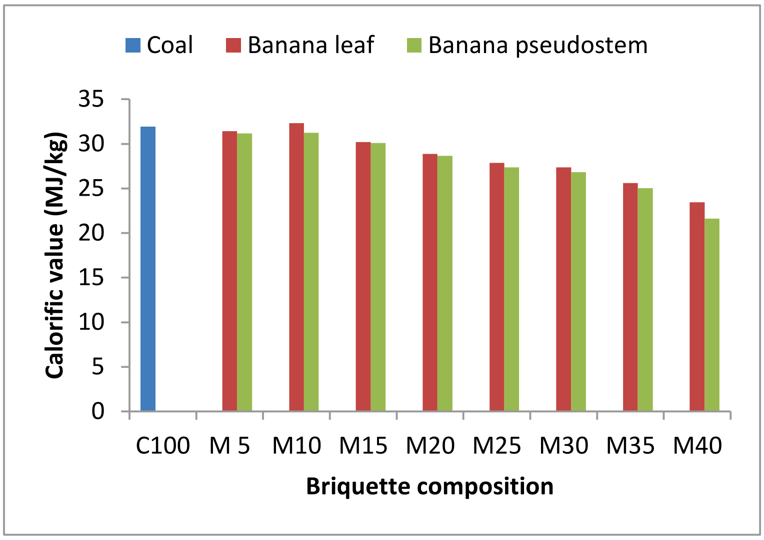

Fig. 4 - Calorific value of briquettes

3.4 *Effect of biomass on the carbon content of bio-coal briquettes*

Figure 5 shows the carbon content of the raw materials and that of briquettes produced. It can be seen that the carbon contents are substantially lower in all the two biomass used with a mean of 43.45% for banana leave and 38.33% for pseudostem while the coal sample has a mean carbon content of 83.51%. These concur with Nag [40] whom wrote that a good coal sample should have high amount of carbon. The higher the carbon content, the higher the calorific value and the better the quality of the coal. As shown in Figure 5, the carbon content decreased as the percentage content of coal decreases. The 100% coal briquette has 81.54% carbon while the coal – banana leave composite briquettes carbon content ranges between 54.16 - 76.32% while the coal – pseudostem ranges between 52.46 and 75.87% The carbon contents of the bio-coal briquettes are high enough to be good fuel for domestic and cottage industrial heat applications.

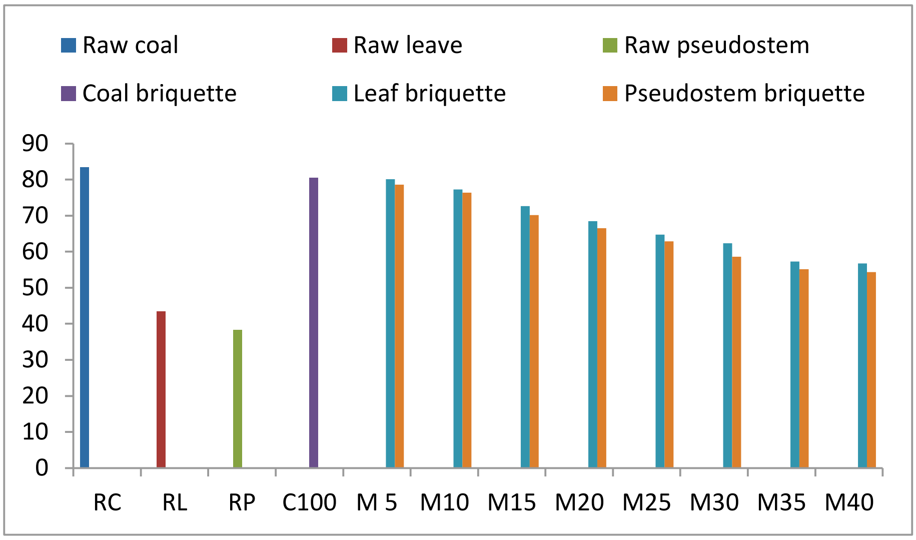

Fig. 5 - Carbon content of raw materials and produced briquettes

3.5 Effect of biomass on the porosity of bio-coal briquettes

The result of porosity property of the briquettes as seen in Figure 6 shows that the 100% coal briquette has the lowest porosity of 21.87%, while the composite briquettes have their porosity increased as the biomass content in the briquette increases. For the coal – banana leave briquette the porosity ranges between 23.34 and 40.54% while for coal – pseudostem ranges between 23.42 – 44.48%. It was observed that the briquetted fuel from banana leave had low percentage of water resistance penetration compared to the briquetted from pseudostem.

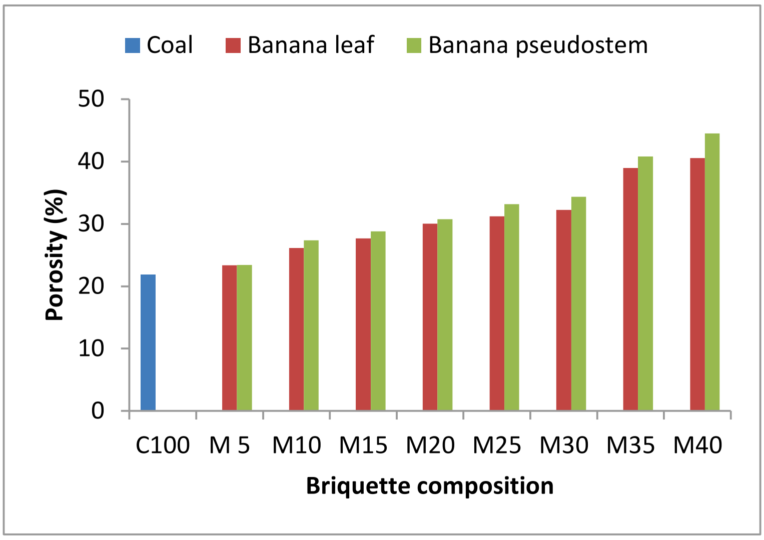

Fig. 6 - Porosity index of briquettes

3.6 Effect of biomass on ignition time of bio-coal briquettes

The ignition time of the briquettes as shown on Figure 7, shows that the 100% coal briquette has the highest ignition time of 181.05 seconds. The effect of banana leave and pseudostem on ignition time of the briquettes varied from 64.08 to 180.96 seconds and 57.24 to 180.52 seconds respectively as shown in Figure 7.

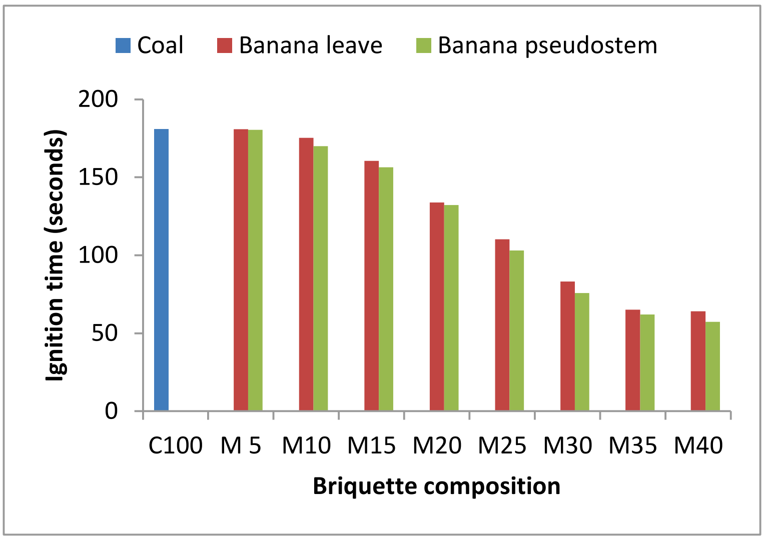

Fig. 7 - Ignition time of briquettes

The obtained trend of the ignition time indicated that ignition time decreases with increasing biomass content of briquettes. The recorded lowest ignition time recorded in M40 briquettes could be attributed to high porosity exhibited between inter- and intraparticles which enable easy percolation of oxygen and outflow of combustion briquettes due to low bonding force. The ignition time of 64.08 – 180.96 and 57.24 – 180.52 seconds obtained for coal banana leaves and coal banana pseudostem respectively in this work is lower than 286 seconds obtained for coal [41]. However the values are within the corresponding values of 66.61 - 107.92 seconds for Water Hyacinth Briquettes with binder ratio of 10 – 50% [42] and of 19 -186 seconds for bio-coal briquettes produced by blending elephant grass and spear grass at different concentration of 10 -50% with coal [43].

3.7 Effect of biomass on the combustion rate of bio-coal briquettes

Combustion rate is one of the important characteristics to show the quality of briquettes, it is the amount of a material that undergoes combustion over a period of time. Table 8, shows the effect of biomass on the combustion rate. As shown in the figure, the 100% coal briquette has the lowest combustion rate of 0.034 g/min, while for the composite briquettes ranges from 0.035 to 0.083 g/min for coal – banana leave briquettes and 0.035 to 0.088 for coal – pseudostem briquettes. The obtained trend of the combustion rate indicated that combustion rate increases with increasing biomass content of briquettes. The recorded highest combustion rate recorded in M40 briquettes could also be attributed to high porosity exhibited between inter- and intra-particles which enable easy percolation of oxygen and outflow of combustion briquettes due to low bonding force. By comparison of these two types of bio-coal briquette, it is found that the coal - pseudostem briquettes have a higher combustion rate than its coal – banana leave counterparts. The implication of this observation is that more fuel might be required for cooking with briquettes produced from M40 for pseudostem than from banana leave.

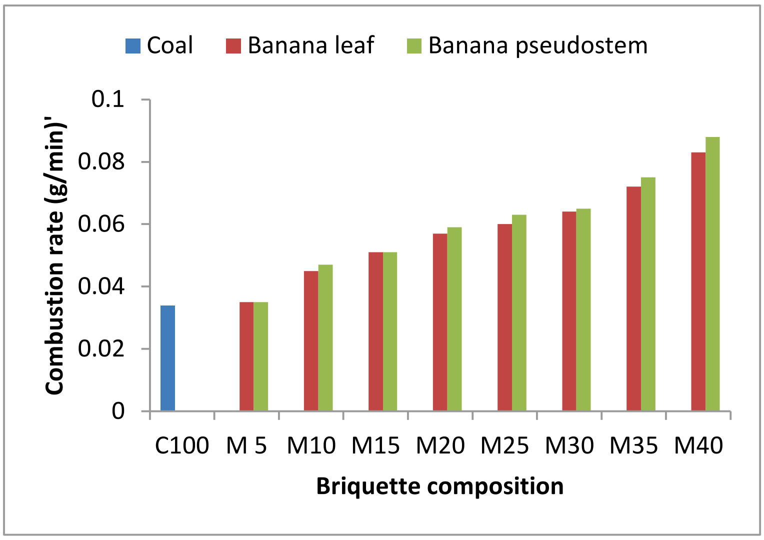

Fig. 8 - Combustion rate of briquettes

3.8 Effect of biomass on the thermal fuel efficiency of bio-coal briquettes

The results obtained from the thermal fuel efficiency test are shown in Figure 9. The results showed that increasing the biomass content subsequently decreases the thermal fuel efficiency of briquettes. The result shows that the coal briquette has the highest thermal efficiency of 16.37%, while for the composite briquettes ranges from 12.73 to 15.65% for coal – banana leave briquettes and 12.61 to 15.65% for coal – pseudostem briquettes. The obtained trend of the combustion rate indicated that combustion rate decreases with increasing biomass content of briquettes. The recorded highest thermal efficiency recorded in 100% coal briquettes could be attributed to high calorific value and by implication the high carbon content of coal. By comparison of these two types of bio-coal briquette, it is found that the coal - leave briquettes have a better combustion rate than its coal – pseudostem counterparts. The implication of this observation is that more fuel might be required for cooking with briquettes produced from M40 for pseudostem than from banana leave. The value obtained in this work compared well with the values obtained in the thermal fuel efficiency of cashew shell briquettes of 15.5% [29], but lower than that of Prasad and Verhaart, [33] whom reported thermal fuel efficiencies for sawdust and rice husk ranged between 19.97 and 21.64%, and 26.20 and 27.27% respectively.

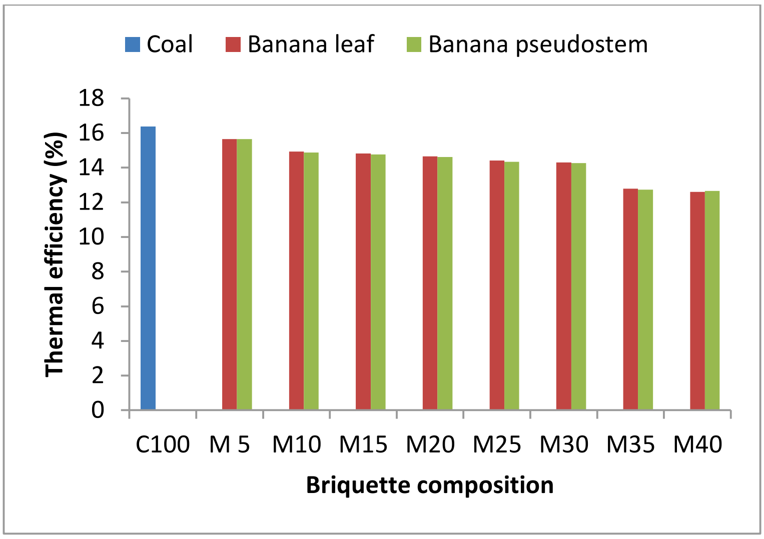

Fig.9 - Thermal efficiency of briquettes

3. Conclusion

From the study carried out on Performance and Combustion Characteristics of Composite bio-Coal Briquette using banana leave and pseudostem, the following conclusions can be drawn. The higher calorific value and the lower volatile matter of the composite briquettes in compare with biomass briquettes make them more favorable as a solid fuel. However, the optimum biomass concentration for improving the cooking efficiency is at 35% banana waste (leave and pseudostem). The bio-coal briquettes produced gave promising results as alternative solid fuel with fuel properties and in agreement with previous works and within the limits set by international standards. The practicability of domestic production of solid fuel from banana waste and coal is feasible.

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