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Combustion characteristics of fuel briquettes made from charcoal particles and sawdust agglomerates

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ABSTRACT

The combustion characteristics of fuel briquettes made from *Idigbo* (*Terminalia ivorensis*) charcoal particles, pinewood (*Pinus caribaea*) sawdust and their agglomerates using gelatinized cassava peels were investigated. The charcoal particles and pine sawdust were blended in the mixing ratios of 90:10, 80:20, 70:30, 60:40, and 50:50, respectively and vice-versa. More so, briquettes were produced from pure charcoal particles and pine sawdust separately for the purpose of comparison with the blended briquettes. The gelatinized binder was 5% of the total briquettes weight. The briquettes were produced using a pressure of 5 MPa with a dwelling time of 5 min in a hydraulic briquetting machine. Proximate, elemental compositions and heating value analyses were carried out on the raw charcoal, sawdust, cassava peel, and their briquettes. The results showed that variations in the mixing ratios of the bio-residues had significant effects on all the properties investigated. An increase in the charcoal particles led to an increase in the fixed carbon content and heating value of the briquettes. Conversely, higher pine sawdust content in the briquette resulted in higher volatile matter content and lower heating value. The briquette made from pure charcoal particles had the highest heating value (24.9 MJ/kg) and ash content (6.0%). Its carbon, hydrogen, and oxygen contents were in the range of 44.6–50.1%, 5.1–5.6% and 34.4–41.5%, respectively. The proximate analysis, elemental composition analysis, and heating values of the produced fuel briquettes depicted that they have better combustion properties when compared to the raw charcoal, pine dust, and cassava peel. Thus, the produced briquettes would serve as good fuel for domestic and industrial applications.

Introduction

With rapidly rising global energy needs by teeming world population [1–3], and rapid industrialization and urbanization [4], biomass-to-energy is a promising alternative energy technology [5]. Biomass (woody bio-residue) has gained prominence

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as one of the widely utilized sources of renewable energy fuel. This advantage is a result of the contribution made to the reduction of net greenhouse gas emission and the security of energy supply [6,7]. Moreover, woody bio-residues have continued to gain significant interest and attention because of their renewability, greenish, and global availability [8]. These woody bio-residues have been proposed as sustainable sources for utilization as domestic fuel [9]. This proposition is due to their potentials as a replacement for conventional energy sources such as firewood [10]. Woody bio-residues could also be a viable substitute for fossil fuels such as coal. However, only small proportions of these woody bio-residues are being utilized as fuel as sustainable energy solutions. This assertion is due to their bulkiness and high moisture present [11]. These properties make woody bio-residues not readily available as excellent sources of energy fuel as they are always present in their loose form. Thus, the densification of bio-residues into briquettes is a promising step to improve their combustion and handling properties. This process will help to overcome logistic economics in sustainable energy solutions [5,12].

Briquetting is a densification process in which loose biomass are compacted under pressure so that the density of biomass residues could be increased up to about 1000–1200 kg/m^3 and the volume be increased by 8–10 times of the loose biomass [13,14]. Briquetting process can be categorized base on binder usage or not. Briquetting with or without binder requires applied compaction pressure for biomass densification [4]. The making of fuel briquettes from blends of forest and agro-residues demonstrate the potential of appropriate technology for the use of biomass residues as energy fuel [15,16]. Recent studies have shown the densification of various combinations of bio-residues from agricultural products and food industries with other additives for heating purposes [17–22]. As replete in the literature, specific biomass in densified mixture performs the function of a natural binder which increases the durability of the produced fuel briquettes [17,18,23–26].

Several research works have been reported on biomass briquetting. For instance, Kuti and Adegoke [9] examined the performance of biomass briquettes produced from sawdust and charred palm kernel shell. Starch gel served as the binder for the agglomerates. The briquettes produced were satisfactory for usage due to the specific fuel consumption (0.0635 kg/s) obtained when the briquettes produced were used for cooking yam and beans. Emerhi [27] investigated the physical and combustion properties of briquettes produced from sawdust of three hardwood species (*Afzelia africana, Terminalia superba, and Melicia elcelsa*) using different organic binders (cow dung, ash, and starch). The results of the study revealed that the produced briquettes have calorific values in the range of 10.04–13.03 MJ/kg. Kuti [28] evaluated the performance of biomass briquette produced from sawdust and palm kernel shell. In this study, sawdust and charred palm kernels were mixed in different ratios and bound by starch gel. The briquettes produced were reported to be suitable for usage for domestic application because the briquettes boiled water between 15 and 30 min. Stephen et al. [29] studied the relationship that existed among physico-mechanical properties, mixing proportion, and compaction pressure for briquette produced. In the study, maize cob particles were mixed with sawdust of low, medium, and high-density timber species. Briquettes were produced using pressure that ranged between 20 and 50 MPa. The results showed that sawdust enhanced the physico-mechanical properties of the produced briquettes.

Numerous biomass residues are in abundance in Nigeria. Organic or inorganic binders are utilized to bind these numerous biomass residues. Therefore, to obtain suitable blends from the bio-residues for briquettes production, the physical properties and combustion characteristics of biomass briquettes are important to be investigated [30]. Thus, this study investigates the combustion characteristics of fuel briquettes produced from wood charcoal fines, pine sawdust, and their blends where the binding agent is cassava peel gel. The combustion characteristics (moisture content, volatile matter, ash content, fixed carbon, and calorific (heating) value) and elemental composition of briquettes made from charcoal, sawdust, and their blends are evaluated.

Materials and methods

Materials

The bio-residues utilized in this study were *Idigbo* (*Terminalia ivorensis*) charcoal particles, pinewood (*Pinus caribaea*) dust, and cassava peels. The charcoal particles were collected from a charcoal merchant in Tanke, Ilorin, Nigeria (8.48 latitude and 4.61 longitude) and pinewood dust from Forest Research Institute of Nigeria, Ibadan, Nigeria (7.40 latitude and 3.92 longitude). The binding agent used was cassava peel obtained from Ganmo, Ifelodun local government area, Kwara State, Nigeria (8.41 latitude and 4.60 longitude). Cassava peel was selected due to its availability, higher physical and mechanical handling characteristics compared to plantain peel, banana peel, or yam peel [31].

Material preparation and briquette formulation

Handpicking technique was employed for the initial removal of foreign materials from the raw samples of charcoal particles, pine sawdust, and cassava peels. The charcoal particles and pine dust were then pulverized to obtain the required fines for the densification process. The charcoal fines and pine sawdust were screened to 0.5 and 2 mm ASTM sieve sizes, respectively. The sieved samples of charcoal fines and pine sawdust were then stored separately in a zip-locked polythene bag. The cassava peel was adequately washed in water and sun-dried for five (5) days for moisture reduction. The average time of sun-drying was five (5) hours per day. After drying, the cassava peels were pulverized using an electrical grinding machine. It was later sieved to particle size lower than 0.5 mm. The pulverized cassava peels (22.5 g) were then dissolved in 60 cm^3 cold water due to its fibrous nature. The dissolved solution (binder) was then gelatinized on a burning stove

Table 1
Mixing ratios of different briquette samples of charcoal fines and sawdust with 5% cassava peel gel.

Sample ID	Charcoal (wt%)	Pine dust (wt%)
B	90	10
C	80	20
D	70	30
E	60	40
F	50	50
G	40	60
H	30	70
I	20	80
J	10	90

*Samples A and K are pure charcoal particles and pine sawdust, respectively.

and continuously stirred until the slurry formed a smooth paste. Charcoal fines and sawdust were weighed using electronic weighing balance and blended at different mixing ratios between 10 and 90 wt% (Table 1). Samples were also formed from only pure (100%) charcoal fines and sawdust, respectively. The binder (gelatinized cassava peel) at 5% of the total mass of the materials was used for the respective agglomerate samples [32].

Briquetting procedure

The briquettes were produced at the Forest Research Institute of Nigeria, Ibadan, Nigeria. The process adopted was a piston press method which involves the usage of a binder and high-pressure briquetting technique. Each agglomerated sample of charcoal fines and pine sawdust was fed into the briquetting machine mold. Cassava peel gel was used as a binding agent in the mixing of raw materials at different ratios. Each briquette sample was subjected to an applied pressure of 5 MPa. Dwelling time of 5 min was allowed for each of the bio-residues consolidations in the mold to prevent the compressed biomass from spring back effect [33]. After the briquettes formed were removed from the molds, the briquettes were placed in an oven (DHG-9053A Model, Movel Scientific Instrument Co., Ltd, China) at 105 °C to remove moisture and to achieve constant weight. After removal from the oven, the samples were kept in a zip-locked bag for characterization.

Combustion properties

Briquettes samples were pulverized and screened to a particle size of $<$ 0.5 mm in preparation for the combustion tests. The combustion properties such as the percentage volatile matter (V_m), fixed carbon (F_c) ash content (A_c), and heating value (HHV) for the briquette samples were determined using different ASTM standard methods. The elemental compositions of the briquettes were determined using various correlations from previous studies.

Moisture content

The moisture content (M_c) of 0.5 g (W_0) sample was determined by heating each sample at a temperature of 105 °C for 1 h in an oven (DHG-9053A model, Movel Scientific Instrument Co., Ltd, China) according to BS EN 14,774-1 standard [34]. The samples were removed from the oven and allowed to cool in a desiccator. The samples were re-weighed to obtain the final (dried) weight (W_d). The moisture content was then calculated using the Eq. (1):

$$M_c\ (\text{wt\%}) = \frac{W_0 - W_d}{W_0} \times 100\% \quad (1)$$

where W_0 is the original weight of the sample and W_d is the final (dried) weight of the sample.

Volatile matter content

One gram of each pulverized briquette samples was measured and placed in a crucible of known mass. It was then oven-dried to constant mass. After, the samples were heated in the furnace (LF3/F4244 Model, Vecstar Ltd, United Kingdom) at a temperature of 900 °C for 7 min and weighed after cooling. The volatile matter (V_m) was then evaluated as the percentage loss in mass of the sample using Eq. (2) expressed as follows [35]:

$$V_m\ (\text{wt\%}) = \frac{B - C}{B} \times 100\% \quad (2)$$

where B is the weight of the oven-dried sample and C is the weight of the furnace-dried sample.

Ash content

One gram of each pulverized briquette sample was measured and then placed in a crucible of known mass and oven-dried to constant mass. These samples were later heated in the furnace (LF3/F4244 Model, Vecstar Ltd, United Kingdom) at a temperature of 800 °C for five hours and weighed after cooling. The ash content was then estimated from the percentage loss in mass of the sample using Eq. (3) expressed as follows [36]:

$$A_c\ (\text{wt\%}) = \frac{D}{B} \times 100\% \tag{3}$$

where A_c is the percentage ash content, D is the weight of ash (furnace dried), and B is the weight of the oven-dried sample.

Fixed carbon

The percentage fixed carbon of each sample of briquette was estimated using the relation in Eq. (4) [37]:

$$F_c\ (\text{wt\%}) = 100 - (V_m + M_c + A_c) \tag{4}$$

where F_c is the (wt%) fixed carbon obtained for each briquette sample, V_m is the (wt%) volatile matter obtained for each briquette sample, M_c is the moisture obtained for each briquette sample and A_c is the (wt%) ash content obtained for each briquette sample.

Calorific value

The calorific or heating value (*HHV*) of each sample of the briquette was estimated using the model developed by Nhuchhen and Afzal [38], which has a good prediction accuracy within the error bar of ±10%. The correlation can be expressed as Eq. (5) [38]:

$$HHV\,(\text{MJ/kg}) = 0.1846\,V_m + 0.0352F_c \tag{5}$$

Elemental composition

Based on the result of the proximate analysis, the elemental composition of common organic elements such as carbon (C), hydrogen (H), and oxygen (O) for the briquettes were estimated using Eqs. (6), (7) and (8), respectively. These were evaluated at an estimate of 95% confidence level [39]:

$$C = 0.637F_c + 0.455V_m \tag{6}$$

$$H = 0.052F_c + 0.062V_m \tag{7}$$

$$O = 0.304F_c + 0.476V_m \tag{8}$$

Results and discussion

Characteristics of the raw samples

Table 2 shows the proximate, elemental and heating values of the raw charcoal particles, pine sawdust (pine) and cassava peel samples used for the study. Table 2 shows that cassava peel has the highest moisture (7.8 wt%) and volatile matter (82.0 wt%) contents. Similarly, pine has high moisture (6.8 wt%) and volatile matter (77.7 wt%) contents. The trend of the volatile matter contents for both pine and cassava are in agreement with the findings of Lasode et al. [40] and Prins et al. [41], where the studies reported 82.3 wt% for teak dust and 79.0 wt% for Switchgrass dust, respectively.

However, the volatile matter of charcoal particles was lower when compared to the other raw materials. This could be due to its production process (carbonization), wherein a degree of devolatilization could have occurred [42]. The carbonization process used in charcoal particle production may have led to its higher calorific value (23.4 MJ/kg) compared to pine (19.7 MJ/kg) and cassava peel (18.4 MJ/kg). The charcoal particles have the highest ash content (5 wt%). This could be detrimental to its overall combustion properties. This means that the pine dust and cassava peel were better with regards to ash

Table 2
Proximate, ultimate and heating value characteristics of raw charcoal particles, sawdust, and cassava peel samples.

Sample	Ash (wt%)	VM (wt%)	FC (wt%)	M (wt%)	C (wt%)	H (wt%)	O (wt%)	HHV (MJ/kg)
Pine	0.3	77.7	15.2	6.8	45.0	5.6	41.5	19.7
*CHP	5.0	42.0	50.0	3.0	50.9	5.2	35.2	23.4
**CP	1.0	82.0	9.2	7.8	43.2	5.6	41.8	18.4

**CP - cassava peel, *CHP - Charcoal particles, Moisture on a wet basis, and VM and Ash on a dry basis.

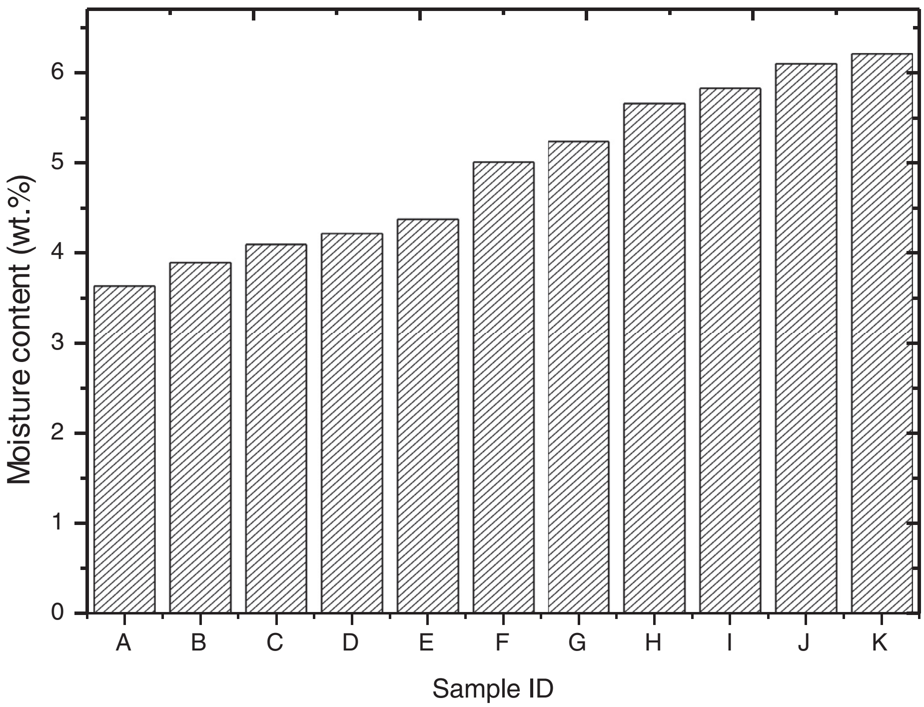

Fig. 1. Variation of moisture contents for the briquette samples (wt%).

content. From the results, a higher calorific value implies that the energy in charcoal particles was greater when compared to other samples. Hence, better combustion characteristics could be achieved by blending both charcoal particles and pine as briquette using cassava peel as the binding agent to obtain a better fuel.

Proximate analyses of the briquette samples

Moisture content

Fig. 1 represents the variation of moisture content for the produced briquette samples. Fig. 1 shows that the moisture content increased with the increasing percentage of pine sawdust in the agglomerates. This could be attributed to the hydrophilic nature of pine sawdust as well as with its coarseness. These might have increased porosity and moisture in the briquettes. However, the results revealed that the moisture contents of the entire briquette samples were lower when compared with those obtained in some briquettes produced from biomass materials such as maize cob (12.2 wt%) and groundnut shell (10.3 wt%) as reported by Ilochi [43].

The moisture content of fuels affects combustion characteristics. Thus, it should be as low as possible because the high moisture content is a challenge when burning and would require excessive energy for drying.

Percentage ash content

The non-combustible component obtained from biomass is ash. Fig. 2 represents the variation of ash content for the produced briquette samples. Fig. 2 shows that the ash content decreased as pine sawdust increased in the agglomerates. The ash content ranged from 1.4 to 6.0 wt%. The highest ash content of 6.0 wt% was obtained from the pure charcoal particle briquette while the lowest ash content of 1.4 wt% for briquette made from pure pine sawdust. The variability in the ash content, when compared with the initial raw materials, depends on the production technique. The ash content of the other mixing ratios was found to be within the acceptable ash limit (5–40 wt%) for a solid biomass briquette [44]. The high ash content of fuel briquette implied that the combustion remnant of such fuel was high but with a low heating value. Ash content has a significant effect on heat transfer and oxygen diffusion to the surface of fuel during combustion [45]. Therefore, the excessive ash content of solid fuel is detrimental to its proper combustion. Hence, the produced briquettes from the blend of charcoal and pine sawdust would perform well based on its ash content.

Percentage volatile matter and fixed carbon contents of the briquettes

Volatile matter consists of elements such as carbon, hydrogen, and oxygen which are present in the biomass. However, volatile matter does not contain water that is usually removed by the biomass carbonization process. Fig. 3 shows a variety of volatile matter and fixed carbon contents for the briquettes produced. The mixing ratios of the biomass used could be said to have a significant effect on the percentage volatile matter of the briquettes produced (Fig. 3). The least volatile

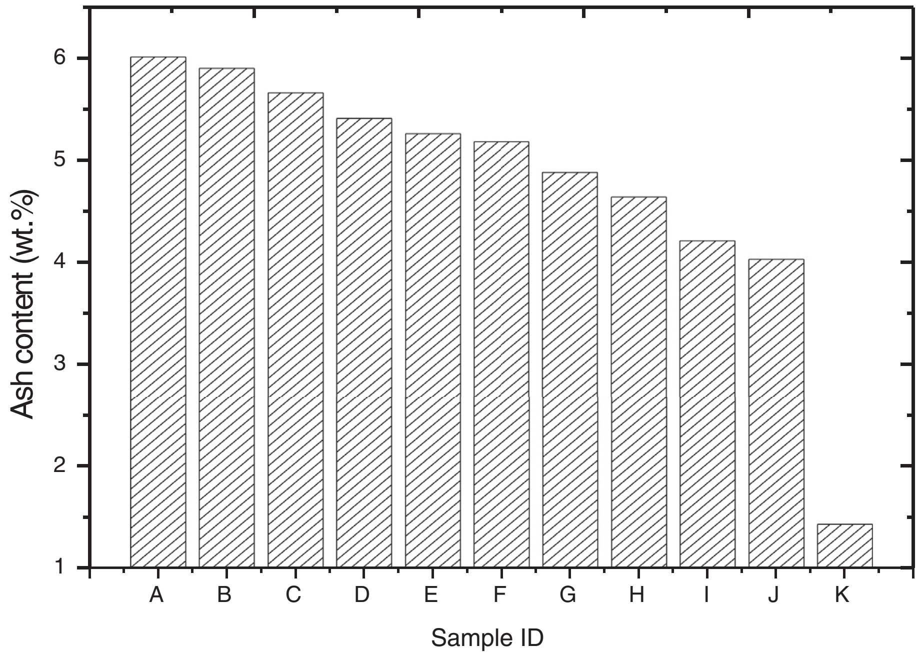

Fig. 2. Variation of the ash content for the briquette samples (wt%).

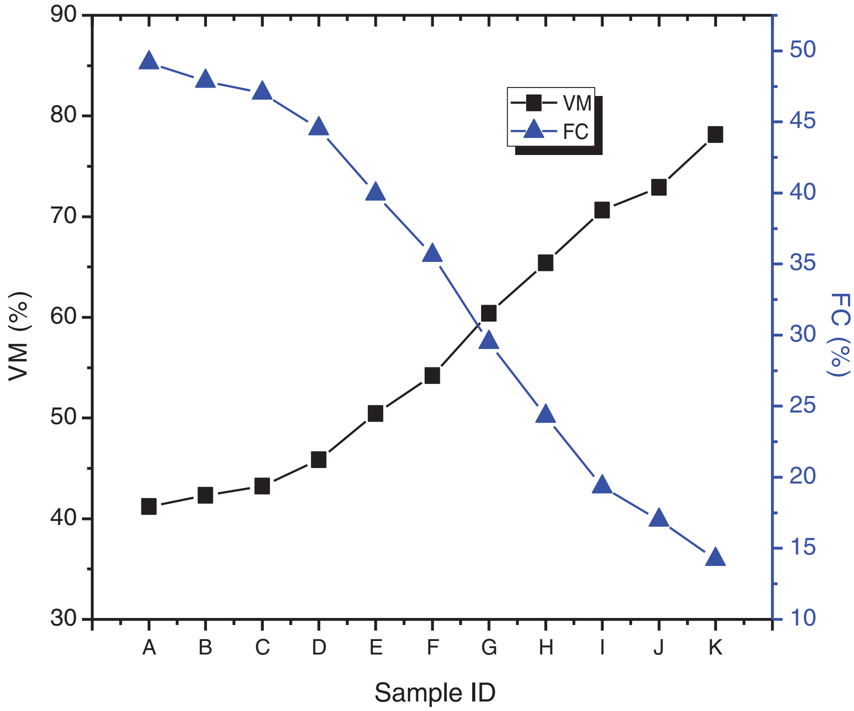

Fig. 3. Variation of volatile matter and fixed carbon contents for the produced briquettes.

matter content (41.2 wt%) was obtained from the pure charcoal particle briquette whereas the highest volatile matter content (78.1 wt%) was obtained from the pure pine sawdust briquette. The result reveals that pine sawdust increment in the agglomerated biomass resulted in the volatile matter percentage increment of the briquettes. High volatile matter content is an indication of the readiness of fuel samples to ignite. In terms of quality of the briquette, the high volatile matter implied that the briquette would readily ignite with a high proportionate flame during combustion [46].

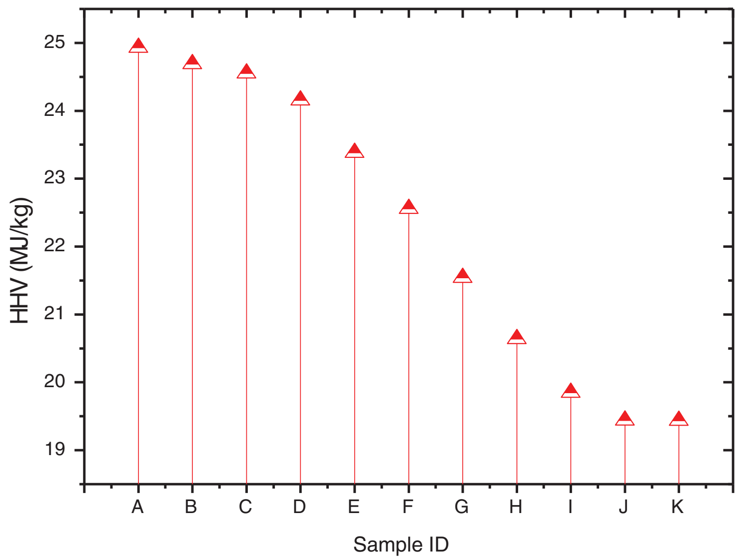

Fig. 4. Variation of calorific values for the produced briquettes.

Table 3
The carbon, hydrogen and oxygen contents of the briquette samples.

Sample ID	C (wt%)	H (wt%)	O (wt%)
A	50.1	5.1	34.4
B	49.8	5.1	34.5
C	49.6	5.1	34.7
D	49.2	5.2	35.2
E	48.4	5.2	35.9
F	47.3	5.2	36.5
G	46.3	5.3	37.6
H	45.2	5.3	38.4
I	44.5	5.4	39.4
J	43.9	5.4	39.8
K	44.6	5.6	41.5

The percentage of carbon available for char combustion was the fixed carbon of a fuel. Fig. 3 shows that the fixed carbon content decreased as the pine sawdust increased in the agglomerates. The result of low fixed carbon content for the pure pine sawdust was much expected. It was revealed that pure pine sawdust exhibited the lowest fixed carbon content of 14.2 wt% (Fig. 3). However, the pure charcoal particles gave the highest fixed carbon content (49.2 wt%). The fixed carbon contents of the briquettes were better than that of pure pine sawdust but were found to be lower than that of pure charcoal. High percentage fixed carbon is an indication of a high heating value of the briquette.

Calorific values and elemental compositions

Fig. 4 presents the variation in calorific values for the pure briquettes as well as those produced with different mixing ratios. Fig. 4 shows that the calorific value increased with an increase in the percentage of charcoal particles in the agglomerates. On a general note, the charcoal particles contributed primarily to the increase in the calorific value of the agglomerates. The calorific values of the briquettes were in the range of 19.4–24.9 MJ/kg. The results also revealed that blending the charcoal and pine sawdust for briquettes production yielded high calorific value than using pure pine sawdust. This could be as a result of the initial carbonization of the charcoal. This has been reported to increase calorific value. The results of the calorific values were found to be higher than 14.1 MJ/kg obtained for maize cob briquette [11] and 18.9 MJ/kg obtained for banana peel briquette [32]. Thus, the briquettes produced from charcoal particles and pine sawdust agglomerates are one of the best briquettes from woody biomass, as they compare favorably with other briquettes.

The elemental compositions of solid fuel have also been reported to affect its energy content and fuel ratio [4]. Table 3 shows the elemental compositions of the briquette samples produced. The carbon contents (C) of the briquettes range from 41.6 to 50.1 wt%. The carbon contents decreased with an increase in pine sawdust in the agglomerates. The hydrogen contents (H) range from 5.1 to 5.6 wt% for all the briquettes produced, while the oxygen contents (O) range from 34.4 to 41.5 wt%. The H and O contents increased as the pine sawdust content increased within the agglomerated samples. This observation is traceable to the higher percentage of H and O contents in pine sawdust compared with charcoal particles.

The results obtained for the elemental composition in the present study was a reminiscence of briquettes made from a blend of rice husk and palm oil mill sludge by Obi and Okongwu [4].

Conclusion

The combustion characteristics of fuel briquettes made from *Idigbo* (*Terminalia ivorensis*) charcoal particles, pinewood (*Pinus caribaea*) sawdust and their agglomerates using gelatinized cassava peel as the binder were examined. The mixing ratios variation of the biomass samples had significant effects on all the properties investigated on the briquette produced. An increase in the charcoal particles increased the fixed carbon content and the heating value of the briquettes. The best calorific values were obtained from pure charcoal particle briquette (sample A) and those briquettes produced from samples B (90:10) and C (80:20). Pine sawdust increased the oxygen and hydrogen contents of the briquettes and lowered their carbon contents. The proximate, elemental, and heating values analyses of the produced fuel briquettes depicted that they have better combustion properties when compared to the raw charcoal, pine sawdust and cassava peel. Thus, the produced briquettes made from charcoal particles and pine sawdust agglomerates would be a good source of energy for domestic and industrial applications.

Declaration of Competing Interest

The authors have declared no conflict of interest.

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