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Research article

Preparation of charcoal briquette from palm kernel shells: case study in Ghana

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ABSTRACT

In Ghana, the potential of palm kernel shells as renewable energy in charcoal production has not been exploited adequately. Using a low-cost instrument (kiln and compressor box) built from local resources, we produced charcoal briquette from palm kernel (*Elaeis guineensis*) shells. Further, we measured and compared its efficiency using starch as a binder to traditional charcoal and commonly used fuelwood (*Acacia*) in Cape Coast. Following the American Standards for Testing and Materials (ASTM), the proximate analysis was conducted for all fuels with results indicating that palm kernel shell (PKS) briquette produced had a moisture content of 1.08 %, as compared to 9.25 % in charcoal and 16.00 % in fuelwood. The volatile matter, ash content and fixed carbon recorded were 71.80 %, 0.06 %, and 27.07 % in PKS briquette, 86.00 %, 0.78 %, and 3.97 % in charcoal and 80.50 %, 2.04 %, 1.46 % in fuelwood respectively. The calorific values for charred PKS increased after binding to form the PKS briquette with the highest value among the other fuels. The calorific value for the other fuels were 17.5 MJ/kg for charcoal, 18.72 MJ/kg for charred PKS, and 18.72 MJ/kg for PKS briquette. We also conducted an ignition test, combustion test, fuel burning rate (FBR), and specific fuel consumption (SFC) on PKS briquette and charcoal to determine their suitability as cooking fuels. Charcoal readily ignited as compared to PKS briquette with respective fuel mass of 5.08 g and 25.5 g. The resultant briquette possesses desirable combustion characteristics such as no smoke emissions and ash formation. The FBR and SFC in PKS briquette recorded the highest in comparison with charcoal. The values recorded were 2.84 g/min and 20.05 g/ml respectively while that of charcoal was 0.42 g/min and 3.48 g/ml respectively. PKS briquette produced from this study showed high calorific value, low moisture content, and a fast burning rate amongst other excellent properties. These properties are potential indicators that the proper utilization and production of PKS briquette as renewable energy in Ghana would contribute to solving the existing energy crisis. Additionally, reduce climate change impacts, via the reduction in the over-dependence on fuelwood and charcoal for domestic and commercial heating.

1. Introduction

Globally, 41 % of households and over 2.8 billion people, rely on solid fuels (coal and biomass) for cooking and heating (Amegah et al., 2019). Cooking fuels have associated linkages with health, Land Use and Land Cover Change (LULCC), and climate change. According to the Ghana Demographic and Health Survey (2014), 70 % of Ghanaian households' predominant sources of cooking fuel are forest resources (charcoal, fuelwood, straw, and agricultural residue). This often leads to indiscriminate and unregulated felling of trees whose various parts are used as fuelwood and charcoal upon drying and processing. Such activities lead to deforestation, as well as other adverse effects on the environment (Mbamala, 2019). Global patterns of degradation indicate that commercial timber extraction and logging activities account for more than 70 % of total degradation, with fuelwood collection and charcoal production, all noted as the most critical drivers of degradation in large parts of Africa (Adeniyi et al., 2014; Kissinger et al., 2012).

Owing to its affordability and convenience, domestic consumers of fuels in low-income countries are traditionally tied to charcoal, especially in urban areas (Mekonnen et al., 2018). Despite forest management systems implemented in some countries, wood is usually sourced from natural forests and very often harvested illegally, defeating the laws in

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place for biodiversity preservation, ecosystem conservation and the countries Intended Nationally Determined Contribution (INDC) for emission reduction.

Traditional charcoal making processes typically lead to the highest emissions of CH4 and carbon dioxide (Figure S 1 of supplementary materials). Additionally, they commonly require 6 kg of wood per kg of charcoal produced (Lohri, 2016; Kammen and Lew, 2005). In the year 2000, indoor air pollution from solid fuel use was responsible for more than 1.6 million annual deaths and 2.7 % of the global burden of disease (World Health Organization, 2019). Despite knowledge of health and environmental impacts, continual dependence on charcoal and wood is still evident (Agyeman et al., 2012; UNDP, 2010; Agyei et al., 2019). Protecting the environment and limiting deforestation can be achieved by making briquette from agricultural waste (Kissinger et al., 2012). Briquette from agricultural waste (biomass) contributes to the energy mix. The advantage of being able to transform biomass, which in its raw form has low density, low heating value, and high moisture content, to highly efficient fuel briquette is now of research interest (Ukpaka et al., 2019).

In rural community settings, palm kernel shells in its raw form are introduced into the fire when cooking. Although this helps to quicken the process of cooking, this however generates excessive smoke due to the organic content property, which is hazardous to health (Ukpaka et al., 2019; World Health Organization, 2019). Usually, after introducing the shells into the fire, most of the energy content is not consumed as incompletely burnt palm kernel shells are a common sight at ash dumps (Ukpaka et al., 2019). Carbonizing and briquetting would make palm kernel shells efficient and sustainable for usage. With the increased activity of energy utilization in the world and the encouragement of renewable energy for sustainability from biomass, a direct look is now in our natural resources that may seem a waste in our environment. An example is a conversion of coconut shell to charcoal briquette as done by Green Africa Youth Organization. Literature as well as scientists have speculated the characteristics of palm kernel shells as one with a high hydrocarbon content and have the potentiality of being able to harness out energy from the shells (Ukpaka et al., 2019; Agyei et al., 2019).

In Ghana, it is estimated that 2,469,763 tonnes of palm oil are produced annually (FAO, 2017). Palm fruits are harvested every month; in peak seasons, as much as 30 tonnes per hectare can be harvested, while in lean seasons, only about 2.2–3.3 tonnes can be harvested (Ofosu-Badu and Sarpong, 2013). Although palm kernel waste products have now been identified as a useful energy source, the waste (palm kernel shells) generated from oil producers far outweighs its consumption by industries (Bediako et al., 2016). There are vast tonnages of these palm kernel shell wastes dumped on sites and around many of the palm oil-producing areas in the country (Ofosu-Badu and Sarpong, 2013; Bediako et al., 2016). Palm kernel shell as one of the by-products accruing from oil palm processing can be suitably converted to renewable energy to meet the demand of the ever-growing population of fuelwood and charcoal (Agyei et al., 2019). Palm kernel shells as a form of renewable energy have not been adequately investigated in Ghana; therefore, this project looks at the suitability of using palm kernel shells to produce charcoal that is clean, affordable, and capable of giving better combustion.

2. Study site

The project was carried out in the Amamoma community, University Cape Coast, Cape Coast Metropolis. The Metropolis is bounded to the South by the Gulf of Guinea, to the West by the Komenda Edina Eguafo Abrem Municipality (at Iture bridge), to the East by the Abura Asebu Kwamankese District, and to the North by the Twifu Heman Lower Denkyira District. It is located on longitude 1°15' W and latitude 5°06' N. It occupies an area of approximately 122 square kilometers, with the farthest point at Brabedze located about 17 km from Cape Coast, the Central Regional capital (Ghana Statistical Service, 2010). For cooking and heating, 58.6 % of households in Cape Coast utilizes charcoal, and 7.1 % utilize fuelwood as the main source of energy (GSS, 2010).

3. Materials and methods

3.1. Materials

Materials used included palm kernel shell, charcoal, cassava starch, metal containers, oven (Figure S 2a of supplementary materials), crusher, weighing scale, sieve, knife, crucible, kerosene, briquette compressor, cooking stove, cooking pot, lighter, thermometer, cooking pot, measuring cylinder, beaker, stirrer, hammer, water, muffle furnace (Figure S 2b of supplementary materials), oven, desiccator, burner, bomb calorimeter, and dish (Figure S 2 c of supplementary materials).

Palm kernel (*Elaeis guineensis*) shells (*Dura* & *Tenera*) were collected from the vicinity of Abura, Cape Coast, Ghana. Traditional charcoal types of low grade, fuelwood (*Acacia*), and cassava starch were sourced from the Amamoma market. The cassava starch was processed and used as the binder (Figure 1b). Combustion was carried out in metallic containers serving as kiln (Figure 1c), and two manual briquette compressor boxes (Figure S 4 of supplementary materials and Figure 1d) fabricated at the University of Cape Coast, College of Agricultural and Natural Sciences workshop were employed.

3.2. Methods

The production of PKS briquettes involved several stages including sample collection, pyrolysis, briquette sample preparation, and test analysis.

3.2.1. Pyrolysis of palm kernel shells

The pyrolysis of the palm kernel shells was done following the experiments conducted by Gregory & Romo (2015) and Amy (2009).

The palm kernel shells (PKS) including *Dura* and *Tenera* mixture (Figure S 3a of supplementary material) were sun-dried in the open air at an ambient temperature of 31 °C for ten days (Figure 1a) before experimentation to reduce the moisture content. The collected sun-dried palm kernel shells (Figure S 3b of supplementary materials) weighing 1500 g were divided into three sections, 500 g each, and then packed into three (3) metallic containers serving as a kiln (Figure 1c). The pyrolysis was carried out within the metallic containers, and the various observations, including quantity used, duration, final portion, and smoke emission color changes were noted (Table 1).

A metallic bucket measuring 20 cm in width on the top and bottom, with a height of 30 cm (Figure 1c) was employed. To achieve controlled burning, the bottom of the metallic container was perforated using a nail (diameter 2.11, and length 31.25 mm) to allow for the slow-burning and equal spread of heat to the biomass. A hole of diameter 15 cm was created at the top of the metal container's cover (Figure 1c) with the aid of a knife. A two-way open cylindrical container measuring 20 cm (length), and 14.9 mm (diameter) was inserted through the created hole within the cover (Figure 1c) to act as a chimney.

A hand full of biomass (dried leaves) was used in the firing portion to ignite the PKS within the metallic container. The first smoke (Figure 2b), from the ignition, was allowed to set out after which the sides of the metallic container was covered with sand to ensure enclosure. After loading the biomass into the container, the top was closed with the cover and attached conical chimney. The metallic combustion container and palm kernel shells are now ready for pyrolysis. In the first stage of combustion, the color of the initial smoke observed from the pyrolysis process of the palm kernel shells was creamy brown, as seen in Figure 2b.

The palm kernel shells were left to burn entirely in 2 h into biochar. The percentage of recovery for the char was recorded (Table 1). The final smoke observed (Figure 2c) was a blue color at the end of pyrolysis. The final stage (smoke emission and color) of complete pyrolysis was in correlation with the experiment conducted by Ugwu & Agbo (2011).

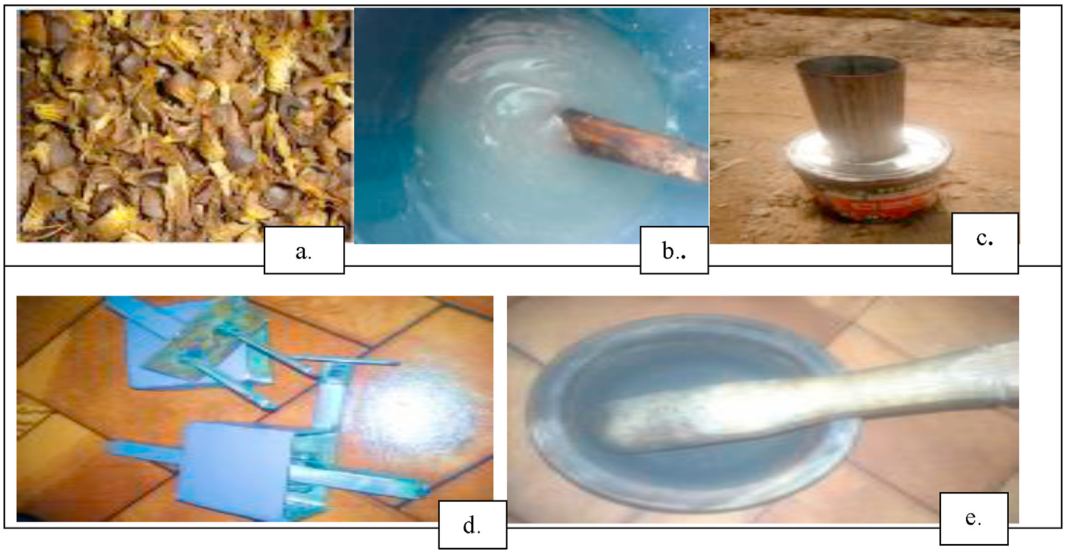

Figure 1. Materials used in charcoal briquette production: a. Palm kernel shells. b. Starch from cassava. c. Combustion kiln. d. Compressor box. e. Mortar and pestle.

Table 1. Result from pyrolysis of palm kernel shells.

Component	Result
Weight of PKS at the start of pyrolysis	1500 g
Weight of PKS at the end of the pyrolysis	1398 g
Percentage recovery of biochar	93.2 %
Number of briquettes produced from biochar	10 briquettes
Quantity of biochar used for 10 briquettes	1350 g

Upon complete combustion, the conical chimney was removed, and the char was allowed to cool down for 40 min. The final products formed were charred shells as shown illustratively in Figure S 3c of supplementary materials. The pyrolysis process was replicated three (3) times with 4500 g of palm kernel shells to obtain thirty (30) prototypes used for the tests analysis conducted.

3.2.2. Briquette samples preparation

The PKS char was pulverized (Figure S 3d of supplementary materials) using mortar and pestle (Figure 1e) and screened through a 2 mm sieve to establish homogeneity. The process flow of the shell briquette is shown in Figure 2. Twenty grams (20 g) of cassava starch was dissolved in a bowl containing 40 ml cold water and mixed initially to obtain a cassava paste. Hundred (100) ml of water was put to boil in a pot after which, it was added to the cassava paste and mixed properly with a stirrer to form a starch gel (Figure 1b). One hundred and thirty-five grams (135 g) of the pulverized biochar was gradually added into the gel and mixed using a stirring stick until a thick, black compound (Figure 2e) was formed. The compaction of the briquette was carried out manually with a hammer and two (2) compressor boxes (Figure 1d) for every 135 g of powdered samples as illustrated in Figure S 4 of supplementary materials.

The total quantity of biochar used as well as the number of briquettes produced were 1350 g and 10 briquettes respectively. The central holes incorporated into the briquettes (Figure 2f) produced by the designed

Figure 2. Sequential stages in shell briquette preparation: a. Shells before combustion; b. Initial combustion; c. Final stage; d. Pulverized charred shells; e. Thick char paste; f. PK briquettes.

compressor box helps to achieve a uniform and efficient combustion. The essence of using this type of pressure was to make the briquettes, as it would be in the absence of costly briquette machines. This procedure is targeted at the rural populace who may not have access to briquette machines. The thickness, height, and length of the fuel briquette as shown in (Figure 2f) are 2.5 cm, 6 cm, and 10 cm respectively. After the briquette stage, the molded thick paste was sun-dried for 7 days. The sun-drying reduces its moisture content and increases its compactness (Hendrich et al., 2004). Proximate, ultimate, and combustion tests were further conducted on the briquette after a week of sun drying.

3.2.3. Analysis and tests

The suitability of the PKS for the production of charcoal briquette was determined by carrying out proximate analysis, ultimate analysis, ignition test, and combustion test in line with the American Standards for Testing and Materials (ASTM). Raw samples (*Dura & Tenera*) of palm kernel shells were introduced into the test to observe the changes of fuel properties from the raw state to the charred and briquette state. Using a sample size of 1 g, the experiment was replicated three (3) times (Figure S 2c and Figure S 2d of supplementary materials) and their mean values were taken (ASTM D-3173).

Proximate Analysis: The moisture content, ash content, volatile matter, and the fixed carbon of the fuels were determined in line with the ASTM D-3173 specification (Chin and Aris, 2013).

Ultimate Analysis: This was carried out in a LECO CHNS 932 analyzer calibrated with 52.78 % carbon, 5.07 % hydrogen, 20.13 % nitrogen, and 11.52 % sulfur for only briquette samples (Chin and Aris, 2013).

Calorific Value: The energy content of charcoal and PKB briquette was measured using the LECO AC- 350 bomb calorimeter (Yin, 2011; Chin and Aris, 2013).

Ignition Test: The time taken (ignition time) for the fuels to start burning was recorded using a stopwatch (Ugwu and Agbo, 2011).

Combustion Test: The combustion test was carried out by boiling water (water boiling test), using materials and traditional tripod stoves in a typical rural household to simulate the normal cooking condition. The experiment was replicated three times and the mean values taken. The water of volume 100 ml at an initial temperature of 30 °C was measured into a cooking pot of weight 212.96 g. Six (6) lumps of the briquettes initially weighing 540.56 g were placed on the cooking stove (Figure 3). The briquettes were ignited (Figure 3a) after being sprinkled with noted (Table 4) quantities of kerosene and lighted with matches.

The temperature of the water was noted using a thermometer at intervals of five minutes until the water boiled at 100 °C. The weight of the evaporated water was calculated from the difference between the final weight of water after cooling and the initial weight of water in the pot (Table 4). The weight of the fuel burnt was calculated from the difference in the initial weight of briquettes kept on the stove and the final weight after the water had boiled at 100 °C (Kuti, 2009). The same process was repeated for the traditional charcoal. During this test, some fuel properties such as specific fuel consumption and burning rates were recorded. Observations including the ignition time and smoke emitted were also made (Table 4).

Fuel Burning Rate: The fuel burning rates were determined during the water boiling test. Palm kernel shell briquette and traditional charcoal samples of masses 135.00 g and 18.26 g were respectively placed in separate coal pots and ignited. Their final masses were recorded after the water boiling test (Table 4). The fuel burning rate (FBR) is the ratio of the mass of burnt matter to the total time taken i.e. $FBR = \frac{Mi - Mf}{T}$ (Bediako et al., 2016). Mi (in grams) is the initial mass of the sample briquette, Mf (in grams) is the final mass of the burnt briquette (charred remnant and ashes), and T (in minutes) is the total time to attain constant burnt briquette mass.

Specific Fuel Consumption: The specific fuel consumption (SFC) is the ratio of the mass of fuel consumed to the volume of water evaporated i.e $SFC = \frac{Mf1 - Mf2}{Vw1 - Vw2}$. $Mf1$ and $Vw1$ are respectively, the mass of fuels and volume of water in the pot before boiling, and $Mf2$ and $Vw2$ are the mass of briquette remnants and volume of water after boiling respectively. SFC is calculated (Table 4) in grams per millilitre (g/ml) (Mbamala, 2019).

4. Results

The summary of the results of the proximate analysis, ultimate analysis, and combustion tests from various fuels are illustrated in the table below.

The initial and final weight of the palm kernel shells were seen to be 1500 g and 1398 g respectively (Table 1). These values were used to calculate the percentage recovery of the biochar to be 93.2 %. Following the final recovered char, a total number of 10 briquettes were produced.

The proximate analysis for the various samples: palm kernel shells (PKS), charred PKS, uncharred PKS, briquette PKS, fuelwood, and charcoal, generally showed clear differences (Table 2). Specifically, PKS briquette recorded the lowest percentage value in moisture content (1.08 %) while fuelwood recorded the highest (16.00 %). A slight difference of 0.5 % was observed for the two types of shells (*Dura &Tenera*), 8.50 % and 8.00 % respectively, while the percentage moisture content in charcoal was seen to be 6.75 % less than the value obtained for fuelwood.

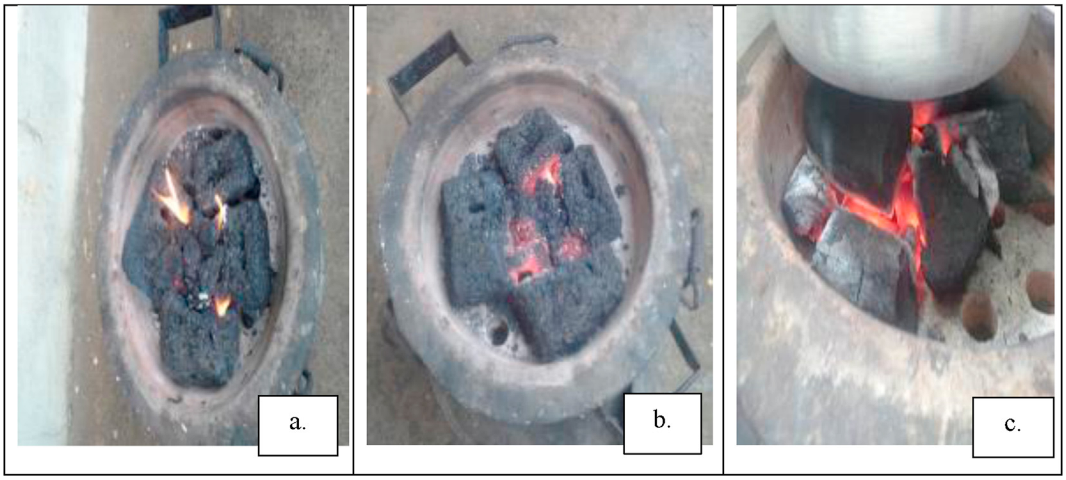

Figure 3. Illustrative diagrams of combustion observed in shell briquettes and charcoal (*Acacia*): a. Appearance of PK briquette after 8 min of ignition, b. Appearance of PK briquette after 30 min of ignition and, c. Appearance of charcoal after 30 min of ignition.

The test for volatile matter recorded the highest for PKS (*Tenera*), 89.00 % followed by charcoal, 86.00 %.

The volatile matter percentage value of PKS (*Dura*) had a slight difference of 0.5 % to the value obtained for fuelwood. There was a reduction for volatile matter in the charred PKS (69.62 %) however, this increased to 71.80 % after briquetting. PKS (*Dura*) recorded the lowest ash content (0.03 %) as compared to fuelwood with the highest value of 2.04 %. This value saw a difference of 1.26 % from that obtained for charcoal (0.78 %). The percentage of ash recorded for PKS (*Tenera*) and charred PKS was the same (0.04 %) but the charred PKS increased after briquetting to 0.06 %. The fixed carbon values of PKS (*Dura, Tenera*, charred, and briquette) increased sequentially with PKS briquette recording the highest (27.07 %) while fuelwood recorded the lowest (1.46 %).

From Table 3, the percentages of carbon, hydrogen. nitrogen, sulfur and oxygen for PKB briquette were respectively 48.90 %, 4.10 %, 1.02 %, 0.22 % and 42.86 %.The calorific value for charred PKS was seen to be 18.27 MJ/kg. This value increased after briquetting to 20.27 MJ/kg. PKS and charcoal recorded the least High Heating Value of 17.50 MJ/kg.

Table 4 gives details on the combustion analysis carried out for PKS briquette and charcoal.

5. Discussion

5.1. Proximate analysis of palm kernel shells and charcoal

From the result in Table 2, PKS briquette moisture content recorded was 1.08 %. According to the research conducted by Onochie et al. (2017), good moisture content for cooking fuels ranges between 8-12 % and less. Additionally, this is considered as key for good and sustainable combustion influencing the energy value of fuels (CHEMIK, 2013). In comparison to the raw residues after pyrolysis, the result of the PKS briquette showed a lesser value of percentage moisture content (1.08 %) as against that obtained from the raw residues (*Dura and Tenera*), 8.00 % and 8.50 % respectively. The palm kernel shell residues, although used in homes in its raw form during cooking, are regarded as not quite suitable as they emit excessive smoke due to organic constituents (Ukpaka et al., 2019). The reduction in moisture content resulted from the pyrolysis. Essentially, it means that PKS briquette is more efficient and sustainable than the raw residues, charcoal, and fuelwood when used as an alternative fuel. Results generated for charcoal i.e. 9.25 % although less than that recorded for fuelwood (16.00 %) is comparatively higher than PKS briquette percentage moisture content. Increased moisture content depicts less efficient burning with excessive smoke emission (Agyei et al., 2019; Onochie et al., 2017). This explains the excessive emission of smoke during combustion for the charcoal. This places PKS briquette at a more advantageous point since fuel produced is efficient and produces no emissions during combustion (Ukpaka et al., 2019).

The high percentage volatile matter content in charcoal i.e. 86.00 % recorded in Table 2, corresponds to the observation made during the combustion test. It was observed that charcoal with a percentage volatile matter of 86.00 % readily ignited against PKS briquette (71.80 %) with a lower percentage volatile matter (Table 2). This contributed to the increased ignition time and demand for kerosene in the PKS briquette. This observation corresponds to Kurnia et al. (2016) stating that charcoal has high volatile matter and therefore ignites and burns out faster. The raw residues (*Dura* and *Tenera*) were seen to possess high volatile content of 81.00 % and 89.00 % respectively. This should have influenced the final percentage of the charred shells to be within the range of 81–89 %, however, this wasn't so as charred PKS recorded a percentage volatile matter of 69.62 %. The raw residues were disproportionately mixed and might account for the decrease in value, as it is possible; a greater quantity of PKS (*Dura*) with a lesser percentage volatile matter 81.00 % was utilized in the experiment. Although charcoal consisting of pure wood ignites relatively quickly and burns out, the briquette is advantageous as it becomes hot evenly and remains at a constant temperature for a longer time during use as observed in the combustion test (Kurnia et al., 2016).

Ash content in biomass is a complex problem. The amount of ash depends on the content of organic and inorganic matter and possible impurities. The ash content in biomass depends on the sampling point, harvesting time, and harvest conditions (Onochie et al., 2017). The calculated ash content in PKS briquette i.e. 0.06 % recorded was less than the value obtained for charcoal (0.78 %) and fuelwood (2.04 %). Fuelwood recorded the highest among all fuel samples and might have resulted from the large organic constituents. The reduced ash content in PKS briquette might have resulted from the low organic constituents after pyrolysis. During the combustion test, PKS briquette produced low ash content, unlike charcoal that burnt faster and incomplete, thus forming many ashwoods. The low ash content of PKS briquette is in agreement with the report of Chin Yee & Shiraz (2013) stating that higher ash values are detrimental to boiler operations. The raw residues (*Dura* and *Tenera*) with respective values 0.03 % and 0.04 % had a slight difference of 0.01 % in the ash percentage composition. The value of the PKS raw residues was still maintained at 0.04 % after the PKS was charred. The increase in percentage value recorded was 0.02 %. Many industries, according to (CHEMIK, 2013), generally consider PKS as good fuel for the boilers as it generates low ash amounts, low potassium, and chlorine facilitating less ash agglomeration when used. Furthermore, the little ash generated after a long time of combustion in PKS briquette contains no toxic heavy metals or other environmental harmful pollutants (CHEMIK, 2013) as compared to charcoal and wood with higher ash content contributing greatly to air pollution and can end up in your food during meal preparation (Onochie et al., 2017).

Fixed carbon acts as the main heat generator during burning. The percentage of fixed carbon from the experiment in the PKS briquette is 27.07 %. This was the highest value among all samples. The percentage fixed carbon in the charcoal was 3.97 % and in fuelwood, 1.96 %. The differences observed in charcoal and fuelwood might have resulted from the processing (carbonization) of fuelwood into charcoal increasing the value of carbon in charcoal by 2.01 %. There were variations in the values obtained for the raw residues (*Dura* and *Tenera*), 10.47 %, and 2.96 % respectively. The variation can be accounted for from the thickness of the shells. PKS (*Dura*), according to Kurnia et al. (2016) possess thick shells while PKS (*Tenera*) possesses the opposite. This property might have increased the carbon content and further contributed to the final charred fixed carbon percentage of 23.65 %. Fixed carbon correlates to the heating value and has a large influence on the time the water took to boil during the combustion test for both fuels (Table 3).

Table 2. Summary of proximate analysis of all fuels.

Component (wt. %)	Palm Kernel Shells	Palm Kernel Shells	Palm Kernel Shells	Palm Kernel Shells	Fuel Wood (*Acacia*)	Charcoal (*Acacia*)
	Dura (Local) (wt. %)	*Tenera* (Agric) (wt. %)	Charred (wt. %)	Briquetted (wt. %)	Fuel Wood (wt. %)	Charcoal (wt. %)
Moisture content	8.50	8.00	6.70	1.08	16.00	9.25
Volatile matter	81.00	89.00	69.62	71.80	80.50	86.00
Ash content	0.03	0.04	0.04	0.06	2.04	0.78
Fixed carbon	10.47	2.96	23.64	27.07	1.46	3.97

Table 3. Ultimate analysis of briquette PKS and associated calorific values of charred PKS, briquette PKS and charcoal.

Component (wt. %)	Briquette palm kernel shell	Calorific value/High Heating Value (HHV), (MJ/kg)		
Carbon (C)	48.90	**Charred PKS**	**Briquette PKS**	**Charcoal**
Hydrogen (H)	7.00	18.72	20.27	17.50
Nitrogen (N)	1.02	n/a	n/a	n/a
Sulphur (S)	0.22	n/a	n/a	n/a
Oxygen (O)	42.86	n/a	n/a	n/a

Table 4. Combustion test on shell briquette and charcoal (*Acacia*).

Test	Data on charcoal	Data on shell briquette
Total weight of fuel at the start of the test (g)	164.36 g	540.56 g
Total number of fuel at the start of the test	9.00 lumps	4.00 lumps
Average weight of each fuel	18.26 g	135.14 g
Total weight of fuel after water boiled	91.63 g	341.49 g
Initial volume of water in pot/Temperature	100 ml/30 °C	100 ml/30 °C
Final volume of water in pot after boiling/Temperature	78.09 ml/100 °C	90.07 ml/100 °C
Physical appearance	The color of the charcoal was black at the initial start-up	The color of the briquette was black, it was brittle to touch and took the rectangular shape of the compressor box
Density (g/ml)	26.65 g/10 ml = 2.67 g/ml	135 g/110.5 ml = 1.22 g/ml
Time for water to boil (minutes)	12.00 min	9.00 min
Ignition	The kerosene burnt out in 1 min and several lumps turned reddish, then the ash	The kerosene burnt out in 8 min and several briquette lumps turned reddish with no ash formation
Odor	The combustion produced a smoky odor	The combustion produced no odor
Spark	The charcoal burnt with lots of sparks	The briquette burnt with no sparks
Cleanliness	The cooking pot outer cover turned black from the emission of black smoke	The cooking pot remained very neat all through the cooking
Moisture content	9.00 %	1.08 %
Specific fuel consumption	3.48 g/ml	20.05 g/ml
Fuel Burning rate	Initial mass of charcoal lump = 18.26 g Final mass = 13.18 g Mass of burnt matter = 5.05 g 0.42 g/min	Initial mass of briquette = 135.00 g Final mass = 109.48 g Mass of burnt matter = 25.52 g 2.84 g/min
Smoke	It burnt with the emission of smoke	It burnt with no emission of smoke
Mass of kerosene used	5.08 g	25.50 g

5.2. Ultimate analysis and calorific value of PKS briquette

From Table 3, the carbon (C), hydrogen (H), nitrogen (N), sulphur (S) and oxygen (O) percentage composition obtained for PKS briquette were 48.90 %, 7.00 %, 1.02 %, 0.22 %, and 42.86 % respectively. All values obtained from the ultimate analysis of PKS were within range and with slight percentage differences to the values C-46.28 %, H-5.59 %, N-0.90 %, S-0.10 %, and O-46.44 %, obtained by Onochie et al. (2017). The slight differences might have resulted from the varying components including different moisture content percentage, varying harvest dates, methods of briquette preparation, weather conditions, plant genetics, and soil composition, etc (Onochie et al., 2017). With PKS known to have a low sulfur content (CHEMIK, 2013), the value obtained (0.22 %) falls within the range of sulfur content for fuels 0.5–0.8 % (CHEMIK, 2013). Additionally, with the low sulfur content in the PKS, it is expected that there would be a slow corrosion rate in coal pots when used. Nitrogen recorded a value of 1.02 %; therefore burning will cause very modest emission of nitrogen dioxide and nitrogen trioxide (CHEMIK, 2013).

PKB briquette calorific value i.e. 20.27 MJ/kg recorded the highest as compared to the value obtained for charcoal (17.50 MJ/kg) which underscores it as a good combustion fuel (Table 3). The calorific value also falls within the ASTM standard range for briquette 18 MJ/kg to 23 MJ/kg. It was observed that briquetting raised the calorific value of PKS from 18.72 MJ/kg recorded for the charred PKS to 20.27 MJ/kg recorded for PKS briquette. The increase in carbon content is in good agreement with those reported for PKS briquette by Ukpaka et al. (2019); Samiran (2015); Chin and Aris, 2013; Bruce et al. (2000). Also, according to the Dulong formula, HHV can be estimated as: $HHV = 32.79C + 150.4 (H–O/8) + 9.26S + 4.97 O + 2.42 N$ (MJ/kg). According to this equation and data reported in Table 3, HHV for PKS briquettes is 20.27 MJ/kg.

5.3. Combustion test

The water boiling tests were carried out to check the suitability of the briquettes in domestic homes as fuel (Aboagye, 2017). From the ignition test result (Table 4), the briquettes did not ignite readily until the addition of more quantities of kerosene. This observation might have resulted from the hard nature of palm kernel shells. Although at the initial stage of ignition, the same quantity of fuel was added (5.00 g), both fuels readily ignited at the spot. Therefore little amount (0.08 g) of kerosene was added. Charcoal (*Acacia*) ignited while PKS briquette required five (5) times the quantity of kerosene required for charcoal (*Acacia*) to ignite (25.05 g). The observed ignition time for PKS briquette (8 min) also corresponds to the same value (8 min) obtained by Kuti (2009).

The varying volumes of kerosene used for both fuels did not affect the time the water in the pot took to boil because palm kernel briquettes are noted for its high calorific value thus contributing to the higher combustion rate (Chin and Aris, 2013; Ugwu and Agbo, 2011). During ignition, a little emission of smoke was observed from the briquette. However, this can be linked to the binder (starch) and kerosene (fuel for ignition) used since, during pyrolysis, the charred shells produced, burnt without smoke as compared to charcoal (*Acacia*) that burnt with lots of smoke emission. The no smoke emission observed from the charred shells underscores one of the important gains of using palm biofuel briquettes for cooking in homes. This is because smoke is deleterious to health and the environment, the effect of which is well documented (Mbamala, 2019; Bruce et al., 2000; Chin and Aris, 2013).

The results of the water boiling test were used to calculate the burning rate and specific fuel consumption (SFC) of the briquette. From the result (Table 4), the burning rate obtained depicts that 2.84 g of the briquette fuel was burnt per minute during combustion. The SFC value obtained for the PKS briquette was seen to be less than 3.20 g/min obtained by Ugwu, & Agbo (2011); Agbo et al. (2011). This might have resulted from the difference in briquette's calorific value, briquette density, etc. The SFC value obtained for charcoal (3.48 g/min) showed a lesser value to PKS briquette. Although PKS briquette burns for a longer time, they disintegrated making it difficult to obtain the final mass as seen in Figure 2b. This caused a drastic reduction in the mass of PKS briquette during combustion as some quantity of disintegrated PKB was lost through the large hole openings in the coal pot.

The value of the specific fuel consumption obtained indicates that 20.05 g of briquette fuel will be consumed to boil 1.0 mL of water. This was caused by the large holes within the coal pot and disintegration of the PKS briquette making it irretrievable after combustion ended. It can be seen that the briquette after 30 min of burning still maintained its black form. No ash was seen as compared to the charcoal that after 30 min turned to ashes (see Figure 2c). Lastly, the time taken for the water to boil in the pot for the PKS briquette (9 min) was lesser than that recorded for charcoal (12 min) which underscores its great benefit in terms of faster combustion (Samiran, 2015).

6. Conclusion

From this study, we achieved the production of charcoal briquettes from palm kernel shells. The PKS briquette from the study was observed to be environmentally clean and less expensive to produce. Analysis after production revealed that moisture content, ash content, volatile matter, fixed carbon, and calorific value of the PKS briquettes were within standards. Observations and outcomes from combustion analysis and tests indicated that although PKS briquette required a longer time to ignite with more fuel, upon ignition, it produced steady heat, burnt longer, and produced no ash as compared to charcoal and fuelwood that burnt with lots of smoke emissions and remnant ash. The qualities of palm kernel shell briquette produced from this study underscore its importance as a suitable fuel. From the experiment, briquette produced possesses suitable combustion properties for household use due to limited smoke emissions contributing to a decrease in indoor and outdoor pollution. The PKS briquette produced from this research can be used in cooking, smoking of fish, ironing of clothes, etc. The materials and methods used can be adapted easily at the local communities, as it does not require expertise or special training.

Further research and development on dried PKS briquettes should include a new model of coal pot and improved cooking stoves designed with smaller holes to obtain efficient combustion and improved briquette performance.

Declarations

Author contribution statement

Osei Bonsu B. & Takase M.: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Mantey J.: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

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