Biocoal production from selected plant wastes through torrefaction

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Abstract: Torrefaction is a thermal treatment process that embroils the roasting of biomass in a low oxygen environment. It is principally exploited to produce a biofuel called torrefied biomass or biocoal. Torrefaction improves fuel characteristics and reduces emission. corn stalk (CS), rice husk (RH), mesocarp fibre (MF) and palm kernel shell (PKS) were used for studying the torrefaction of plant wastes, preparation and performance characterization of biocoal. Torrefaction was conducted using a muffle furnace at temperature of 250°C for 20 minutes and resulting samples were milled to fine particles. Samples of different ratios were prepared (CS:RH:MF:PKS (10:20:30:40), (20:30:40:10), (30:40:10:20) and (30:40:10:20) using corn starch as the binder. Manual briquetting machine was used to compound the mixture into solid shapes and subjected to physicochemical and combustion properties to determine the moisture content, ash content, fixed carbon content, volatile matter, bulk density, heating value, time to ignite, burning time with burning temperature respectively. The properties of biocoal were compared with that of wood to access their potential as a renewable energy source. The result for the physicochemical properties shows that the moisture content ranged from 15.64% to 24.88%; volatile matter (20.00 to 71.00), ash content (7.00% to 26.50%), fixed carbon (2.86% to 35.96%) and bulk density (1.16 to 1.92); for the physical properties; time to ignite ranged from 19.33 to 72.15 secs, burning time (1039.58 to 2347.89 secs), temperature (59.89°C to 273.80°C) and heating value (3080.79 to 4484.11). Sample CS:RH:MF:PKS with ratio of 30:40:10:20 have the best Combustion and Physicochemical properties.

Keywords: Torrefaction, biocoal, briquetting, physicochemical properties, renewable energy, mesocarp fibre, plant wastes

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1 Introduction

Excessive increase in carbon dioxide released into the atmosphere as a result of extensive use of fossil fuels such as coal, oil, and natural gas for energy generation has become a significant contributor, contaminating the environs and contributing significantly to global warming. There is also acid rain, resulting from atmospheric pollution which poses significant harm to vegetation and stationary water bodies (Abali et al., 2018). For many decades, the majority of Nigerians living in rural areas have relied primarily on wood fuel (charcoal, firewood, and sawdust) to meet their energy needs (Halder et al., 2014). According to Ajibola et al. (2020), Nigeria now utilizes 43 109 kg of wood as fuel annually.

Heavy dependence on crude oil for energy production makes it a leading contributor to greenhouse gases of up to 1.01% of global emissions. Also, indicators are suggesting that crude oil will

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become less significant in the energy sector in the coming years (Okonkwo et al., 2021).

Renewable energy typically comes from various sources including hydro, biomass, wind, and sun (Sukiran et al., 2017). Biomass materials commonly used for energy production include plants, wood, and waste products. These can be directly combusted to generate heat or converted into biofuels for indirect use. Different energy generation methods include direct firing, co-firing, pyrolysis, gasification, and anaerobic decomposition, all of which involve thermal conversion processes (Tumuluru et al., 2011). Thermal conversion entails heating biomass feedstock to achieve burning, dehydration, or stabilization. One such process, known as torrefaction, typically occurs at temperatures above 200 °C, during which the biomass undergoes partial thermal decomposition to improve its energy density and stability (Bioenergy Europe, 2020; Michigan State University Extension, 2012). The resulting briquettes exhibit high energy density and enhanced fuel properties.

Biomass constitutes the fourth most significant energy reserve and is responsible for fulfilling 14% of the world’s energy requirements Plant biomass, such as straw, is an important renewable resource, accounting for more than half of the annual raw material production. Straw is heterogeneous and consists mainly of inedible roots, stems, leaves, and other waste in the crop residues, and its chemical composition includes organic mixtures of cellulose, hemicellulose, and lignin, as well as carbon, oxygen, hydrogen, nitrogen, sulphur, phosphorus, potassium, and other elements (Koul et al., 2022).

About 10% of oil is extracted from oil palm, while the remaining 90% is biomass waste, including palm kernel shell (PKS), mesocarp fruit fibre (MFF), and empty fruit bunch (EFB) (Loh, 2017). For every metric ton of fresh fruit bunches produced, the palm oil industry produces biomass, which includes (12%) mesocarp fibre (MF), (5%) PKS, and (23%) empty fruit bunches. The commonly utilized palm biomasses for fuel are MF and PKS. These biomass wastes have potential for various applications, such as furniture manufacturing, fertilizer production, and energy generation (Rahman et al., 2014).

Biocoal is produced by processing dry biomass in an enclose environment (no oxygen) at high temperature, this process can be called pyrolysis or torrefaction depending on the temperature and the characteristics of the end product. Conversion of biomass to biocoal varies depending on the characteristics of the source material. Generally, biomass is processed at temperature between 500 to 800-degree faherient at a specific retention time to produce the biocoal product. It can be densified to improve its capacity and handling characteristics (Negi et al., 2020).

Biocoal has properties similar to typical fossil fuel and can be used in place of coal or wood pellets. Plant waste such as PKS, MF, rice husk(RH), and corn stalk(CS) have high calorific value, low sulphur content, and are readily available with little dust or impurities, making them ideal raw materials for bio-oil production through fast pyrolysis (Yunus et al., 2012). The resulting product is a highly hygroscopic, energy-dense, dark brown to black solid. The aim of this study is to produce biocoal from selected plant waste (CS, RH, MF and PKS).

2 Materials and methods

2.1. Materials

Samples of MF remnants and dura PKS were taken from a palm oil mill in Ibadan (7.3775^{0}N 3.9470^{0}E), Oyo State, Nigeria. The CS were obtained from a farm, RH was obtained from a rice mill at Gidan-Kwano village, Minna, Niger State, Nigeria and the corn flour from Minna market, Minna, Niger State, Nigeria Equipment used include: Muffle furnace, milling machine, drying platform, weighing equipment, Crucible, moisture can, oven, manual briquetting machine and desiccator.

2.2 Sample preparation

Dura PKS of 2874 g, 2342 g of MF, 513 g of CS and 2002 g of RH were oven dried at 180 °C for 72 hours. Water was added to 100 g of corn flour gradually and stirred until a ribbon texture of corn flour and water mixture was formed. Water boiled at 100℃, was gradually poured and stirred until the thick corn starch was formed. The weight fraction of starch was 12.34 wt%.

2.3 Torrefaction

A muffle furnace was used to torrefy the biomass, which consisted of PKS, MF, RH and CS. The biomass was torrified at 350 °C for 20 minutes. The Torrefied biomass was allowed to cool till the furnace temperature was <100°C. In order to determine the mass loss during cooling, the samples' mass were measured both before and after the process (Nyakuma et al., 2023). Figures 1 and 2 shows the torrefied samples (mesocarp, RH, CS and PKS).

(a) mesocarp fibre (b) rice husk

Figure 1 Samples of both mesocarp fibre and rice husk

(a) palm kernel shell (b) corn stalk

Figure 2 Samples of both palm kernel shell and corn stalk

2.4 Preparation of briquette samples

Samples of torrefied PKS, MF, CS and RH were milled and prepared by weighing 6 g (10%), 12 g (20%), 18 g (30%) and 24 g (40%) respectively (Table 1). The prepared samples were mixed at different proportion of CS:RH:MF:PKS: (10:20:30:40), (20:30:40:10), (30:40:10:20) and (40:10:20:30); modified starch binder of 60 g was then added to each of the mixed samples to form a biocoal. The compression of the biocoal was done using a manual briquetting machine and dried in the oven at 104ºC after which the produced biocoal samples were subjected to tests and the best biochar sample was selected.

Table 1 Experimental design of the study

Mixture	Corn stalk	Rice husk	Mesocarp fibre	Palm kernel shell
A	100%	0	0	0
B	0	100%	0	0
C	0	0	100%	0
D	0	0	0	100%
E	10%	20%	30%	40%
F	20%	30%	40%	10%
G	30%	40%	10%	20%
H	40%	10%	20%	30%

2.5 Analysis

2.5.1 Moisture content

Moisture content of each sample was determined by weighing each sample of the biocoal as Wi and placed into an oven whose temperature was set at 105ºC. The samples were removed after 24 hours and re-weighed as W_f after cooling (Moore and Johnson, 2009; Maciejewska et al., 2006). The difference in mass as per moisture was calculated as percentage moisture content were computed from Equation 1.

$$\%Moisture\ content = \frac{w_i - w_f}{w_f} \times 100 \qquad (1)$$

2.5.2 Ash content

Ash content of the samples was determined by weighing each sample of the biocoal as W2 and placed in a pre-weighed crucible (W_1). The crucible was heated in a muffle furnace for 2 hours at 550ºC. It was allowed to cool at room temperature and re-weighed as W_3 (Moore and Johnson, 2009; Maciejewska et al., 2006). Each sample's proportion of ash was determined using Equation 2.

$$\%Ash = \frac{w_3 - w_1}{w_2 - w_1} \times 100 \qquad (2)$$

2.5.3. Volatile matter

Volatile matter of the samples was determined by weighing each sample of the biocoal as W2 and placed in a pre-weighed crucible (W_1). The crucible was heated in a muffle furnace for 7 minutes at 910ºC. It was allowed to cool at room temperature and re-weighed as W_3 (Moore and Johnson, 2009; Maciejewska et al., 2006). Each sample's proportion of ash was determined using Equation 2.

$$\%volatile = \frac{w_3 - w_1}{w_2 - w_1} \times 100 \qquad (3)$$

2.5.4 Fixed carbon

The fixed carbon of the biocoals was also determined using the formula according to ASTM standard (1992). It was calculated using Equation 5 (Menon et al., 2021).

$$FC = 100 - M - VM - ASH \qquad (4)$$

Where, M represents moisture(%), VM represents volatile matter (%), and ASH represents ash(%).

2.5.5 Heating value

Higher heating value (HHV) of the biomass was determined before and after torrefaction using an IKA C5000 calorimeter calibrated to ISO 1928:2009. The biomass samples were completely dried out at a temperature of 105 degrees Celsius before analysis. A glass crucible was supplied with approximately less than 1 mm-sized ground biomass, weighing 0.5 g for each analysis. In order to ignite the sample, a cotton thread was attached to it. The crucible was then inserted inside a bomb-like container. 30 bars of purified oxygen were used to ignite the sample. Each sample was analysed in duplicate, and the average values were reported in MJ kg^{-1} (Williams et al., 2016).

$$Heating\,value = 7115.197 - 123.971 \times MC - 81.312 \times Ash + 20.742 \times FC \qquad (5)$$

2.5.6 Bulk density

Bulk density of the samples was determined by using a venier calliper to measure the height and diameter of each of the sample of the biocoal, weighing the mass of the samples. Volume of biocoal was estimated using the relationship π r^2h $\pi r^2 h$ (Olorunnisola, 2007).

$$Density = \frac{mass\ of\ biocoal(g)}{volume\ of\ biocoal(cm^3)} \times 100 \qquad (6)$$

2.5.7 Time to ignite

Samples of biocoal was weighed (1 g each), ignited at base and adjusted to give a steady light, the time taken for the ignition was taken using a stop watch and recorded in seconds as time to ignite (Oladeji, 2010).

2.5.8 Burning time

Samples of biocoal was weighed (1 g each), ignited and allowed to burn until the biocoal sample burnt into ash, the burning time was recorded in seconds for each of the samples using a stop watch (Onuegbu et al., 2011).

2.5.9 Burning temperature

Burning temperature is the temperature required to initiate and maintain combustion of the biocoals (Akuma and Charles, 2017). 1 g of the biocoal sample was weighed, ignited and allowed to burn. The burning temperature was recorded in degree Celsius using Fluke 62 MAX Mini Infrared Thermometer. Figures 3 and 4 show the biocoals and burning samples.

Figure 3 Biocoal sampels

Figure 4 Burning of samples

Table 2 Physicochemical properties of the produced biocoal

Biocoal Mixture	Moisture content, %	Volatile matter, %	Ash content, %	Fixed carbon, %	Bulk density
CS (100%)	19.75 ± 0.04^{d}	71.000 ± 4.00^{e}	7.00 ± 1.00^{a}	3.24 ± 0.09^{a}	1.16 ± 0.04^{a}
RH (100%)	17.35 ± 1.43^{bc}	20.00 ± 2.65^{a}	25.00 ± 1.32^{c}	35.96 ± 2.11^{d}	1.19 ± 0.07^{a}
MF(100%)	17.34 ± 0.57^{bc}	61.00 ± 1.73^{c}	19.50 ± 1.50^{b}	2.17 ± 0.51^{a}	1.72 ± 0.16^{b}
PKS(100%)	21.46 ± 0.85^{e}	64.00 ± 3.61^{c}	8.00 ± 1.00^{a}	6.54 ± 0.72^{b}	1.22 ± 0.18^{a}
CS/RH/MF/PKS (10:20:30:40)	24.88 ± 1.21^{e}	52.67 ± 4.04^{b}	9.50 ± 0.50^{a}	12.62 ± 1.67^{c}	1.17 ± 0.04^{a}
CS/RH/MF/PKS (20:30:40:10)	15.64 ± 0.45^{a}	55.00 ± 2.65^{b}	26.50 ± 0.50^{d}	2.86 ± 0.25^{a}	1.92 ± 0.08^{b}
CS/RH/MF/PKS (30:40:10:20)	16.61 ± 0.46^{ab}	62.00 ± 1.00^{b}	23.00 ± 2.65^{c}	7.39 ± 0.72^{b}	1.93 ± 0.36^{b}
CS/RH/MF/PKS (40:10:20:30)	18.48 ± 0.52^{cd}	62.00 ± 1.00^{c}	7.60 ± 1.28^{a}	12.02 ± 0.06^{c}	1.28 ± 0.10^{a}

3 Results and discussion

3.1 Moisture content

From the results shown in Table 2, moisture content of the biocoal samples produced from 100% RH and MF were not significantly different (17.35 ± 1.43^{bc} and 17.34 ± 0.57^{bc}), but, they were both significantly different compared with the other biocoal samples produced from 100% CS and PKS at 19.75 ± 0.04^{d} and 21.46 ± 0.85^{e}. According to Maciejewska et al. (2006), the moisture content of biocoal should be as low as 10%-15% so that there will be complete combustion of the briquettes and will also help in their storage (prevents rotting and decomposition). Samples CS:RH:MF:PKS at ratios 20:30:40:10 and 30:40:10:20 were not significantly different (15.64±0.45^{a} and 16.61±0.46^{ab}), however, they were significantly different from the biocoal samples with ratios 10:20:30:40 and 40:10:20:30 at 24.88±1.21^{e} and 18.48±0.52^{cd}. Drying decreased the moisture content of biocoal, the lower the moisture content of biocoal, the higher the burning rate (time) and temperature generated (Akuma and Charles, 2017). Mixture ratio 10:20:30:40 has low moisture content, high burning rate (time) and high temperature. Figure 5 shows the mean variation of moisture on all the biocoal samples.

Table 3 Physical properties of the produced biocoals

Biocoal mixture	Time to ignite (secs)	Burning time (secs)	Temperature (^{0}C)	Heating value
CS (100%)	22.08±1.07^{a}	1039.58±12.05^{a}	178.20±2.10^{d}	4166.11±2.11^{de}
RH (100%)	72.15±1.76^{e}	1254.44±14.87^{c}	59.89±2.19^{a}	3710.74±124.48^{bc}
MF(100%)	39.25±0.96^{d}	1316.92±101.11^{cd}	254.60±10.44^{e}	3426.27±174.49^{ab}
PKS(100%)	26.89±7.08^{b}	1146.00±54.44^{b}	78.96±1.72^{b}	3940.27±59.85^{cd}
CS/RH/MF/PKS (10:20:30:40)	41.00±0.39^{d}	2347.89±61.28^{e}	157.83±4.55^{c}	3520.56±480.86^{b}
CS/RH/MF/PKS (20:30:40:10)	31.98±1.43^{c}	1394.33±17.95^{d}	156.00±2.65^{c}	3080.79±93.90^{a}
CS/RH/MF/PKS (30:40:10:20) CS/RH/MF/PKS (40:10:20:30)	19.33±0.22^{a}	1250.75±63.96^{c}	149.00±1.18^{c}	3339.65±181.47^{ab}
CS (100%)	33.48±1.65^{c}	1403.07±63.93^{d}	273.80±6.32^{f}	4484.11±144.37^{e}

Note: In this table, values separated by the same superscript letter are not significantly different from one another at the 0.05 level. Values represent means + standard errors of three measurements.

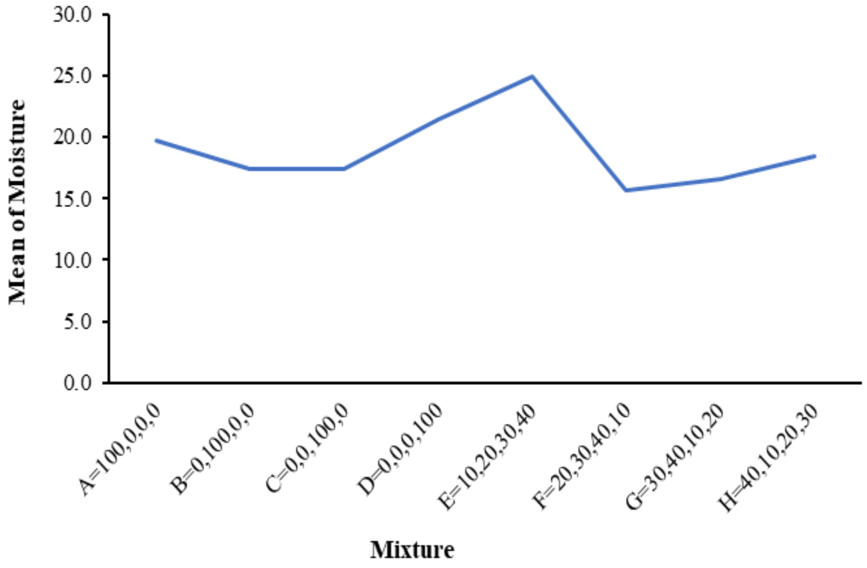

Figure 5 Mean of moisture of bio-coals

3.2 Volatile matter

The results of the volatile matter determined is shown in Table 2. The volatile matter of the biocoal samples from 100% MF and PKS were not significantly different (61.00±1.73^{c} and 64.00±3.61c) but they were significantly different compared with the other biocoal samples produced from 100% CS and RH (71.000±4.00^{e} and 20.00±2.65^{a}). Biocoal mixture CS:RH:MF:PKS at ratios 10:20:30:40, 20:30:40:10, 30:40:10:20; were not significantly different (52.67±4.04^{b}, 55.00±2.65^{b} and 62.00±1.00^{b}) but are all significantly different compared with mixture of ratio 40:10:20:30 (64.00±3.61^{c}). Higher volatile matter is an indication of easy ignition of the biocoal. It was observed that the higher the volatile matter the faster it ignites and the lower its ash contents, 100% CS and mixture ratio 30:40:10:20 have high volatile matter, low time to ignite and ash content. Figure 6 shows the mean volatile matter of the biocoal samples.

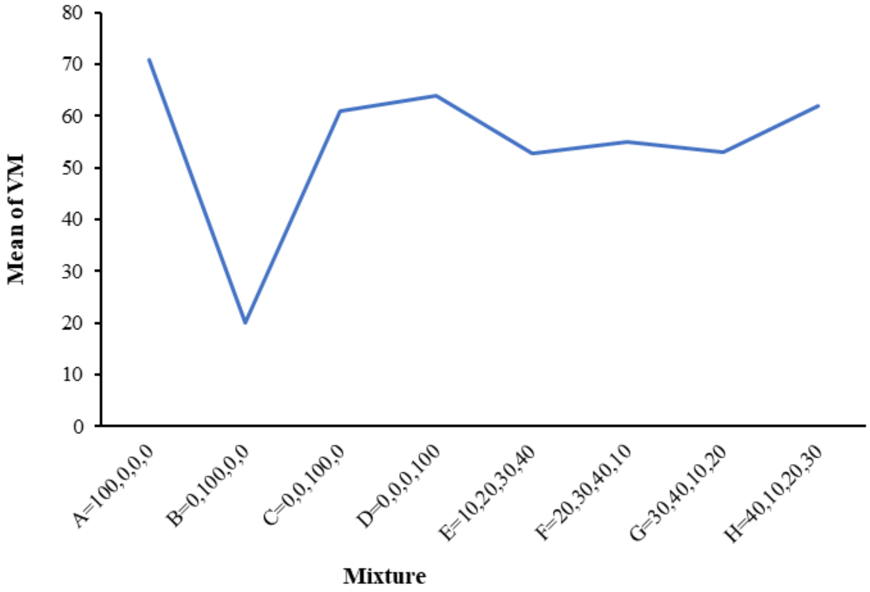

Figure 6 Mean volatile matter of biocoal samples

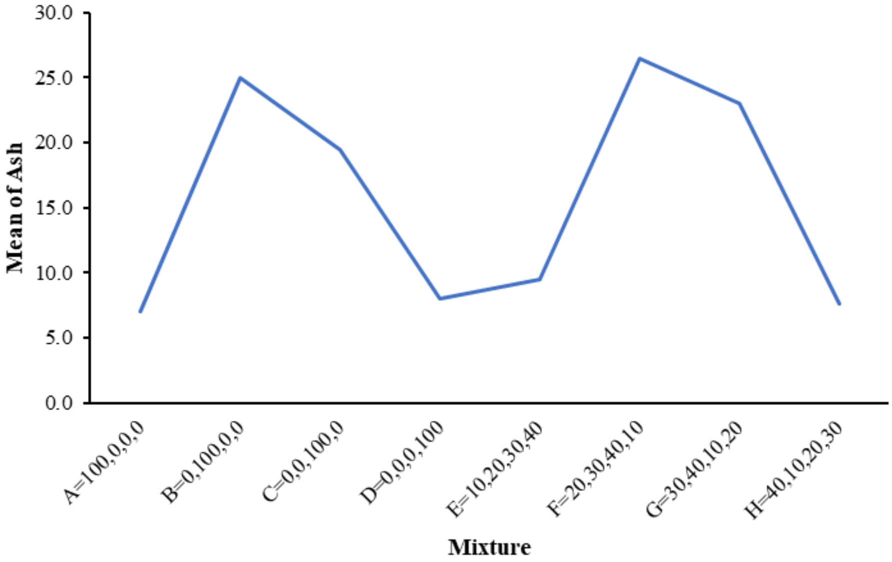

Figure 7 Mean ash content of biocoal samples

3.3 Ash content

Results of the ash content determined is shown in Table 2. Ash content of biocoal sample from 100% CS and PKS were not significantly different (7.00±1.00^a and 8.00±1.00^a) but were significantly different compared with other biocoal samples produced from 100% RH and MF (25.00±1.32^c and 19.50±1.50^b) Ash content is the complete quantity of material remaining after combustion of biocoal. Biocoal mixture CS:RH:MF:PKS at ratios 10:20:30:40 and 40:10:20:30, were not significantly different (9.50±0.50^a and 7.60±1.28^a), however, they were significantly different compared to mixture ratios 20:30:40:10 and 30:40:10:20 (26.50±0.50^d and 23.00±2.65^c). Ash content is the complete quantity of material remaining after combustion of biocoal. It was observed that a rise in ash yield correlates to a decrease in heating value while low ash content correlates with increase in heating value, 100% CS and mixture ratio 40:10:20:30 have low ash content and high heating value. Ash causes dust particle emissions and burning effects of biocoal, therefore, biocoal with low ash content are preferred (Davies and Abolude, 2013). Figure 7 shows the mean variation of ash content of the biocoal samples.

3.4 Fixed carbon

Fixed carbon is the amount of non-volatile carbon that is still present in a coal sample; the higher the fixed carbon content, the better the biocoal (Li et al., 2016). Result presented in Table 2 shows that Fixed carbon of the biocoal sample from 100% CS and MF were not significantly different (3.24±0.09^{a} and 2.17±0.51^{a}), however, they were significantly different compared with biocoal samples produced from 100% RH and PKS (35.96±2.11^{d} and 6.54±0.72^{b}). Biocoal mixture CS:RH:MF:PKS at ratios 10:20:30:40 and 40:10:20:30, were not significantly different (12.62±1.67^{c} and 12.02±0.06^{c}), however, they were significantly different compared with 20:30:40:10 and 30:40:10:20 (2.86±0.25^{a} and 7.39±0.72^{b}). It was observed that high fixed carbon content corresponds to high heating value and the better the bio-coal, 100% RH and mixture ratio 40:10:20:30 The mean variation between the samples are presented in Figure 8.

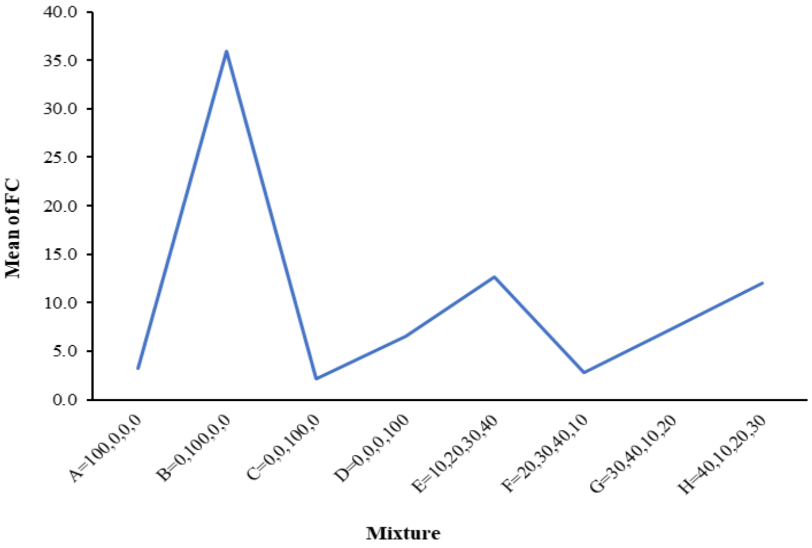

Figure 8 Mean fixed carbon of biocoal samples

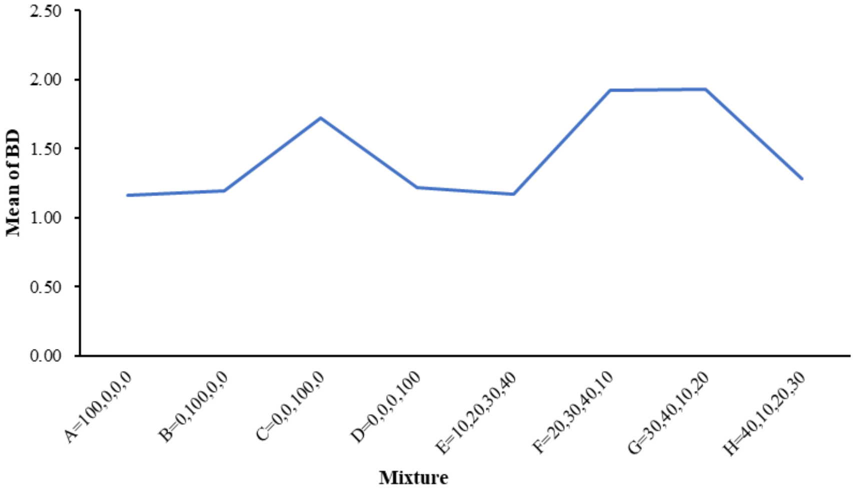

Figure 9 Mean bulk density of the biocoal samples

3.5 Bulk density

Briquetting process increased the density of the biocoal and improved the handling characteristics. The recorded results in Table 2 show that, bulk density of biocoal sample from 100% CS, RH and PKS were not significantly different (1.16±0.04^{a}, 1.19±0.07^{a} and 1.22±0.18^{a}), however, they were significantly different compared with biocoal produced from 100% MF (1.72±0.16^{b}). Biocoal mixture CS:RH:MF:PKS at ratios 10:20:30:40 and 40:10:20:30 were also not significantly different (1.17±0.04^{a} and 1.28±0.10^{a}), they were however significantly different when compared with ratios 20:30:40:10 and 30:40:10:20 (1.92±0.08^{b} and 1.93±0.36^{b}) respectively. Density of the coal determines the duration they will ignite as well as how much ash will be produced during combustion (Halder et al., 2014). It was observed that biocoal sample with high bulk density produced more ash content and takes longer time to ignite. Figure 9 shows the mean bulk density of the biocoal samples.

3.6 Time to ignite

Ignition time (time to ignite) was taken as the average time taken to achieve a steady glowing flame. The results of the time taken for the biocoal samples to ignite in Table 3 shows that samples from 100% CS, RH, MF and PKS were all significantly different. Biocoal mixture CS:RH:MF:PKS at ratios 20:30:40:10 and 40:10:20:30 however, were not significantly different (31.98±1.43^c and 33.48±1.65^c) but both were significantly different, compared with the other mixed samples, 10:20:30:40 and 30:40:10:20 (41.00±0.39^d and 19.33±0.22^a) respectively. It was observed that biocoal sample with short ignition time will catch fire easily (100% CS and CS:RH:MF:PKS 30:40:10:20). Figure 10 shows the mean values of time to ignite of the biocoal samples.

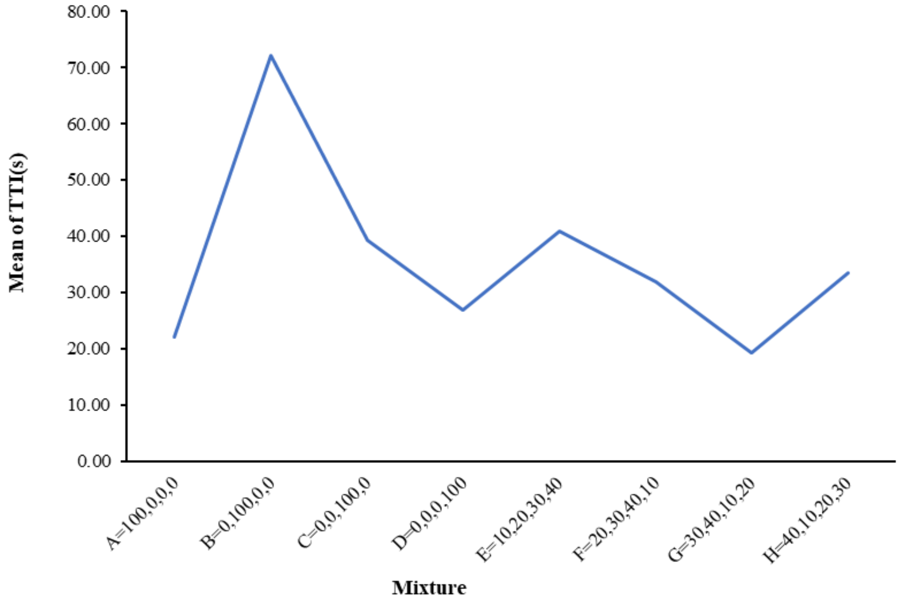

Figure 10 Mean values of time to ignite of the biocoal samples

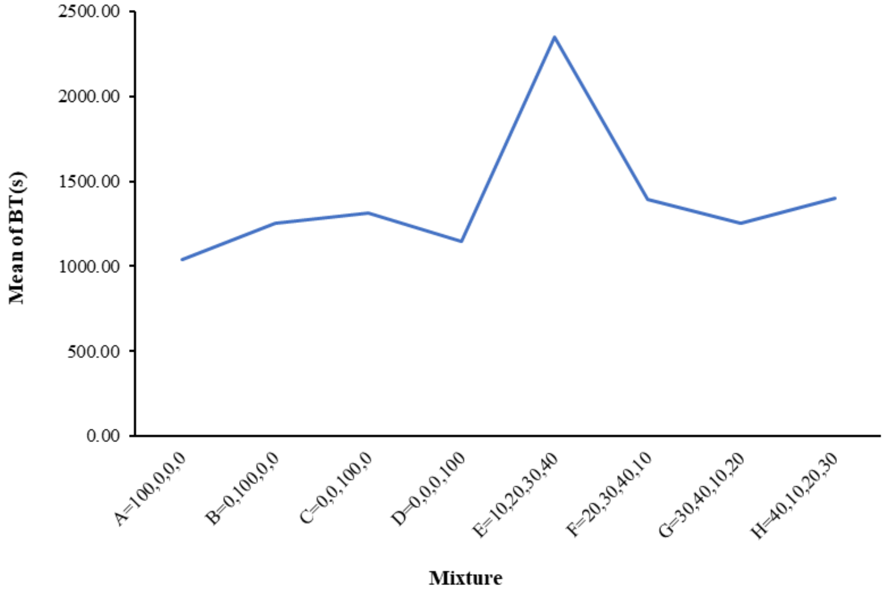

Figure 11 Mean burning time of the biocoal samples

3.7 Burning time

Burning time is the time taken for each of the biocoal sample to burn completely into ashes under similar condition. Result presented in Table 3 shows that biocoal samples from 100% RH and MF were not significantly different (1254.44±14.87^{c}and 1316.92±101.11^{cd}), however, they were significantly different from 100% CS and PKS (1039.58±12.05^{a} and 1146.00±54.44^{b}). Biocoal mixture CS:RH:MF:PKS at ratios 20:30:40:10 and 40:10:20:30 (1394.33±17.95^{d} and 1403.07±63.93^{d}) were not significantly different, however, they were significantly different compared with ratios 10:20:30:40 and 30:40:10:20 (2347.89±61.28^{e} and 1250.75±63.96^{c}) respectively. It was observed that the mixture with ratio 10:20:30:40 have the highest burning time of 2347.89 seconds. Figure 11 shows the mean burning time of the biocoal samples.

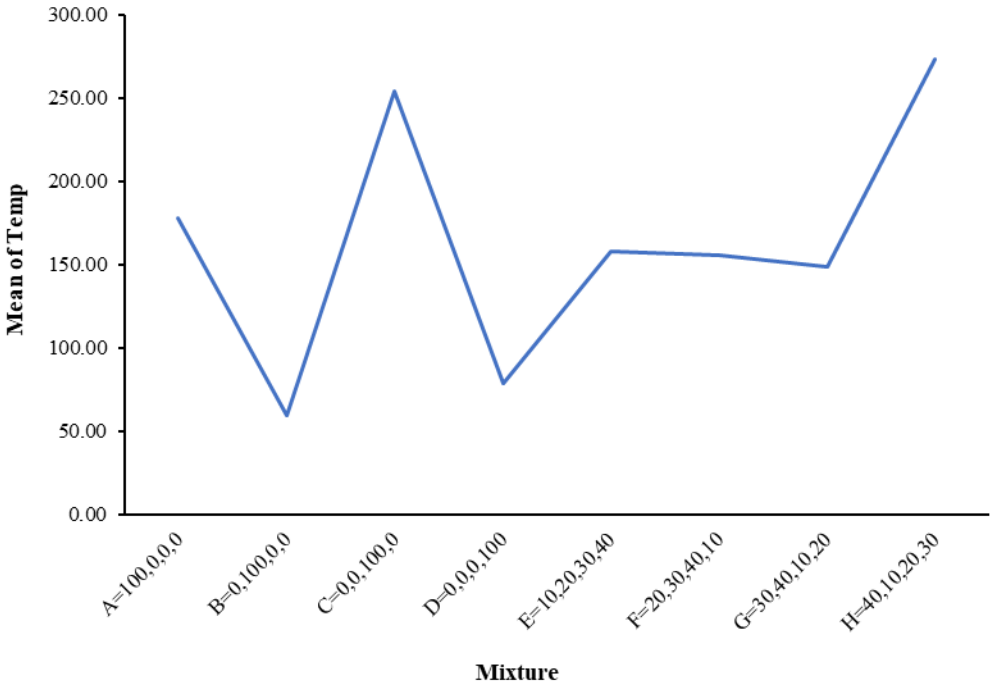

Figure 12 Mean burning temperature of the biocoal samples.

3.8 Burning temperature

Results presented in Table 3 shows that biocoal samples produced from 100% CS, RH, MF and PKS are significantly different (178.20±2.10^{d}, 59.89±2.19^{a}, 254.60±10.44^{e} and 78.96±1.72^{b}). However, biocoal mixture CS:RH:MF:PKS at ratios 10:20:30:40, 20:30:40:10 and 30:40:10:20 were not significantly different (157.83±4.55^{c}, 156.002.65^{c}, and 149.00±1.18^{c}) respectively, but they all differed significantly compared with ratios 40:10:20:30 (273.80±6.32^{f}). It was observed that the mixture with ratio 40:10:20:30, have the highest burning temperature of 273.80℃ while 100 RH have the lowest temperature. Figure 12 shows the mean burning temperature of the biocoal samples.

3.9 Heating value

Results of the heating value determined is shown in Table 2. Heating value of biocoal sample from 100% CS and PKS were not significantly different (4166.11±2.11^{de} and 3940.27±59.85^{cd}), however, they were significantly different from RH and MF (3710.74±124.48^{bc} and 3426.27±174.49^{ab}). Biocoal mixture CS:RH:MF:PKS at ratio 10:20:30:40 and 30:40:10:20 were not significantly different (3520.56±480.86^{b} and 3339.65±181.47^{ab}), however, they were significantly different from ratios 20:30:40:10 and 40:10:20:30 (3080.79±93.90^{a} and 4484.11±144.37^{e}) respectively. Heating value is the most important fuel property, higher heating value of a biocoal is required (Ajibola et al., 2020). It was observed that 100% CS and ratio 40:10:20:30 have the highest heating value of 4166.11 and 4484.11

respectively. Fig. 13 shows the mean heating value of the biocoal samples.

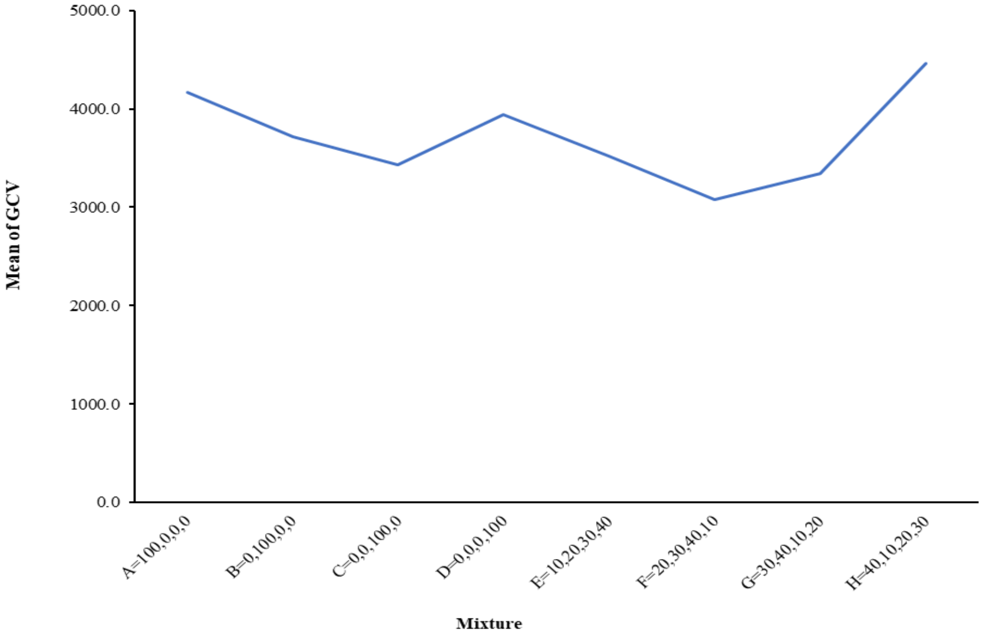

Figure 13 Man heating value of the biocoal samples

4 Conclusion

The findings from this study have shown that the briquettes produced from these agricultural wastes residues produced good biocoal. It can however be concluded that the physical (combustion) properties of the produced biocoal shows that CS, RH, MF and PKS at 30:40:10:20 mixture have the lowest time to ignite at 19.33secs while mixture 10:20:30:40 at 41.00secs have the highest time to ignite. Mixture 10:20:30:40 at 2347.89secs have the highest burning time followed by mixture 40:10:20:30 at 1403.07secs. Mixture 40:10:20:30 at 273.80^0C have the highest temperature and heating value.

The Physicochemical properties of the produced biocoal were obtained as follows: Cs, Rh, Mf, Pks at 20:30:40:10 have the lowest moisture content at 15.64% followed by 30:40:10:20 at 16.61%. Mixture 30:40:10:20 at 62.00% have the highest volatile matter while 10:20:30:40 at 52.67% have the lowest volatile matter. Biocoal with the lowest ash content was mixture 40:10:20:30 at 7.60% followed by mixture 10:20:30:40 at 9.50% and mixture 30:40:10:20 at 23.00%. Mixture 20:30:40:10 at 2.86% have the lowest fixed carbon followed by mixture 30:40:10:20 at 7.39%. Furthermore, mixture 10:20:30:40 at 1.17% have the lowest bulk density followed by mixture 40:10:20:30 at 1.28%.

The ratio with the best properties is the CS:RH:MF:PKS at 30:40:10:20, as high heat was generated during combustion, high temperature was attained, lesser ash was generated and no smoke was produced.

References

Abali, H. W., O. M. Etebu, and T. G. Leton. 2018. Corossitivity of pollutants from gas flares on galvanized roofing sheets in Idu, Rivers State, Niger Delta of Nigeria. *Journal of Environment Pollution and Human Health*, 6(1): 1-6.

Ajibola, A. F., R. M. Olalekan, S. O. Catherine, A. A. Olusola, and A. P. Adekunle. 2020. Policy responses to addressing the issues of environmental health impacts of charcoal factory in Nigeria. Necessity today; essentiality tomorrow. *Communication, Society and Media*, 3(3): 1-36.

Akuma, O., and M. Charles. 2017. Characteristics analysis of bio-coal briquette (coal and groundnut shell mixtures). International *Journal of Scientific Research in Science and Technology*, 2(3): 30-38.

ASTM Standards. 1992. ASTM designation: C187-92, Standard Test Methods for Normal Consistency of Hydraulic Cement. West Conshohocken, PA, USA.: ASTM.

Bioenergy Europe, 2020. Torrefaction – Glossary entry.

Bioenergy Europe. Available at: https://bioenergyeurope.org/glossary/torrefaction [Accessed 16 September 2025].

Davies, R. M., and D. S. Abolude. 2013. Ignition of burning rate of water Hyacinth briquette. *Journal of Scientific Research and Report*, 2(1): 111-120.

Halder, P. K., N. Paul, and M. R. A. Beg. 2014. Assessment of biomass energy resources and related technologies practice in Bangladesh. *Renewable and Sustainable Energy Reviews*, 39: 444-460.

Koul, B., M. Yakoob, and M. P. Shah. 2022. Agricultural waste management strategies for environmental sustainability. *Environmental Research*, 206: 112285.

Li, A., H. Liu, H. Wang, H. Xu, L. Jin, J. Liu and J. Hu. 2016. Effects of temperature and heating rate on the characteristics of molded bio-char. *Bioresources*, 11(2): 3259-3274.

Loh, S. K. 2017. The potential of the Malaysian oil palm biomass as a renewable energy source. *Energy Conversion and Management*, 141: 285–298.

Maciejewska, A. K., H. Veringa, J. P. M. Sanders, and S. D. Peteves. 2006. Co-firing of biomass with coal constraints and role of biomass. *International Journal of Biomass and Constraint*, 79(34): 786-789.

Menon, S. D., K. Sampath, and S. S. Kaarthik. 2021. Feasibility studies of coconut shells biomass for downdraft gasification. *Materials Today: Proceedings*, 44(Part2): 3133-3137.

Michigan State University Extension, 2012. Torrefaction: What is that? Michigan State University. Available at: https://www.canr.msu.edu/news/torrefaction_what_is_that [Accessed 16 September 2025].

Moore, W. E., and D. B. Johnson. 2009. *Procedures for the Chemical Analysis of Wood and Wood Products. Revised edition*. Forest Products Laboratory, Forest Service, U.S. Department of Agriculture. University of Minnesota, U.S.A. 390 pages.

Negi, S., G. Jaswal, K. Dass, K. Mazumde, S. Elumalai, and J. K. Roy. 2020. Torrefaction: a sustainable method for transforming of agri-wastes to high energy density solids (biocoal). *Reviews in Environmental Science and Bio/Technology*, 19(2): 463-488.

Nyakuma, B. B., O. Oladokun, S. L. Wong, and T. A. T. Abdullah. 2023. Torrefaction of oil palm empty fruit bunch pellets: product yield, distribution and fuel characterisation for enhanced energy recovery. *Biomass Conversion and Biorefinery*, 13(2): 755–775.

Okonkwo, C. C., F. O, Edoziuno, A. A. Adediran, E. M. Ibitogbe, R. Mahamood, and E. T. Akinlabi. 2021. Renewable energy in Nigeria: Potentials and challenges. *Journal of Southwest Jiaotong University*, 65(3): 528-539.

Oladeji, J. T. 2010. Fuel characterization of briquettes produced from corncob and rice husk residues. *The Pacific Journal of Science and Technology*, 11(1): 101-106.

Olorunnisola, A. 2007. Production of fuel briquettes from waste paper and coconut husk admixtures. CIGR Ejournal, IX: EE06006.

Onuegbu, T. U., U. E. Ekpunobi, I. M. Ogbu, M. O. Ekeoma, and F. O. Obumselu. 2011. Comparative studies of ignition time and water boiling test of coal and biomass briquettes blend. *International Journal of Research*, 7(2): 153-159.

Rahman, A. A., N. Abdullah, and F. Sulaiman. 2014. Temperature Effect on the characterization of pyrolysis products from oil Palm fronds. *Advances in Energy Engineering*, 2(1): 14–21.

Sukiran, M. A., F. Abnisa, W. M. A. W. Daud, N. A. Bakar, and S. K. Loh. 2017. A review of torrefaction of oil palm solid wastes for biofuel production. *Energy Conversion and Management*, 149: 101–120.

Tumuluru, J. S., S. Sokhansanj, C. T. Wright, J. R. Hess, and R. D. Boardman, 2011. A review on biomass torrefaction process and product properties. *Biofuels*, 2(5): 549–565.

Williams, O., G. Newbolt, C. Eastwick, S. Kingman, D. Giddings, S. Lormor, and E. Lester. 2016. Influence of mill type on densified biomass comminution. *Applied Energy*, 182: 219-231.

Yunus, R., R. Omar, Z. Z. Abidin, and D. R. A. Biak. 2012. Oil palm as bioenergy feedstock, In Palm Oil: Production, Processing, Characterization, and Uses, eds. O. M. Lai, C. P. Tan, and C. C. Akoh, ch. 22, 653-692. Urbana, IL: AOCS Press / Academic Press.

Appendix

Nomenclature

Mf	Mesocarp fibre
Cs	Corn stalk
Rh	Rice husk
Pks	Palm kernel shell
EFB	Empty fruit brunch
FC	Fixed carbon
BD	Bulk density
TTI	Time to ignite
BT	Burning time
VM	Volatile matter
MC	Moisture content
HHV	Higher heating value