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ABSTRACT

Combustion characteristics of high-density briquettes produced from sawdust admixture at three moisture contents of 12%, 10%, and 8% using screw press extruder was investigated in this work. The briquettes were burnt in free air and developed briquette stove and the combustion characteristics data collected and analyzed. The burn characteristics investigated include ignition time, total burning time, mass reduction, normalized burn rate, the effects of density on briquette characteristics, and stove performance. The results indicated that briquettes' self-ignition time in open air and stove was slow, however, burns with a steady flame. High density of the briquette was responsible for slow flame propagation resulting in a longer time to burn out while lower density briquettes reach the burning phase faster than higher-density briquettes. The normalized burn rate increases with an increase in briquette density. The stove performance characteristics most depend on the quality of fuel material. There is an inverse relationship between specific fuel combustion and thermal efficiency of the stove. The specific fuel consumption increases with decrease in moisture content. From these results, the higher the briquettes particle moisture, the higher the specific fuel combustion and the lower the stove thermal efficiency and vice versa.

Keywords: briquette, high-density, extruder, burn rate, normalized, thermal, efficiency.

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ABSTRACT

Combustion characteristics of high-density briquettes produced from a screw press extruder using sawdust admixture at three particle moistures of 12%, 10%, and 8% was investigated in this article. The briquettes produced were burnt in free air and briquette stove while the combustion data collected was analyzed. The combustion characteristics investigated include ignition time, total burning time, mass reduction, and burn rates. The effects of particle moistures and briquette density on stove performance were also evaluated. The results show that self-ignition time and flame propagation for each briquette in open air and the stove was slow. Briquetes from lower particle moisture reach the burning phase faster than higher particle moisture briquettes. The normalized burn rate for all briquettes increased with an increase in density. The specific fuel consumption increases with decrease in particle moisture. At higher particle moisture, the specific fuel combustion reduces and vice versa for all briquettes. This result is indicative of an inverse relationship between specific fuel combustion and stove thermal efficiency.

Keywords: Briquette, high-density, extruder, burn rate, normalized, thermal efficiency.

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I. INTRODUCTION

Among the several energy resources available, fossil fuel remained the most exploited resource in today's technological world. Economic growth, urbanization, population increase, and global energy needs have led to overdependence and increased demands on the use of fossil fuels, which consequently had contributed to the outrageous increases in fuel prices in developing countries of Africa and Asia, especially in Nigeria. This increasing trend of fossil fuel prices coupled with worsening effects of global warming have prompted the exploration of alternative sources of energy such as wood and briquettes (Lim, 2007). However, these resource-based materials are under pressure from both human activities and natural factors, including draught.

According to a 2010 report of the Energy Commission of Nigeria, Nigeria, as of 2010, was consuming about 43.4 x 10^9 kg of fuel-wood annually (Ajiboye *et al.,* 2016) with an average daily consumption of about 0.5 to 1.0 kg of dry fuel-wood per person (Olorunnisola, 2007). This invariably made the demand for fuel wood to have risen to about 213.4x10^3 metric tons, while the supply would have decreased to about 28.4x10^3 metric tons by the year 2030 (Adegbulugbe, 1994). The complete reliance on the use of wood, which, is on the increase on daily basis especially in the less technologically developed countries of the world as stated by Aremu and Agarry (2013), for industrial and domestic cooking would not solve the present energy crisis; rather it would lead to deforestation or desertification resulting in further scarcity of this resource (Salunkhe, *et* *al*, 2012). As noted by Olorunnisola, (2007), this should, of necessity be characterized by a departure from the present subsistence energy usage levels, to more sustainable and diversified energy options such as densification into briquettes.

Different raw material properties produce different conditions during the densification process, and this causes differences in the final quality of the products (Qian *et al.,* 2013, Križan *et al.,* 2015). It is necessary, therefore, to characterize these material properties to know out their optimal factor for densification. It is equally important to determine the impact of the technological and material variables: raw material parameters; technological process; and structural variables (Križan *et al.,* 2015), known to grossly affect the final quality of the briquettes.

Variability in biomass materials and structural requirements have made applicable technological processes and machines used in high-density briquette production defer. The utilization of high-pressure technologies in the densification of loose materials and their use in boiler furnace chambers for remote industrial and domestic heating are strong reasons to study their combustion characteristics and increased applications (Risović *et al*., 2008).

Chin and Siddiqui, 2000 and Faizal *et al,* (2011) gave a good review of research works on the combustion characteristics of biomass. Husain *et al,* (2002) documented the combustion characteristics of low-density briquettes containing fiber and shell residues in 60:40 ratio using 10% starch (of the weight of residues) as binding agent. Li (2003) investigated the ignition temperature of coal briquette with plastic (polyethylene) addition and found that the ignition temperature decreased from 413 to 373°C when plastic was added. Currently, there are relatively few published works on the combustion characteristics of high-density briquettes produced from sawdust admixtures and its effect on different property behaviours compared to its low and medium-density briquettes. In producing high quality briquettes, several combustion characteristics such as burning rate, fuel consumption rate, smoke generation, flame propagation, ignition time, gross calorific values, and heat release values among others are required.

However, the majority of these studies were extensively carried out and reported for low and medium-density (using manual or piston press technologies). However, the present level of literature and data are not sufficient to fully exploit the full potential of high-density briquettes from sawdust admixture. Consequently, more studies are required for its characterization. This work investigates the novel combustion characteristics of briquettes produced from composite sawdust under steady-state experimental conditions.

II. MATERIALS AND METHOD

Briquette samples: In this study, samples of high-density briquettes (Figure 1) produced from sawdust admixture at 12%, 10%, and 8% particle moistures using a screw press extruder.

Briquette stove: As noted by Bello *et al*., (2013), the effects of smoke around the cooking environment make existing stoves environmentally unfriendly and uncomfortable during cooking. Therefore, a focused effort on stove design and technology, and other factors needed to deliver the health and climate benefits associated with reducing the emissions and improving the health of citizens and their economic and social impacts (Bello *et al*., 2013) necessitated the development and testing of an updraft high-density briquette/ biomass stoves (Bello *et al*., 2019).

Figure 1: Briquette samples and stove used for the test

III. METHODOLOGY

A measured quantity of briquettes was burnt and two recommended performance tests: (water boiling test (WBT) and controlled cooking test (CCT)) to evaluate quantitative and qualitative information about the fuel combustion characteristics and stove performances(Stewart, 1987) .

Water boiling test (WBT): Dry weights of experimental materials like pot and stove were taken and recorded. The pot was filled with an initial known weight of water and the same weight was maintained throughout the course of the experiment. The water temperature data was recorded at intervals of five (5) minutes until the moment the water came to a vigorous boil.

Controlled cooking test (CCT): Controlled cooking test was carried out with rice and yam and the performance characteristics of the briquettes in the stove. When the cooking was properly done, the mass of the cooked yam and time to achieve cooking were recorded with the aid of a stopwatch.

Statistical analysis tools and models: Statistical analysis was carried out to verify the significance of the variations in the selected briquettes. The model parameters were estimated using SPSS 16.0 program (Release 16.0.0 for Windows) and Excel (Microsoft Corp., 2003) software to establish relationships between briquette burn characteristics. The effects of briquette density and moisture content on the burn characteristics of the briquette was done to determine the level of significance of each parameter on measured variables.

Correlation analysis was used to examine the relationship among the variables to provide a standard index of variability between the correlation coefficients. Regression analysis was also carried out to establish the relative contributions of briquette density, and material moisture in the prediction of the combustion characteristics of each briquette. The results of the unstandardized (β) and standardized Beta (B) regression coefficients, multiple correlation coefficient (R), adjusted R^2, and its associated p values for each of the variables that suggest whether the generated regression model is a good predictor of briquettes' properties or not (Mitchual *et al.*, 2013) were determined.

Performance test variables and equations: The variables used in the calculation of stove and briquette parameters were based on the approach used by FAO (1990), Ahuja *et al.* (1997) and Olorunisola (1999). Four sets of variables used in the evaluation of test procedures are as follows:

i. *Briquette burn rate:* The procedure for the determination of briquette burn rate employed by Onuegbu *et al.* (2012) and Bello *et al.* (2015) was adopted in the experiment. Briquette sample of known weight was ignited with a burner and the weight loss measured every 10 seconds throughout the combustion process using a stopwatch until constant burnt weight was obtained. The weight loss at specific time was computed from the expression:

$$\text{Burn rate} = \textit{Total weight of burnt briquette (kg)/Total time taken} \text{ (hr)} \quad (1)$$

ii *Time spent in cooking per kilogram of cooked food (T_s):* Ratio of time spent in actual cooking to the total weight of the cooked food.

$$T_s = \textit{Total time spent in cooking (hr)/Total weight of cooked food (kg) (hr/kg)} \quad (2)$$

iii *Specific fuel consumption:* Specific fuel consumption is defined as the amount of solid fuel equivalent used in achieving a defined task divided by the weight of the task. It can be expressed as:

$$PHU = Mass\ of\ fuel\ consumed/Total\ mass\ of\ cooked\ food \quad (3)$$

iv *Thermal efficiency (η):* Thermal efficiency is a measure of the proportion of the total energy which is gainfully employed in any thermody-namic system. This is a ratio of the work done by heating and evaporating water to the energy consumed by burning wood. According to Clarke (1985) the thermal efficiency of a cooking stove depends largely on how well the heat generated is transferred from hot gas fuel line to the pot or vessel on the stove (convective heat transfer). Thermal efficiency is calculated from the percentage heat utilized (PHU) given by:

$$\eta th(100\%) = Burn\ rate\ x\ PHU \quad (4)$$

IV. RESULTS

4.1 Briquette burning characteristics

Free air and stove combustion tests were used to determine the briquettes burn characteristics. Each briquette was ignited by lighter and supplemental fuel (kerosene) enough to ensure the whole of the surface of the briquette was ignited simultaneously. Figure 2 shows the different stages of combustion processes from ignition to burnout. Figure 2(a) is the ignition phase, fire establishment can be observed burning around the briquette, Figure 2(b) & (c) are phases in the flaming combustion stage (d), is at the end of flaming combustion (burnout), and finally, in stage (e), there is no flame and the briquette decomposes purely by char combustion.

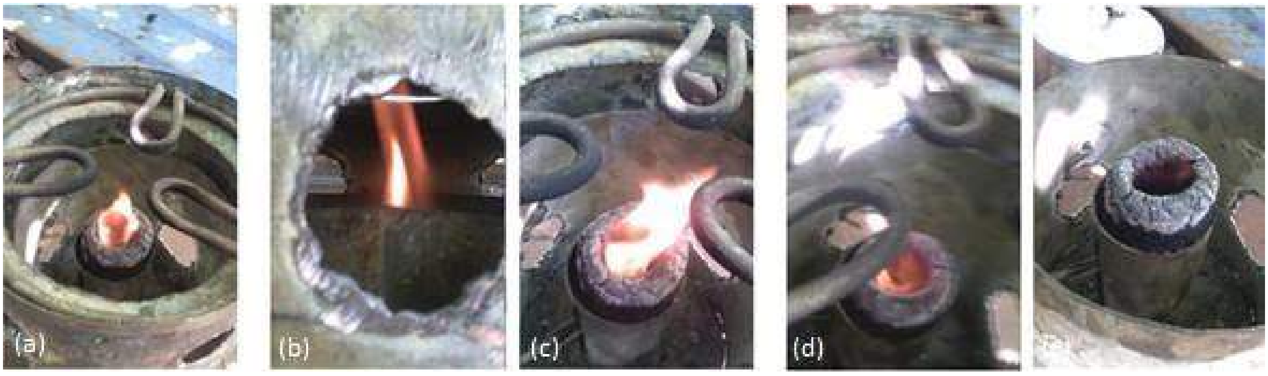

Figure 2: Flame propagation of briquette in stove combustion chamber

After igniting the lighter was removed, the combustion proceeded with flame heights of up to 46 cm. From this preliminary observation, it was evident that the designed combustion chamber could contain the flame height within the chamber as seen from Figure 2.

4.2 Briquette mass reduction rate

Table 1 shows the rate of each briquette reduction by mass consumed during burning. Mass loss was recorded for each briquette burnt at intervals until the mass of the briquette was 5% of its initial mass (Chaney, 2010).

Table 1: Mass of materials consumed in stove and normalized mass

Time (hr)	Mass of Fuel (kg)			Normalized Mass			Briquette Length (m)		
	12%	10%	8%	12%	10%	8%	12%	10%	8%
0.00	1.05	1.09	1.60	1.00	1.00	1.00	0.90	0.90	0.90
0.17	0.96	1.01	1.49	0.91	0.93	0.93	0.78	0.74	0.70
0.33	0.88	0.90	1.40	0.84	0.83	0.88	0.67	0.62	0.59
0.50	0.76	0.78	1.27	0.72	0.72	0.80	0.52	0.47	0.45
0.67	0.62	0.66	1.16	0.50	0.61	0.73	0.47	0.38	0.32
0.84	0.47	0.57	1.08	0.45	0.52	0.68	0.38	0.27	0.21
1.01	0.34	0.45	1.0	0.32	0.41	0.63	0.28	0.22	0.15

4. 3 Effect of density on NBR

The impact of mass-volume reduction on density is shown in Table 3 to find relationships between reduced mass and density of all test samples.

Table 3: Effect of mass-volume reduction on briquette density

Time (hr)	Mass of fuel (kg)			Reduced volume of briquette			Reduced density of briquette		
	12%	10%	8%	12%	10%	8%	12%	10%	8%
0.00	1.00	1.00	1.00	1.49	1.49	1.49	0.71	0.73	1.07
0.17	0.91	0.93	0.93	1.29	1.22	1.16	0.74	0.83	1.29
0.33	0.84	0.83	0.88	1.11	1.02	0.97	0.79	0.88	1.44
0.50	0.72	0.72	0.80	0.98	0.78	0.74	0.78	1.00	1.72
0.67	0.50	0.61	0.73	0.82	0.63	0.53	0.76	1.05	2.19
0.84	0.45	0.52	0.68	0.63	0.45	0.45	0.75	1.27	2.40
1.01	0.32	0.41	0.63	0.46	0.36	0.25	0.74	1.25	4.00

4.4 Briquette performance characteristics in stove

The briquette was tested in a special briquette stove to determine the variations in time required to raise water temperature to 100 °C in water boiling test (WBT) and time taken to boil specific quantity of food in controlled cooking test (CCT)

Figure 3: Water boiling and cooking test setups

4.5 Briquette burn rate determination in boiling water (WBT)

The summary of results of water boiling test (WBT) and controlled cooking tests (CCT) using each briquette sample in order to determine briquette consumption (burn rate) in briquette stove is presented below in Table 4 and 5. The controlled cooking tests (CCT) were conducted under various conditions for two varieties of food; rice and yam, respectively were presented in Table 5.

Table 4: Water boiling test (WBT) performance results

Parameter	12%	10%	8%
Time before fuel reaches steady burning (min)	3.35	7.23	2.32
Time spent to boil 1.5kg of water to 100 °C (hr)	0.14	0.09	0.07
Total time spent for total fuel combustion (hr)	0.69	0.78	0.90
Mass of consumed fuel (kg)	1.62	1.09	1.05
Burn Rate (kg/hr)	2.35	1.34	1.17

Table 5: Controlled cooking test (CCT) performance results with rice and yam

Parameters	12%	10%	8%
Initial mass of raw food (kg)	1.00(1.00)	1.00(1.00)	1.00(1.00)
Final mass of cooked food (kg)	2.39(2.33)	2.38(2.45)	2.40(2.35)
Initial mass of fuel before cooking (kg)	1.60(1.60)	1.09(1.09)	1.05(1.06)
Final mass of fuel after cooking (kg)	0.60(1.04)	0.40(0.40)	0.71(0.43)
Mass of consumed fuel (kg)	1.00(0.56)	0.69(0.69)	0.34(0.62)
Total time spent for cooking (hrs)	0.66(0.39)	0.62(0.34)	0.54(0.31)
Burn Rate (kg/hr)	1.52(1.44)	1.11(2.03)	0.6(2.00)

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Burn Rate (kg/hr)	1.52(1.44)	1.11(2.03)	0.6(2.00)

5.6 Stove performance evaluation

The performance of the stove was evaluated by determining its specific fuel consumption (SFC) and thermal efficiency and the result presented in Table 6.

Table 6: Performance evaluation of each briquette parameters

Parameters	12%	10%	10%
Specific fuel consumption (SFC)	0.75	0.68	0.61
Thermal Efficiency (TE) (%)	34.56	52.64	64.38

IIV. DISCUSSIONS

Briquette burning characteristics: Briquette self-ignition time in open air and stove was low, but when supported with little quantity of kerosene, it burns with a steady flame. Each briquette retained its shape during burning and did not expand, hence lasts significantly longer compared to medium or low-density briquettes. The flame characteristics of the burning briquette revealed a progressive smoldering within the briquette hole, followed by a growing yellow flame at the periphery and simultaneous blue flame within the center hole. This flame propagates into high yellow flame with a brilliant white flame at the center and glowing flame at the surrounding. As the briquette burns out, the flame degenerates and gradually dies off as char combustion set-in.

Briquette mass reduction rate: Briquettes with lower burn rates have better performance than those of high burn rates which burn out within a short time.

The gradients of the steady-state combustion phase for each briquette were plotted to find the normalized burn rate (NBR) for each briquette according to equation 5 is shown in Figure 4.

$$NBR = Be^{-þX} \quad (5)$$

Where

x = the density in kg/m^3

B = exponential frequency factor is a function of briquette burn time in hours.

þ= constant determined for briquette by a least-squares fit of Equation 5.

The exponential equations for each of the lines are: For 12%, 10% and 8% MC briquettes respectively:

$$NBR = 1.1003e^{-1.128s} \quad (6)$$

$$NBR=1.0924e^{-0.938s} \quad (7)$$

$$NBR = 1.02775e^{-0.526s} \quad (8)$$

An exponential function for each curve shows that the least-squares fit line is satisfactory.

To determine the values of B and β for each of the three normalized burn rates of briquette, the mean value for the constant β was determined for each briquette samples as shown in Table 7 which gives a mean of 0.864±0.002 for the sawdust briquettes burnt and the normalized burn rate (NBR) for the briquette expressed as:

$$NBR = 1.0632e^{-0.864s} \quad (9)$$

Table 7: Values of B and β for briquette moisture on NBR

MC (%)	B(hr^{-1})	β
12	1.1003	1.128
10	1.0624	0.938
8	1.0275	0.526
Mean	1.0632	0.864

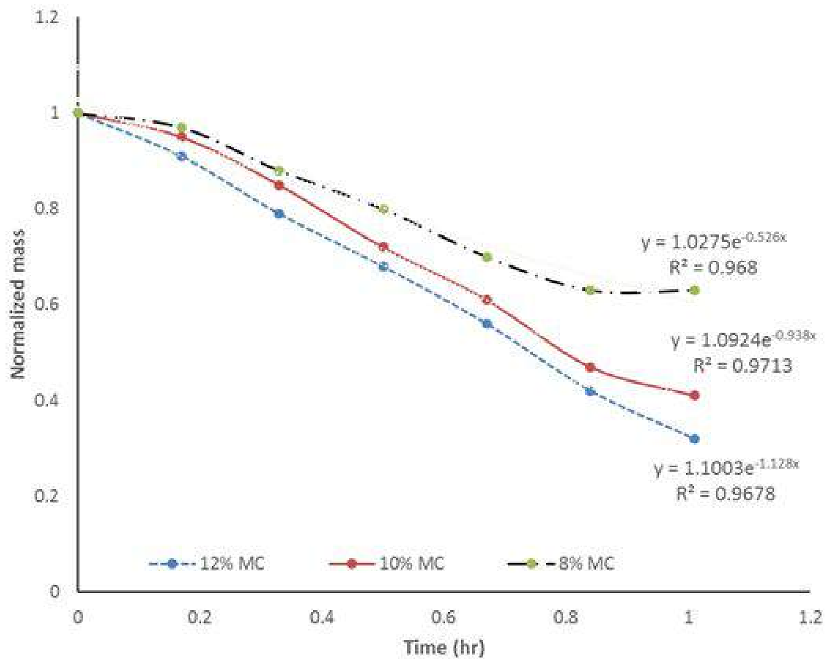

Figure 4: Plot of phase burning of each briquette and burn rate

Effect of density on NBR: The relative importance of density on the normalized burn rate is required to understand the degree to which each factor is needed to be controlled in briquette manufacture. The normalized burn rate was determined and a least-squares fit of the normalized mass was plotted against the density (Figure 5a).

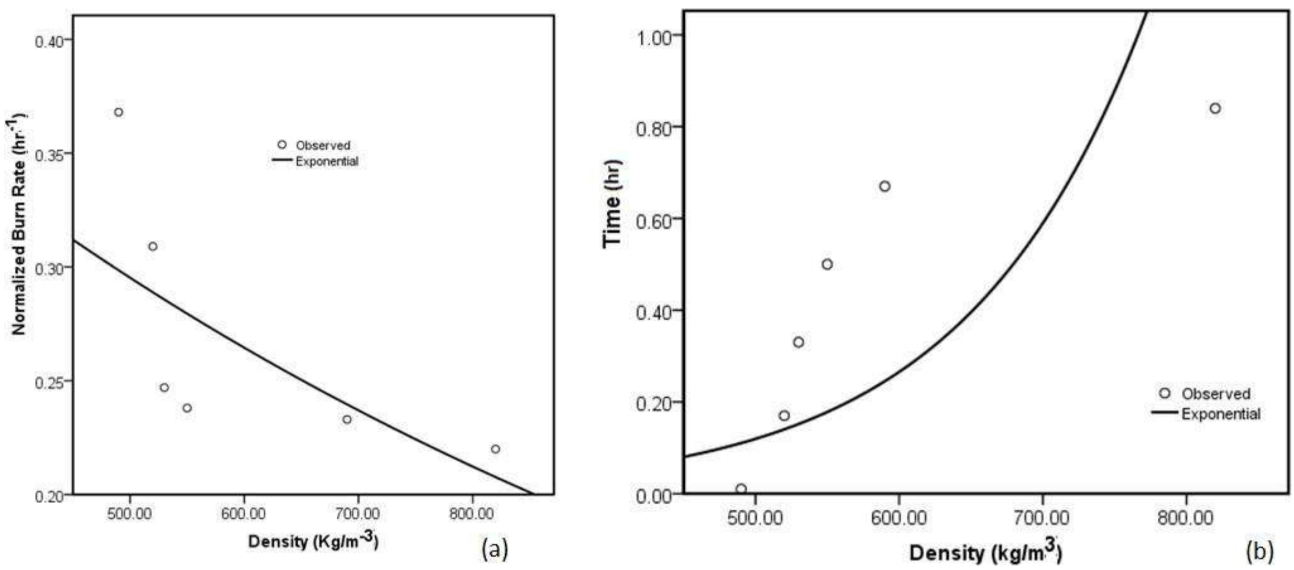

Figure 5: Effects of briquette density on a) NBR and b) total burning time (TBT)

The trend in Figure 5(a) indicates that normalized burn rate increases with an increase in briquette density. After an exponential fit on the scattered plot of NBR versus density, values of constants B and β were estimated for the curve by regression analysis as B=0.501 and β = −0.001 the NBR equation for the exponential curve is:

$$NBR = 0.501e^{-0.001s} \qquad 10$$

From the equations, the NBR shows a clear tendency to decrease as the density increases, as predicted from literature (Chaney, 2010). The result shows the significance of density on normalized burn rate; higher density briquettes have a lower normalized burn rate.

Effect of density on briquette total burning time: Considering the total time taken to burn the whole briquette starting from the initial mass to the maximum mass loss (approximately 5% of initial mass (Mandal *et al.,* 2012) to determine the total burning time (TBT), a plot of time against density (Figure 5b) gives a good estimation of (TBT). An exponential regression analysis provided the best fit curve with the regression equation (11) predicting the total burning time at a given density:

$$TBT = 0.002e^{-0.008s} \qquad 11$$

The result indicates that high briquette density was responsible for slow flame propagation resulting in longer burning time. By implication, the higher density briquette takes more time to burn out while a lower density briquettes took shorter time but reach burning phase 2 faster than higher density briquettes.

Effect of briquette density on burn rate: It is equally significantly important to note that the density of briquette increases as the mass to volume ratio reduces. The impact of mass-volume reduction on density is graphically illustrated for briquette samples in Figure 6 and these show some inverse relationships between reduced mass and density of all test samples with significant correlations in lower moisture briquettes: (0.0413, 0.969 and 0.948) for 12%, 10%, and 8% briquettes respectively.

Briquette burn rate in boiling water (WBT) and control cooking tests (CCT): From Table 4, it takes a shorter time (0.07hrs), to boil 1.50kg of water with 8% moisture content briquette, and consuming 1.05kg of fuel, while it takes longer time (0.9<0.78<0.07) hrs to consume the relatively same quantity of fuel for other briquettes.

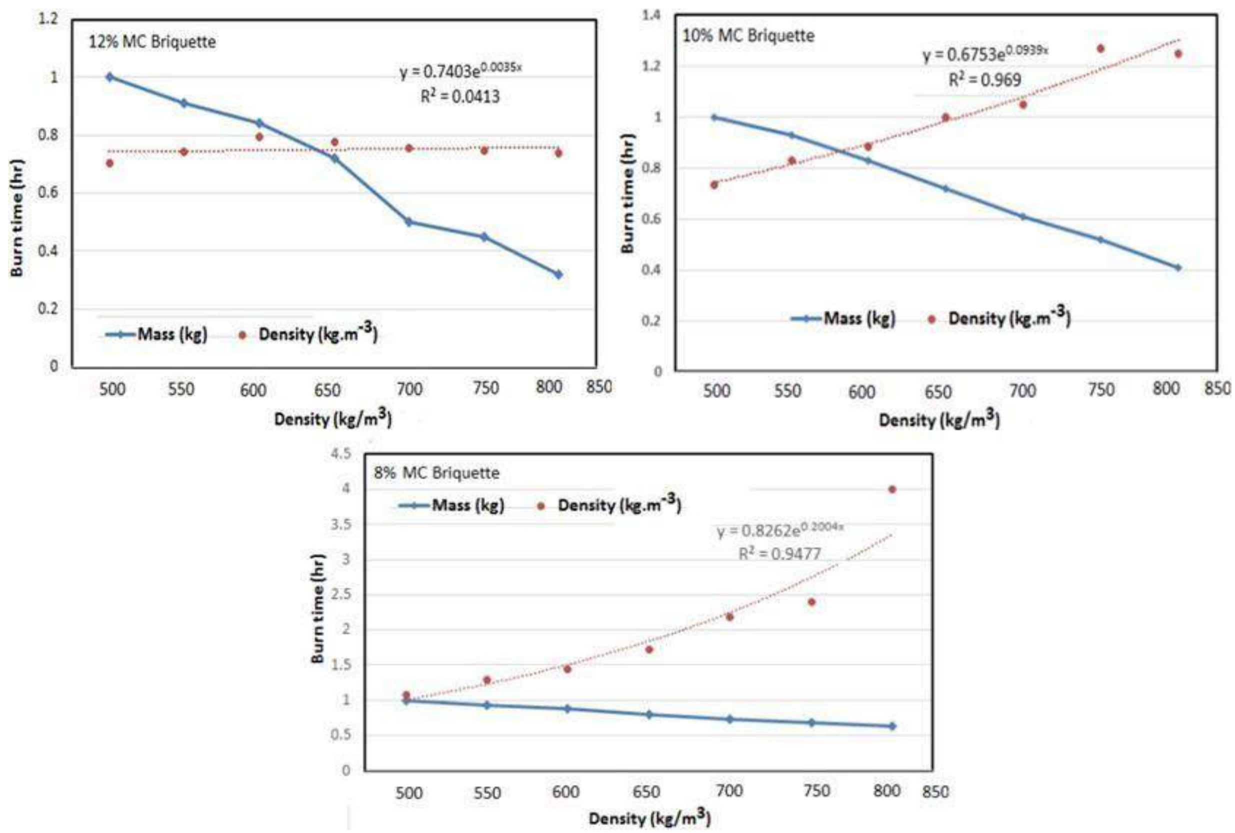

Figure 6: Effect of burn rate on mass reduction and density of 12%, 10% and 8% briquette

The rate of burning of each briquette in the stove significantly varied. The burn rate values decrease with an increase in feedstock moisture content. The implication of this is that more fuel is required for cooking with briquettes produced from higher moisture briquettes than for low moisture briquettes. Variations in the amount of briquette do not significantly affect the resulting burn rates in the cooking of each food. Total time spent in burning off the fuel varied at each stove but maintained a time range of 32-39min. Time spent in cooking rice and yam were as indicated in each operation. Relatively, the time spent in cooking ~1 kg of food; rice (yam) is not significantly different for all the briquettes burnt in the stove (minimum 0.54/0.31 hrs. for 8% moisture briquettes and maximum 0.66 (0.39) hrs. for 12% moisture briquettes). The practical implication is that a lesser quantity of 8% moisture briquettes will be required to cook the same quantity of food compared to the 12% moisture briquettes.

Stove performance evaluation: from the results, the stove has different thermal efficiencies and specific fuel consumption (SFC) when tested with different briquette samples. The result of the thermal efficiency and the average specific fuel consumption of the stove obtained from the experiment are (64.38%, 52.64% and 34.56%), and (0.6, 0.68, 0.75) kg/hr. for 12%, 10% and 8% briquette samples respectively. The thermal efficiency of the stove increases with an increase in briquette material moisture content while the specific fuel consumption increases with a decrease in moisture content. This result implies that stove performance characteristics are largely dependent on fuel material quality. Equally, from the result, it is evident that the fuel burn rate has a significant effect on the stove's thermal performances. The ability to control fuel burn rate is therefore essential if thermal stove performances are to be optimized and that there is an optimum fuel burn rate that could give maximum stove efficiency for a given configuration (Kandpal *et al.,* 1994).

IIIV. CONCLUSION

Form the experimental considerations; the briquette burn characteristics improves with increase in briquette quality. Burn rate increased for briquettes produced at lower moisture content, and reduced for higher density briquettes. Briquette combustion characteristics are dependent on the environmental conditions under which it is burned and also on the medium in which they are burned. Briquette burn rates vary from open-air burning, to controlled air (stove) burning. The briquette stove's thermal efficiency is dependent on the quality of fuel. There is an inverse relationship between specific fuel combustion and thermal efficiency of the stove. The higher the briquettes particle moisture, the higher the specific fuel combustion and the lower the stove thermal efficiency and vice versa.

Conflict of Interests

The authors declared that there is no conflict of interests regarding the publication of the article..

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