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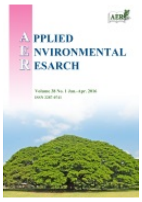

Synergetic Effects of Feedstock Mixture and Torrefaction on Some Briquette Characteristics of Cornhusk and Sawdust Wastes

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Abstract

Agricultural waste management through energy recovery is one of the critical options that could drive the clean energy production industry and properly replace the use of coal in Nigeria if done sustainably. The objective of this work therefore is to study the synergetic effect of waste feedstock mixture and torrefaction pre-treatment on some physical and performance characteristics of briquettes from cornhusk (CH) and sawdust (SD) wastes. In this work, CH and SD wastes were processed raw and torrefied at 200 to 300 °C and were mixed in the ratios between 90/10 and 10/90 for briquette production using D-optimal crossed design. Cassava starch of 20 g to 100 g of the feedstock (w/w) was used as binder. The performance characteristics of CH/SD briquettes were evaluated using standard procedures while the generated data were processed using ANOVA, regression and pareto analysis. The thermal efficiency of 29.94% and water boiling time of 12 min were obtained for CH/SD briquette blend of ratio 10/90 torrefied at 300 °C. The maximum density and water resistance index of the torrefied briquettes at different blends respectively increased between 5.78–9.77% and 75.70–85.45% over those of the raw briquettes due to torrefaction and water preconditioning. Furthermore, the lowest value of burning rate was obtained for briquettes torrefied at 300 °C at 50/50 (CH/SD) ratio. ANOVA revealed that torrefaction and feedstock blending significantly influenced the characteristics of CH/SD briquette at $p<0.05$. This study showed the potential use of torrefied briquettes from cornhusk and sawdust wastes as alternative for coal and forest wood and a new source of energy for heating applications.

Keywords: Synergetic effects; Sawdust; Cornhusk; Mixture; Torrefaction

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Introduction

Energy for domestic and heating applications remain one of the essential requirements of mankind. The efficient and commonly used devices for application have been designed to use fossil fuels such as; coal, kerosene, diesel and liquefied petroleum gas [1]. However, many rural households in Nigeria still use wood as fuel for several applications, cooking inclusive, because it is cheap and readily available. This has led to continual deforestation which enormously poses serious challenge to the environment if not abated, as it will disrupt the hydrological cycle. Agricultural wastes such as rice husk, cassava peel, groundnut shell, melon pod, including cornhusk and sawdust present an alternative, clean, cheap and sustainable energy source for applications especially in rural communities. Their use in raw state, however, is limited because of their low-energetic characteristics [2–3] and smoke caused by high moisture content (MC) and volatile matter (VM) content attributes of raw biomass [2]. Okafor [4] reported that about 1.6 million people, mainly women and children, usually die annually due to smoke from raw biomass.

Since burning of biomass fuel in their raw form has low calorific value and high MC and VM, it has been established that biomass torrefaction, which is the thermo-chemical transformation of biomass to bio-coal, and water preconditioning could upgrade raw biomass to more useful forms [5–6] and make them highly available for many heating applications.

Imoisili et al. [7] said that the use of single feedstock produces less energy required for domestic and industrial applications. Feedstock blending is therefore said to improve the strength and heating performance of agricultural wastes [3, 5, 7]. For instance, rice husk mixed with corncob improved the durability of corncob briquettes [8]. Aliyu et al. [9] stated that corncob and orange peel waste improved their suitability for solid fuel in terms of maximum density (MD). Atan et al. [10] stated that banana waste on rice husk wastes improved the strength ability and water boiling capacity of the produced fuel and was found suitable for domestic applications. Furthermore, many agricultural wastes were combined with sawdust for improvements in briquette characteristics [3, 6, 11–12] instead of using sawdust alone.

Many authors have carried out extensive work on water resistance index (WRI) determination. They stated that the increase in WRI is affected by the decrease in particle size [13], increase in binder levels [14–15], mixing of two feedstock [6, 16] and increase in temperature [3, 15]. It was further stated by Orisaleye et al. [15] that melted closely packed and insoluble substances in the voids of capillary systems of biomass, such as lignin, etc. will not allow the cell wall of biomass to soak in water.

Some researchers evaluated the performance of several feedstocks which are widespread in many rural communities [17–19]. For instance, Parmigiani et al. [20] used raw rice husk and obtained an average low thermal efficiency (TE) of 18% and high specific fuel consumption (SFC) of 4.2 MJ kg^{-1}. Oyelaran et al. [21] used groundnut shell briquettes at different binder proportions as feedstock and reported an increase in the TE from 14.47 to 18.46%; burning rate (BR) (0.587–0.881 kg h^{-1}) and SFC (0.067–0.267 J g^{-1}). Furthermore, Rajaseenivasan et al. [22] reported that the decrease in neem content on sawdust increased the BR and decreased the SFC and WBT. The low TE values (< 20%) obtained by these authors were attributed partly to the type of fuel used and its calorific value [1, 23]. This implies that the combustion performance of a fuel in terms of water boiling performance studies could be improved for better performance if appropriate briquette fuel, well processed, with high calorific value was used. Further studies show that the oxygen to carbon (O/C) and hydrogen to carbon (H/C) atomic ratios in the raw biomass blend of CH/SD reduced with the increase in the torrefaction temperature [24].

Since the calorific value (CV) of the torrefied briquette blends approached that of coal, the reduced O/C and H/C ratio through torrefaction is an indication of maximized energy [24].

Since there are scanty studies on the fuel characteristics of hybrid torrefied briquettes [5, 10], it is needful to know if the MD and WRI of feedstock blends at different torrefaction temperature is suitable for briquettes production with better qualities than firewood. This work therefore intends to study the fuel characteristics of raw and torrefied briquettes from cornhusk and sawdust wastes at different blending ratio of 90/10 to 10/90, as replacement for firewood. The model fitting, its significance and percentage contribution of densification variables to the responses were also evaluated.

Materials and methods

1) Feedstock preparation, torrefaction and water preconditioning

Cornhusk and sawdust wastes are used in this work as feedstock due to their abundance in the vicinity of Abeokuta. They are usually discarded and burnt in waste dumps leading to energy wastage and health risk to man. The CH samples cut and sieved into 1.18 mm particle size at the moisture content (MC) of 19.44% were dried at the temperature of 104.5 °C for 5 hours in an oven model DHG 9030A to the point of crispiness (MC of 8.89%) for ease of milling. SD sample at the particle size of 1.18 mm and MC of 53.93% was sun-dried for 2 weeks to the MC of 9.91%. Cassava starch was selected as binder for this work. 100 g each of these milled feedstock were poured into a thin walled crucible and torrefied with furnace model ELF 11/6 Carbolite-Gero (30-3000 °C), UK, to the torrefaction temperature of 200, 250 and 300 °C for 60 min residence time at the heating rate of 10 °C min^{-1} in an atmosphere of 78% nitrogen and 21% of oxygen. The solid yield and enhancement factor which is the calorific value enhancement value of torrefied biomass in relation with raw biomass for CH and SD was determined in line with Zhang et al. [25]. The torrefied samples were cooled, milled and sieved into less than 1.18 mm particle sizes to enhance the binding ability of the samples [26]. The torrefied CH and SD samples having the MC of 2.50 and 2.28% respectively were thereafter preconditioned by the spraying of 10% deionized water on mass basis and kept under 4 °C storage condition for 2 days for moisture distribution in line with Bai et al. [5] and Waheed and Akogun [27]. The processed feedstock was analysed for further experiments.

2) Design of experiment

A D-optimal crossed design was adopted using Design Expert (version 6.08) software. This design approach is a collection of statistical and mathematical techniques that assess the effect of experimental conditions in terms of both mixture properties and process variables useful for process development and improvement. The independent factors investigated were chosen based on literature, trial experiment and their expected influence on the fuel performance attributes. Two biomass mixtures of CH and SD at five different ratios of 90/10, 70/30, 50/50, 30/70 and 10/90 and a process variable (torrefaction temperature condition at raw, 200, 250 and 300°C) were the densification variables for the experimental design. The experiments were set up to investigate the effect of the independent factors on each response factor such as maximum density, water resistance index, burning rate, thermal efficiency, specific fuel consumption, water boiling time, oxygen to carbon ratio, and hydrogen to carbon ratio. In total, 20 experiments were required while each experiment was carried out thrice and the average presented. The synergy between the densification variables and each response factor was correlated with design expert software (D-optimal crossed design) through the polynomial model in Eq. 1 to fit the experimental data [28].

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} X_i X_j + e \quad \text{(Eq. 1)}$$

where Y, β_O, β_i, and X_i and X_j denote the predicted dependent factor, the intercept term, the linear coefficients and the coded densification factors, respectively. The parameters β_{ij} are the interaction coefficients and e is the residual error between the predicted and the real experimental values while i and j take the values of 1, 2, 3, . . , n.

3) Briquettes production and characterisation

A piston-press type briquetting machine presented in Figure 1 was used for the production of 50 mm diameter briquettes from the CH and SD briquette blends. The briquetting conditions were experimentally defined from preliminary tests carried out in the laboratory. The feedstock each in raw and torrefied condition was blended at different ratios of 90/10 to 10/90 for the blends total mass of 100 g. The blend was homogenously mixed with gelatinized cassava starch powder of 0.426 mm particle size at the binder amount of 20 g to feedstock quantity of 100 g. At the end of the feedstock mixing, the ram press was lowered with the aid of a relief valve while the bolts holding the top cover was unbolted to allow the CH and SD already mixed with the binder to be fed into the moulds. The materials were compressed at a pressure of 150 bar and dwell time of 5 min at room temperature. The mass and dimensions of the ejected briquettes were respectively taken using a digital weighing balance at 0.01 g accuracy and a digital caliper at 0.1 mm. These ejected briquettes (Figure 2) were dried for 3 weeks under the sun.

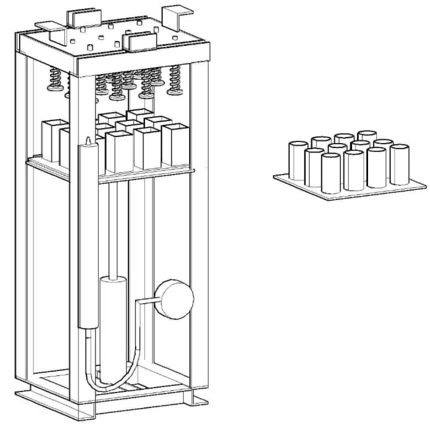

Figure 1 Schematic sketch of the briquetting machine.

Figure 2 Briquette samples.

3.1) Maximum density

The maximum density (MD) of briquette was determined immediately after the briquetting process in line with ASTM D2395-17 [29]. The MD of briquettes was determined using Eq. 2;

$$MD = \frac{W_c}{V_c} \quad \text{(Eq. 2)}$$

where, W_c = weight of briquette on received basis; V_c = volume of briquette.

3.2) Water resistance index

The briquette sample was submerged in water at room temperature for 30 s in line with Orisaleye et al. [15]. The percentage water absorbed (PWA) was evaluated using Eq. 3.

3.3) Carbon, hydrogen and oxygen content

The carbon (C), hydrogen (H), and oxygen (O) composition of both raw and torrefied cornhusk and sawdust briquettes at different blending ratios were estimated using the derivations by Nhuchhen [30] from the proximate analysis and calorific value of briquettes from CH and SD wastes as shown in the Supplementary Material (SM) 1 cited from Akogun et al. [6].

$$PWA = \frac{Final\ weight\ of\ briquette - initial\ weight\ of\ briquette}{Initial\ weight\ of\ briquette} \times 100 \quad \text{(Eq. 3)}$$

While the water resistance index (WRI) was obtained through the following expression in Eq. 4:

$$WRI = 100 - PWA \quad \text{(Eq. 4)}$$

3.4) Water boiling performance test

The briquette fuel of 300 g was loaded into a stove and then sprinkled with 15 mL of kerosene to aid ignition. An aluminium container was weighed empty and dry; the container was thereafter filled with 1000 mL of water and placed on the stove. The boiling of the water was monitored, with a digital thermometer placed at the centre of the container and at about 1 cm from its bottom, until it began to boil. The temperature of water was recorded at every 3 min interval. The container was removed from the stove at boiling and another feedstock added for subsequent experiment. Each experiment was carried out three times while the average value was presented to calculate the following performance attributes:

The burning rate (BR) was determined using Eq. 5 [31].

$$BR = \frac{M_1 - M_2}{t} \quad \text{(Eq. 5)}$$

where, t = time for fuel burning (mins), M_1 = mass of the briquette before burning in gram, M_2 = mass of briquette after burning in gram.

The thermal efficiency (TE) was evaluated with Eq. 6 [32-33].

$$TE = \frac{(M_{WC} \times SH_W(T_2 - T_1)) + (LH_E \times M_{EW})}{M_{FC} \times CV} \times 100 \quad \text{(Eq. 6)}$$

where; M_{WC} = mass of water in the container in gram, SH_W = the specific heat of water (4.186 J g^{-1} °C^{-1}), T_2 = the final temperature of water at boiling, T_1 = intial temperature of water in the container, LH_E = the latent heat of evaporation of water (2260 J g^{-1}), M_{EW} = mass of water evaporated from the container (g), M_{FC} = mass of fuel consumed (g) and CV = the calorific value of the fuel briquette (MJ kg^{-1}).

The specific fuel consumption (SFC), a proxy for the measurement of fuel performance and stove efficiency was calculated using Eq. (7) [21, 34].

$$SFC = \frac{M_{fc}}{A_{BW}} \quad \text{(Eq. 7)}$$

where, M_{fc} = the mass of briquette consumed (g), A_{BW} = the amount of boiled water (L).

4) Statistical analysis

Analysis of variance (ANOVA) was carried out on the experimental data to determine the relationship between the densification factors and each dependent factor at ($p<0.05$) in line with Akogun et al. [3, 6] and Iftikhar et al. [35]. Each dependent parameter was investigated using the F-test. Mean, standard deviation (SD), regression coefficient (R^2) and adjusted R^2, the predicted residual sum of square (PRESS) values and coefficient of variance (CoV) were investigated to fit the experimental data and to avoid collinearity issues. Pareto analysis was also carried out to study the percentage contributions of the main and interaction factors to the responses in line with Waheed and Akogun [26] and Iftikhar et al. [35].

Results and discussion

1) Solid yield and enhancement factor of torrefied cornhusk and sawdust wastes

The solid yields and enhancement factors of the torrefied CH and SD wastes in response to different torrefaction temperatures of 200, 250 and 300 °C for 60 min are presented in Table 1.

The lowest solid yields have been obtained at 300 °C and 60 min and the values were between 49 and 55%. This implies, that approximately 50% of the two biomass is lost by torrefaction. During torrefaction, the most reactive biomass polymer is hemicellulose [2]. This suggests that SD has more hemicellulose than CH residue, hence the result obtained for mass loss. Torrefaction of SD and CH at 300 °C however showed calorific value enhancement factor of 1.33 and 1.29 respectively.

2) Briquette characteristics of cornhusk and sawdust wastes

2.1) Maximum density

The lowest value of MD (0.68 g cm^{-3}) was observed at the 10/90 ratio for raw CH/SD briquette while the highest value of 0.83 g cm^{-3} was observed at the 90/10 for torrefied CH/SD briquette at 300 °C (Figure 3).

This result of MD is within the range of values obtained for charcoal briquette in the work of Gesase et al. [36]. The MD of the raw and torrefied briquettes generally increased as the blending ratio of corn husk residue to sawdust increased from ratio 10/90 to 90/10. The addition of CH both in the raw and torrefied form causes the MD of the briquette produced to increase between 12 to 19% depending on the mixture level compared with the briquette composed of 100% of torrefied SD. This increased trend was also observed when palm oil mill sludge was mixed with rice husk [37] and when sawdust was mixed with cassava peel [3]. Increase in density is also dependent on binder amount and type [31]. The increase in MD was also caused by the sprinkling of distilled water on the biomass samples before densification as obtained in Bazargan et al. [38]. The increase in the torrefaction temperature secretes binding agent between and among biomass particles which consequently leads to the increase in density and reduced resistance against applied load during densification [39]. This could be the reason why the MD of torrefied briquette at 300 °C showed a 20% improvement in MD over the briquette produced with raw CH and SD wastes.

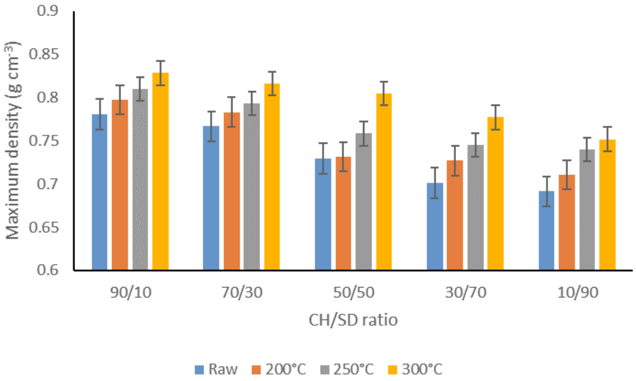

Figure 3 Maximum density of briquettes from CH and SD blends.

Table 1 Solid yield and enhancement factor of torrefied cornhusk and sawdust wastes

Parameter	Feedstock	Raw	200 °C	250 °C	300 °C
Solid yield (%)					
	Sawdust	100.00	92.86	86.65	49.33
	Cornhusk	100.00	88.61	76.13	55.36
Enhancement factor					
	Sawdust	1.00	1.09	1.24	1.33
	Cornhusk	1.00	1.08	1.20	1.29

2.2) Water resistance index

The water resistance index (WRI) ranged between 12.92–16.73% for raw briquettes while it ranged between 21.26–27.29, 57.38–58.80 and 86.63–88.79% for treated CH and SD mixture at the torrefaction temperature of 200, 250 and 300 °C, respectively. This indicate an increase in WRI for blends subjected to torrefaction temperature of 200–300 °C over the raw ones, that is, an increase of 75.70–85.45% over the raw briquettes (Figure 4). Similar effect was also observed for torrefied wood pellets [40]. Particle voids in capillary network of raw biomass briquette enable it to absorb water [41]. Orisaleye et al. [15] and Kaliyan and Morey [42] stated that the subjection of biomass to thermal pre-treatment releases lignin component which is hydrophobic in nature. This lignin also improves the bonding ability among and between biomass particles and thereby leads to increase in the WRI of briquettes. Zandersons et al. [43] corroborated that melted lignin among briquette particles does not allow the easy soaking of a fuel in water. Moreover, at raw condition, the WRI slightly increased when the proportion of CH (at 90%) was increased on CH and SD briquette. At the torrefaction of 300 °C however, the WRI slightly increased with the increased in the proportion of SD which showed that torrefied SD binds and resists water better than CH. The values obtained for briquette blends torrefied at 300 °C in this work compares well with that obtained by Rajaseenivasan et al. [22] (>70%) for SD and neem briquettes. Therefore, torrefied briquettes blends at 300 °C fall within the acceptable standard reported by Eriksson and Prior [44]. This work suggests that the torrefied briquette blends at 300 °C from cornhusk and sawdust can be transported and stored, and that a mild exposure to humid environment would not seriously damage them because it is not hygroscopic when compared with raw biomass blends.

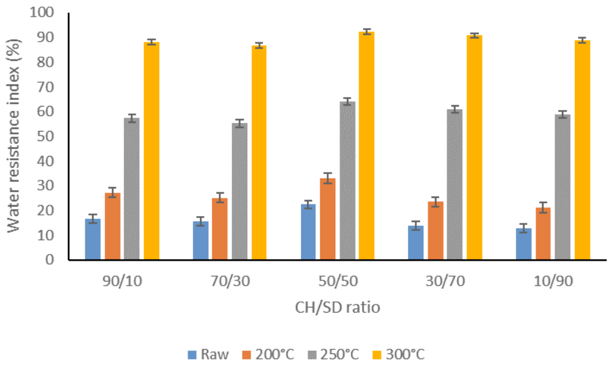

Figure 4 Water resistance index of CH and SD briquettes.

2.3) Burning rate

The burning rate (BR) is the ratio of the mass of briquette consumed to the time it took the fuel to burn. The results of the burning rate of briquettes produced from CH and SD at different blending ratios are presented in Figure 5. The lowest value (0.00432 kg min^{-1}) for BR was obtained for briquettes torrefied at 300 °C at 50/50 (CH/SD) ratio while the highest value (0.00859 kg min^{-1}) was attained at raw blending ratio of 90/10. The advantage of high BR during the combustion of briquette fuel, as observed in raw CH/SD briquette is in the enhancement of self-sustenance of fire. This high value of BR for raw CH/SD at 90/10 ratio could also be due to its high VM content compared with that torrefied at 300 °C with low VM [6]. This results to ease in briquette's ignition and increase in the length of flame during burning. Nonetheless, the BR decreases with the increase in the torrefaction temperature at different CH/SD briquette blends. The torrefied briquettes burn steadily, longer and produce red hot charcoal which is an indication of a good solid fuel for cookstoves. That is, CH/SD briquettes subjected to severe torrefaction (300 °C) characterised with lower BR, burn for a longer time during combustion than that with high value of BR. The torrefied briquettes also burn longer (low burning rate) due to the water preconditioning of the torrefied CH and SD used to produce briquettes to aid friction reduction among and between briquette particles

[5]. Akande and Olorunnisola [26] similarly observed that there was a decrease in BR (0.00189 kg min^{-1}) for torrefied blends of paper and cabbage in comparison with that of the raw ones (0.00483 kg min^{-1}). Furthermore, the increased proportion of SD on CH/SD briquettes increased the BR value at all torrefaction temperature condition. In a similar work by Rajaseenivasan et al. [22], the increase of SD proportion on raw SD and neem briquette blends increased the BR value.

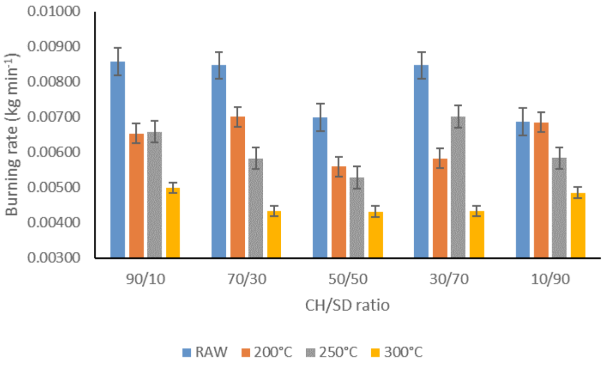

Figure 5 Burning rate of CH and SD briquettes.

2.4) Specific fuel consumption

The specific fuel consumption (SFC) is the ratio of the amount of briquette consumed to the amount of water that remains after water boiling performance test. The SFC ranged from 0.066 g L^{-1} at the blending ratio of CH/SD (10/90) torrefied at 300 °C to SFC (0.187 g L^{-1}) at the 90/10 blending ratio for raw mixture (Figure 6).

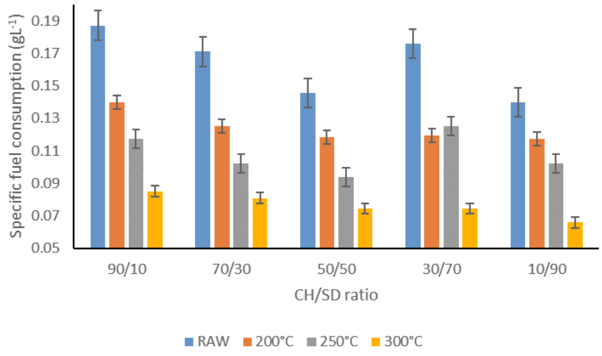

Figure 6 Specific fuel consumption of CH and SD briquettes.

This result shows that SFC of CH/SD briquettes reduced when the torrefaction temperature increase from 200 up to 300 °C. This is due to the process of devolatilization and depolymerization via mild and severe torrefaction which makes the fuel to burn longer. The torrefied CH/SD briquettes at 300 °C consume lesser fuel when subjected to boil some significant amount of water in comparison with raw briquette blends of the same mass. This could be caused by the release of gaseous portion of the raw briquette blends during combustion, which ultimately led to reduced VM content in the torrefied fuel. In clear terms, CH/SD briquette fuel with low VM burns slowly and thereby consumes less fuel. This indicates that raw briquette blends requires more kilogram of fuel than that torrefied at 300 °C to boil the same quantity of water. Also, there are visible smoke emissions during the heating process of raw briquette fuel in comparison with tested torrefied briquette blends. The results obtained for raw 30/70 (CH/SD) briquette ratio is close to the SFC value of 0.175 g L^{-1} for charcoal obtained in the work of Abasiryu et al. [32] and within the range of results obtained for SFC by Oyelaran et al. [21].

2.5) Water boiling time

The time required to boil water decreases with increased torrefaction temperature from 200 up to 300 °C as presented in Table 2. At all torrefaction conditions, WBT decreases with the increase in the proportion of SD in CH/SD briquettes. At both raw and torrefaction conditions, SD was said to improve the CV of briquettes [6].

The rate of mass loss was also higher in the briquettes with high proportion of SD than in CH briquettes. This invariably led to the reduction in the WBT of the produced briquettes. Generally, all torrefied briquettes particularly at temperature of 300 °C boiled water faster than raw briquette blends. This could be due to the increase in FC and CV on biomass from the process of torrefaction [2, 27, 45–46]. Moreover, the rate of heat energy expended per time is higher with SD briquettes than in CH and SD briquettes. This could be attributed to the higher FC and CV of SD which is greater than that of CH [6].

Table 2 Water boiling time of raw and torrefied CH and SD briquettes

CH (g)	SD (g)	C:TEMP (°C)	WBT (min)
30	70	300	15
30	70	Raw	18
90	10	300	15
90	10	Raw	18
10	90	250	15
90	10	250	15
90	10	Raw	18
90	10	200	18
10	90	200	15
30	70	250	15
90	10	300	15
50	50	200	18
50	50	Raw	18
50	50	300	15
50	50	250	15
90	10	250	15
10	90	Raw	18
10	90	300	12
30	70	200	18
90	10	200	18

2.6) Thermal efficiency

The thermal efficiency (TE) is the ratio of the work done by heating and evaporating water to the energy consumed by briquette burning. The TE ranged from 22.79% at 90/10 for raw blends to 29.94% for blends of ratio 10/90 torrefied at 300 °C (Figure 7). The briquette's TE from raw CH and SD, and the torrefied blends at 200, 250 and 300 °C at different blending ratios ranges between 22.79–25.94% and 23.68–26.13%; 25.33–28.75% and 26.56–29.94%, respectively. The enhanced TE is due to the increased proportion of SD in CH/SD briquettes torrefied at 300 °C. It was also caused by the perforated metal shield under the combusted fuel which enhanced the efficiency of heat transfer by reducing heat loss through convection and radiation. There was lower total smoke emissions for the torrefied briquettes at 300 °C, especially at the 90/10 (CH/SD) ratio. This was associated with low value of VM and MC in 90/10 (CH/SD) ratio caused by the removal of smoke-producing compounds (volatiles and water) by mild and severe torrefaction pre-heating. Meanwhile, the high value of VM and MC for briquettes produced from raw mixture of 90/10 caused the high smoke emitted during combustion.

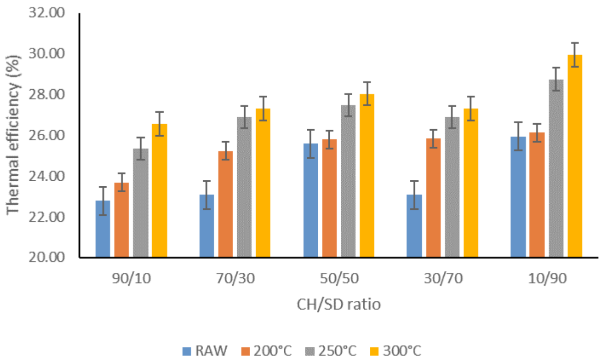

Figure 7 Thermal efficiency of CH and SD briquettes.

Abasiryu et al. [32] recorded a TE of 20.02% for metal charcoal stove using locally dominant wood species in Mubi, Nigeria. Oyelaran et al. [21] recorded a TE of 18.46% for groundnut shell briquette blended with 20% cassava starch. Jenkins et al. [47] reported that TE ranged between 10–20% when fuelled with raw solid biomass. These low values of TE could be caused by the condition of briquette feedstock used which was not subjected to torrefaction and feedstock blending. In order to maintain the high value of TE for cooking stoves, the exposure of fuel briquettes to humid environment or rain during transportation or storage should be avoided. The TE could be improved by using briquettes produced from torrefied single or hybrid feedstock blends. For instance, a TE of 31.1% obtained by Igboanugo et al. [48] when wood fuel was used on stove with improved design was close to the present result obtained for CH/SD (10/90) briquette blend torrefied at 300 °C when used on poorly designed stove. Moreover, Abasiryu et al. [32] used firewood on a metal shield stove and they reported a SFC of 0.225 kg min^{-1}, TE of 9.46%, WBT of 15 min, 48 sec and BR of 0.0285 kg min^{-1}. The O/C and H/C atomic ratios in raw biomass blend of CH/SD briquette reduced with the increase in the torrefaction temperature. Since the heating value of the torrefied briquette blends approached that of low rank coal [3, 27], reduced O/C and H/C ratios through torrefaction is an indication of maximized energy [49]. The carbon content, hydrogen content and calorific value obtained for torrefied CH/SD briquette compared well with fossil coal [50].

3) ANOVA, regression and pareto analysis

The effects of torrefaction on briquette blends have been investigated using statistical methods of analysing D-optimal crossed design. Here, ANOVA showed the significant influence of densification factors (feedstock mixture and torrefaction temperature) on MD, WRI, WBT, SFC, TE, BR, H/C and O/C at $p<0.05$. The P-value or F-value was ranked by the significant factors at 95% confidence level. It was observed that the F-value models are significant, and the corresponding p-value of 0.0001 and 0.0005 (for BR) is very low, indicating that all the model terms are significant. The results of the ANOVA summary output are presented in the SM 2. When the p-values are less than 0.05, the model terms are said to be significant. In this case, the crossed linear by main effects, linear mixture and other model terms are the significant model terms for all the fuel performance characteristics while quadratic by main effects, linear mixture and other model terms are the significant model terms for MD and WRI. Other model-terms with $p>0.05$ show that the model terms are insignificant. The accuracy of the models was verified by the coefficient of determination (R^2) where the R^2-value for the model ranged between 0.8458 and 0.9580 as presented in the SM 3.

These R^2 values are in reasonable agreement with the adjusted R^2. The plots of predicted response versus actual response for MD, WRI, WBT, SFC, TE, H/C, O/C and BR were analysed to fit the model, as presented in the SM 4a–4f. The plots depict a good model fit, as all the values lie close to the diagonal line. These results suggest that the regression equation and associated plots presents a good understanding between the independent factors (feedstock blends and torrefaction condition) and the responses.

$$MD = 0.80\,C_{\mathrm{CH}} + 0.72\,C_{\mathrm{SD}} - 0.031\,C_{\mathrm{CH}}\,C_{\mathrm{SD}} - 0.02454\,C_{\mathrm{CH}}\,C_{\mathrm{T}} - 0.027\,C_{\mathrm{SD}}\,C_{\mathrm{T}} - 0.08235\,C_{\mathrm{CH}}\,C_{\mathrm{SD}} \quad \text{(Eq. 8)}$$

$$WRI = 47.54\,C_{\mathrm{CH}} + 44.66\,C_{\mathrm{SD}} + 21.27\,C_{\mathrm{CH}}\,C_{\mathrm{SD}} - 20.73\,C_{\mathrm{CH}}\,C_{\mathrm{T}} - 43.96\,C_{\mathrm{SD}}\,C_{\mathrm{T}} - + 7.02\,C_{\mathrm{CH}}\,C_{\mathrm{SD}}\,C_{\mathrm{T}} \quad \text{(Eq. 9)}$$

$$SFC = 0.13\,C_{\mathrm{CH}} + 0.11\,C_{\mathrm{SD}} + 0.045311\,C_{\mathrm{CH}}\,C_{\mathrm{T}} + 0.040428\,C_{\mathrm{SD}}\,C_{\mathrm{T}} \quad \text{(Eq. 10)}$$

$$BR = 0.006538\,C_{\mathrm{CH}} + 0.005979\,C_{\mathrm{SD}} + 0.00166527\,C_{\mathrm{CH}}\,C_{\mathrm{T}} + 0.00148964\,C_{\mathrm{SD}}\,C_{\mathrm{T}} \quad \text{(Eq. 11)}$$

$$TE = 24.65\,C_{\mathrm{CH}} + 27.31\,C_{\mathrm{SD}} - 1.82\,C_{\mathrm{CH}}C_{\mathrm{T}} - 1.85\,C_{\mathrm{SD}}C_{\mathrm{T}} \quad \text{(Eq. 12)}$$

$$WBT = 16.66\,C_{\mathrm{CH}} + 15.63\,C_{\mathrm{SD}} + 1.34\,C_{\mathrm{CH}}\,\mathrm{C}_{\mathrm{T}} + 2.37\,C_{\mathrm{SD}}\,C_{\mathrm{T}} \quad \text{(Eq. 13)}$$

$$H/C = 0.21\,C_{CH} + 0.18\,C_{SD} + 0.030\,C_{CH}\,C_{SD} + 0.0686\,C_{CH}\,C_{T} + 0.0207\,C_{SD}\,C_{T} - 0.064\,C_{CH}\,C_{SD}\,C_{T} \quad \text{(Eq. 14)}$$

$$O/C = 1.09\,C_{CH} + 0.99\,C_{SD} + 0.16\,C_{CH}\,C_{SD} + 0.382\,C_{CH}\,C_{T} + 0.163\,C_{SD}\,C_{T} - 0.28\,C_{CH}\,C_{SD}\,C_{T} \quad \text{(Eq. 15)}$$

where C_{CH}, C_{SD} and C_{T} represent corn husk composition (g), sawdust composition (g) and torrefaction conditions (°C) respectively. In addition, MD, WRI, WBT, SFC, TE, BR, H/C and O/C indicate maximum density, water resistance index, water boiling time, specific fuel consumption, thermal efficiency, burning rate, hydrogen to carbon ratio and oxygen to carbon ratio for CH/SD briquettes. The developed regression models to predict the response variables (MD, WRI, WBT, SFC, TE and BR) of CH/SD briquettes are presented in Eqs. 8–15. The effect of each variable (in percentage) on the attributes of CH/SD briquettes is shown in the SM 5. The cornhusk composition (C_{CH}) and sawdust composition (C_{SD}) were found to have a high contribution of 54.82% and 44.40% towards MD. A high contribution effect towards other attributes was also obtained. Actually, factor C_{CH} with 44.67% showed less contribution for TE in comparison with factor C_{SD} (54.83%). Nonetheless, the interaction factors $C_{CH}C_{T}$ and $C_{SD}C_{T}$ contributed less significantly in all the responses of the briquette blends (<10%) except for factor $C_{SD}C_{T}$ that gave 27.15% for WRI. Inferentially, the WBT, SFC and BR increase with the increase in CH composition in CH/SD briquettes while SD has more effect than CH/SD briquette for TE.

Conclusion

Torrefied blends of CH and SD wastes when preconditioned with deionized water favourably improved the characteristics of CH/SD briquettes which are improvement over the use of raw sole feedstock or their blends. The briquettes tested through fuel performance studies in a conventional stove showed that CH/SD briquette torrefied at 10/90 ratio has the highest TE and lowest WBT in comparison with the raw ones. The lowest values of H/C and O/C ratio were obtained at 90/10 (CH/SD) when torrefied at 300 °C. The raw CH/SD (90/10) blends had the highest SFC, BR and high visible smoke emissions. This implies that raw briquette blend at 90/10 (CH/SD) would not be best applicable for most heating applications when not torrefied. The performance of CH/SD briquette blends torrefied at 300 °C when used as fuel to fire conventional stove for water boiling performed better in comparison with firewood. The use of torrefied CH/SD briquettes over raw ones therefore minimises fuel consumption and air pollution due to low volatile matter and high fixed carbon content. Furthermore, concerns about energy input to produce feedstock mixture that may be higher than energy output from the briquette and concerns about availability and costs of some raw materials such as deionized water and starch should be highly considered for sustainable energy production. Torrefied CH and SD wastes are therefore better alternatives to raw feedstocks, firewood and coal when used sustainably.

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