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Optimizing energy properties and performance of household briquettes from Co-torrefied Sugarcane bagasse and Bamboo Dust

K.O. Oladosu[1, 2], A. S. Olawore[1] and N.O. Alabi[1]

[1]*Department of Mechanical Engineering, Kwara State University, Malete, Nigeria*
[2]*Centre for Sustainable Energy, Kwara State University, Malete, Nigeria*
kamoru.oladosu@kwasu.edu.ng; ayodeji.olawore@kwasu.edu.ng; alabiopeyemyh111@gmail.com
Corresponding Author: kamoru.oladosu@kwasu.edu.ng; https://orcid.org/0000-0002-5073-1739

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Abstract

This study investigates the co-torrefaction of sugarcane bagasse (SGB) and bamboo dust (BD) to produce high-performance household briquettes. Co-torrefaction was carried out in a tubular furnace, and the effects of temperature, retention time, particle size, and biomass blend ratio on higher heating value (HHV) and energy yield (EY) were optimized using Optimal Combined Design (OCD). The torrefied SGB-BD under optimal conditions was briquetted using a manually operated machine. Physicochemical analyses were performed on both torrefied and non-torrefied samples to assess the effects of thermal treatment, while mechanical performance was evaluated through compressive strength tests and water-boiling experiments. The optimal HHV of 22.45MJ/kg was achieved at 300°C with a retention time of 23min. The best-performing briquettes, formulated from 60 wt.% SGB and 40 wt.% BD, demonstrated improved ignition time (reduced from 232 s to 179 s), a slower fuel combustion rate (from 0.039 g/s to 0.027 g/s), and a reduction in water-boiling time (from 998 s to 847 s) when compared with the least desirable formulation. However, traditional charcoal still achieved the shortest boiling time (591 s) and lower fuel combustion rate of 0.019 g/s. These results suggest that co-torrefied SGB–BD briquettes offer competitive combustion performance and practical suitability for domestic energy applications.

1.0 Introduction

Energy plays an essential role in modern life, supporting daily domestic activities and ensuring thermal comfort. Growing environmental concerns, particularly climate change and pollution associated with fossil-fuel-based energy systems, have intensified global interest in renewable and sustainable energy alternatives (He et al., 2023). Biomass has become one of the most promising renewable resources in this regard, currently supplying an estimated 10–15% of the world's total energy demand (Oladosu et al., 2022; Bonsu et al., 2020, and Oladosu et al., 2020). Converting biomass residues into useful energy not only addresses waste-management challenges but also provides a low-cost, environmentally friendly fuel option. Biomass refers to organic material derived from plant- and animal-based sources. The energy stored in biomass originates from solar radiation, captured through photosynthesis as plants convert water and carbon dioxide into chemical energy-rich compounds (Zhu et al., 2019). Several thermochemical processes including pyrolysis, torrefaction, gasification, and direct combustion are employed to transform biomass into biofuels suitable for heat and power generation. Among these technologies, torrefaction has gained attention as an effective pretreatment technique for agricultural residues. It enhances fuel quality by reducing moisture, improving grindability, increasing homogeneity, boosting energy density, and elevating the calorific value of the resulting solid product (Garciamaraver et al., 2014). Torrefied biomass or biochar also offers benefits such as easier transport and storage, lower sulfur emissions, and potential use as a heating fuel or soil amendment (Fournel et al., 2015 and Lamberg et al., 2013). Because torrefaction performance depends on interacting parameters such as temperature, residence time, and particle size, researchers frequently apply response surface methodology (RSM) and other statistical tools to optimize and model the higher heating value (HHV) and energy yield (EY) of various biomass feedstocks.

Previous studies have examined materials such as Jatropha curcas residues (Lim et al., 2015), pomegranate peel waste (Konsomboon et al., 2011), sugarcane bagasse (Kongto et al., 2021), palm kernel shell (Kishinevsky et al., 1996), perennial grasses (Kareem et al., 2018), municipal solid waste (Kethobile et al., 2020), and waste bamboo chopsticks (Oladosu et al., 2024). Although these studies confirm that torrefaction improves the energy content of agricultural residues, the selection of appropriate feedstock combinations remains essential for ensuring fuel performance in practical applications. SGB and BD present a technically complementary pairing because SGB offers fibrous structure and higher volatile content that enhance ignition and binding during densification (Kongto et al., 2021), whereas BD provides higher fixed carbon, lower ash content, and improved bulk density, contributing to longer burning duration and improved heating value (Oladosu et al., 2024). Combining these residues can therefore overcome the limitations of each material when used independently and produce briquettes with higher combustion and mechanical characteristics. Despite these advances, there is currently no published study examining the fuel characteristics of briquettes produced from a torrefied blend of sugarcane bagasse and bamboo dust. Therefore, this study aims to optimize the HHV and energy yield of sugarcane bagasse–bamboo dust (SGB-BD) mixtures torrefied in a tubular furnace, identify the optimal processing conditions, and evaluate the suitability of the resulting torrefied material for producing briquettes intended for household energy applications.

2.0 Materials and Methods

2.1 Biomass Preparation and Briquetting Process

2.1.1 Biomass Collection and Pre-Processing

Sugarcane bagasse and bamboo dust were selected as feedstocks due to their availability and widespread use in agro-industrial operations. The SGB was obtained from the BUA sugar estate in Lafia, while BD was collected from the Saboline sawmill in Ilorin, Kwara State, Nigeria. Both materials were initially sun-dried for seven days and subsequently oven-dried at 105 °C for three days to achieve a moisture content of approximately 4.5–6%, determined according to the oven-drying method (ASTM E871-82). The dried sugarcane bagasse was size-reduced using a hammer mill, while bamboo fibres were separated from the finer dust fraction. Each material was then passed through a 1-mm sieve to obtain a uniform particle size suitable for co-torrefaction. Proximate analysis followed established procedures described in (Lamberg et al., 2013), and elemental composition was determined using a CHNS elemental analyser (vario EL cube V3.0.23, serial number 25,146).

2.1.2 Torrefaction Procedure and Determination of HHV and Energy Yield

Torrefaction was performed following the procedure reported in Kethobile et al., (2020), using a tubular torrefaction system consisting of an electric furnace, nitrogen gas cylinder, thermocontroller, and mass-flow controller (±1 °C and ±1 min accuracy) (Figure 1). The experimental conditions were generated using Design-Expert (Version 13), resulting in 35 torrefaction runs. For each experiment, the empty crucible was weighed before loading 2 g of biomass. The crucible was then inserted into the furnace, and the specified temperature and residence time were set. Nitrogen gas was continuously supplied at 3 mL/min to maintain an inert atmosphere and prevent oxidative reactions during heating (Khan et al., 2021). After each torrefaction cycle, the furnace was switched off and the system allowed to cool until the char temperature reached 30 ± 2 °C. The crucibles were removed, transferred to a desiccator, and reweighed. Mass yield and energy yield were subsequently computed using Equations 1 and 2.

$$\% \, Mass \ yeild = \frac{M_t}{M_r} \times 100 \quad (1)$$

$$\% \, EY = Mass \ yield \times \frac{HHV_T}{HHV_R} \quad (2)$$

where; Mt- represents the mass torrefied product, and Mr - the mass of the non-torriefied sample (SGB and BD), on a dry basis. Similarly, HHV_T and HHV_R indicate the heating value of the torrefied and non-torrefied samples.

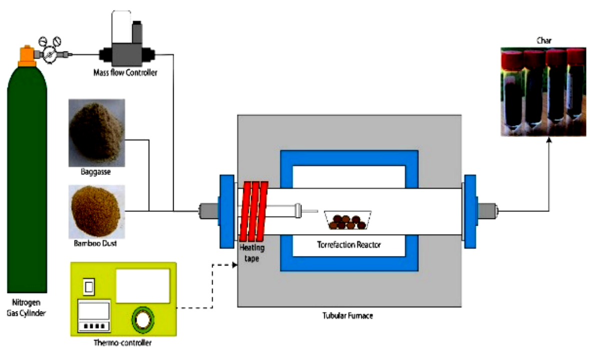

Figure 1: Experimental setup; tubular furnace with user-controlled nitrogen atmosphere and heat regulator

In this study, an optimal combined design under the Custom Design framework was employed to identify the process conditions that maximize the HHV and energy yield of torrefied SGB–BD blends. Using Design-Expert version 13.0, thirty-five experimental runs were generated for analysis. The design incorporated two mixture components (SBG and BD) and two process variables; temperature and residence time. The corresponding mixture proportions and factor settings used in the experimental matrix are presented in Table 1.

Table 1. Minimum and Maximum Level of Components Selected

Mixture		Units	Min	Max
Components	SGB	%	50	70
	BD	%	30	50
Factor	Temp	ºC	200	300
	Time	min	15	30

ANOVA and regression techniques were applied to examine how the independent factors such as SGB, BD, torrefaction temperature, and residence time, affect the output responses (HHV and EY). The F-statistics and corresponding p-values generated for the SGB–BD mixtures were used to judge whether the proposed model was statistically reliable. A coefficient of determination (R^2) close to 1 reflects a strong model fit and is considered satisfactory. Furthermore, the model is regarded as adequate when the gap between the predicted R^2 and the adjusted R^2 is below 0.2 (Kareem et al., 2018).

2.1.3 Briquette Production from Torrefied SGB-BD Blends

Torrefied residues, including both optimal and non-optimal samples, were cooled, crushed, and sieved to 0.5 mm to promote uniform compaction and effective binder distribution (Bonsu et al., 2020). A cassava-starch binder was prepared by heating water to boiling and gradually adding starch powder under continuous stirring until a homogeneous gelatinized paste was formed. The binder was incorporated into the torrefied SGB–BD mixtures at 5% of the total biomass mass and thoroughly mixed to ensure uniform coating. The biomass–binder blend was then fed into the cylindrical moulds of a manually operated briquette press (Figure 2). Compression was applied through a lever mechanism, producing up to six briquettes per cycle. The briquettes were removed from the moulds and sun-dried for three to five days, depending on weather conditions, to achieve stable, moisture-reduced solid fuels

Figure 2: Biomass Preparation and and Briquetting Process

2.2 Combustion Characteristics of Briquettes

2.2.1. Ignition time

The ignition time (ti) of the briquetted SGB-BD blends and wood charcoal was measured using a stopwatch. The recorded values were then compared to evaluate which fuel option provides the most suitable and efficient ignition characteristics.

2.2.2. Water Boiling Test

A water heating performance evaluation for 500 ml was conducted on the optimal SGB-BD briquette specimen and the reference wood charcoal to determine the most suitable fuel material. The boiling time (tb) was recorded with a stopwatch, measured from the point of ignition until the water reached 100 °C, while a thermometer was used to track the temperature

2.2.3 Fuel Combustion Rate

Fuel consumption analysis was performed concurrently with the water heating evaluation. Equal portions of briquette blends from the best run, and with reference charcoal, were tested in briquette stoves. The fuel combustion rate (FCR) was calculated as fuel mass consumed divided by burning time as expressed in Equation 3

Fuel Combustion Rate, $FCR = \frac{m_f}{t}$ (kg/sec) (3)

where m_f is the mass of fuel; t is time

2.2.4 Compressive strength

The compressive strength of the SGB–BD briquettes and the reference charcoal was evaluated using a universal testing machine (UTM) equipped with a 50 kN load cell, following the guidelines of ASTM 2166–85. This assessment was carried out to compare the durability of the optimal briquette with that of the reference charcoal. During testing, the samples were subjected to an increasing compressive load at a controlled rate of 0.01667 N/mm²/s until structural failure was observed.

3.0 Results and Discussions

3.1 Physicochemical Analysis of Untreated and Torrefied SGB and BD Samples

Table 2 presents the results of the ultimate and proximate analyses for raw charcoal, as well as for untreated and torrefied SGB–BD blends. Upon torrefaction at 300 °C, the carbon content of the SGB–BD mixture increased from 39.50% at 200 °C to 48.30% at 300 °C, reflecting progressive carbonization. Hydrogen content decreased slightly from 5.58% to 4.67%, while oxygen content declined from 55.48% to 46.51%, mainly due to the loss of volatile oxygen-containing compounds during heating (Kethobile et al., 2020). Proximate analysis showed fixed carbon increased from 34.6% at 200 °C to 49.1% at 300 °C, whereas volatile matter decreased from 57.45% to 39.23%. Ash content rose from 11.1% at 200 °C to 15.4% at 300 °C. These compositional changes of the higher fixed carbon, lower volatile matter, and increased in ash yield are characteristic of torrefaction and enhance the fuel quality of the treated blends (Oladosu et al., 2024).

3.2 Experimental Results and Statistical Analysis

The data in Table 3 were modeled using quadratic and KCV equations to separately determine how the higher heating value (HHV) and energy yield vary with the mixture components (SGB and BD) as well as process parameters including temperature, residence duration, and particle size (see Eqns. 4 and 5).

$$\boldsymbol{HHV} = 20.69X_1 + 19.73X_2 - 2.52X_1X_2 + 0.7234X_1X_3 + 0.0921X_1X_4 - 0.7933X_1X_5 + 0.3902X_2X_3 + 0.1776X_2X_4 + 3.48X_1X_2X_3 - 0.3413X_1X_2X_4 + 0.5636X_1X_2X_5 + 0.4279X_1X_3X_4 + +0.1572X_1X_4X_5 - 0.7324X_1{X_3}^2 + 0.5319X_1{X_4}^2 \quad (4)$$

$$\boldsymbol{EY} = 60.32X_1 + 61.49X_2 - 9.54X_1X_2 - 4.21X_1X_3 - 0.3661X_1X_4 - 1.30X_1X_5 - 2.89X_2X_3 - 1.24X_2X_4 - 3.62X_2X_5 + 1.13X_3X_4 - 0.4024X_3X_5 - 1.81X_4X_5 + 2.39{X_3}^2 + 3.92{X_4}^2 - 5.07{X_5}^2 \quad (5)$$

where, X_1=SGB, X_2=BD, X_3= temperature, X_4 = time and X_5 = particle size. At 95% confidence level, the X_1X_2, X_1X_3, X_1X_4, X_2X_3, X_2X_4, X_3X_4, $X_1X_2X_3$, $X_1X_3X_4$, $X_2X_3X_4$, ${X_1}^2$, ${X_2}^2{X_4}^2$, and ${X_5}^2$ are significant terms for HHV yield where; X_1= SGB, $X_2 = BD$, X_3 = temperature, X_4 = residence time and X_5 = particle size. Likewise, in the case of energy yield the significant terms are $X_1X_2, X_1X_3, X_1X_4, X_1X_5, X_2X_3, X_2X_4, X_2X_5, X_3X_4,$ $X_4X_5, {X_3}^2{X_4}^2$, and ${X_5}^2$ while the particle size had the least influence on energy yield. Furthermore, the coefficient of determination R^2 of 0.99 and 0.98 and R^2Adj of 0.98 and 0.96, the standard deviation of 0.0463 and 0.0195 and the coefficient of variations were 0.234 and 0.56 for HHV and energy yield respectively. Accordingly, the results of the model analysis are excellent (Fig. 3a and 3b) are therefore deployed for prediction.

(a)

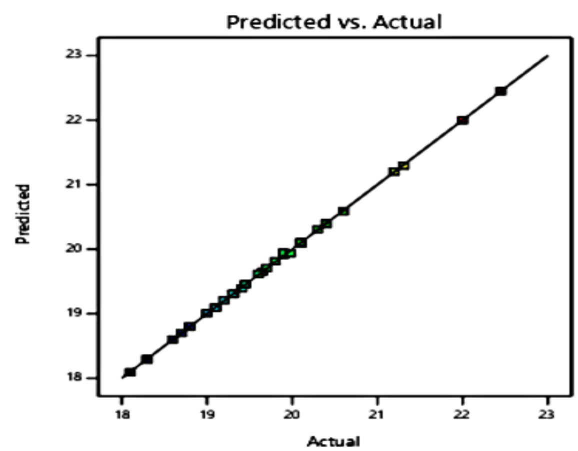

Figure 3a: Comparison of actual and projected values of the responses for HHV

(b)

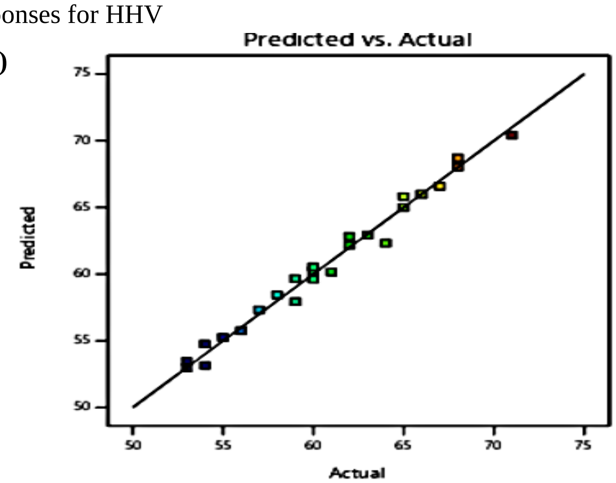

Figure 3b: Comparison of actual and projected values of the responses for Energy yield

Table 2. Proximate and Ultimate Analysis of Non-torrefied and Torrefied SGB-BD Fuel Mixtures

Sample	Temp (°C)	Time (min)	PS (mm)	V_M (%)	F_C %	A_C (%)	C (%)	H (%)	N (%)	S (%)	O (%)	HHV (MJ/kg)
Raw Charcoal				48.67	33.61	5.40	71.50	22.21	1.55	0.80	3.39	22.70
NT (SGB)				59.26	30.6	10.1	41.90	4.57	0.28	0.45	47.62	18.00
NT(BD)				61.15	32.3	7.2	34.90	5.27	0.35	0.56	58.92	17.23
(T)at (50:50)	200	15	5	57.45	34.6	11.1	39.50	5.58	0.32	0.53	55.48	18.10
(T) at optimal (60:40)	300	23	1	39.23	49.1	15.4	48.30	4.67	0.27	0.44	46.51	22.45

Table 3. Experimental Trials and Corresponding Responses Using Optimal Combined Design

	X_1	X_2	X_3	X_4	X_5		HHV			Energy yield	
Run	SGB (%)	BD (%)	Temp. (° C)	Time (min)	Particle Size (mm)	Actual (%)	Predicted (MJ/kg)	Residual (%)	Actual (%)	Predicted (%)	Residual (%)
1	70	30	200	15	3	19.32	19.35	-0.0293	67.00	67.63	3.370
2	64	36	295	23	5	19.50	20.35	-0.8458	64.00	55.79	8.210
3	50	50	300	21	5	19.60	20.24	-0.6416	62.00	59.46	2.540
4	65	35	216	25	2	19.41	19.65	-0.2405	64.00	62.33	1.670
5	50	50	202	23	3	19.70	19.07	0.6344	66.00	67.13	-1.130
6	70	30	232	20	4	19.90	19.51	0.3852	62.00	63.28	-1.280
7	70	30	245	30	3	20.10	19.97	0.1281	58.00	62.52	-4.520
8	60	40	245	15	3	19.65	19.85	-0.2008	63.00	61.37	1.630
9	50	50	255	15	3	19.30	19.56	-0.2611	69.00	65.53	3.470
10	70	30	200	30	1	19.00	19.00	0.0048	65.00	65.54	-0.539
11	70	30	298	22	3	20.60	20.96	-0.3589	58.00	57.80	0.204
12	60	40	262	30	1	19.10	19.78	-0.6810	60.00	57.40	2.600
13	60	40	300	15	1	20.10	20.50	-0.4015	55.00	55.14	-0.136
14	50	50	237	30	5	19.80	19.45	0.3468	61.00	59.16	1.840
15	50	50	300	15	1	20.40	19.68	0.7228	62.00	62.39	-0.389
16	70	30	300	30	5	20.10	20.57	-0.4714	59.00	58.42	0.578
17	70	30	264	15	5	19.10	18.91	0.1945	60.00	62.02	-2.020
18	70	30	200	24	5	18.19	18.39	-0.2885	69.00	66.62	2.380
19	60	40	200	30	4	18.80	19.14	-0.3384	65.00	64.56	0.437
20	50	50	200	15	5	18.10	18.49	-0.1911	71.00	68.98	-1.980
21	60	40	200	21	1	18.79	19.23	-0.4387	60.00	62.40	-2.400
22	60	40	300	23	1	22.45	21.00	1.45	50.00	56.56	-6.560
23	70	30	245	22	1	21.31	20.17	1.14	54.00	57.35	-3.350
24	60	40	300	30	5	22.00	20.83	1.17	53.00	55.08	-2.080
25	69	31	300	30	1	21.20	21.00	0.1959	59.00	55.97	3.030

26	56	44	249	23	3	19.45	20.00	-0.5517	67.00	59.87	7.130
27	51	49	200	15	1	18.60	18.68	-0.0782	68.00	68.68	-0.684
28	60	40	200	15	5	18.70	18.43	0.2729	66.00	66.47	-0.465
29	50	50	300	30	3	19.90	20.46	-0.5575	60.00	61.53	-1.530
30	50	50	200	30	5	18.29	18.00	0.2904	68.00	67.38	0.619
31	50	50	256	23	1	19.20	19.19	0.0074	61.00	61.76	-0.763
32	60	40	245	23	5	19.50	19.56	-0.0611	53.00	57.84	-4.840
33	60	40	300	15	5	20.40	19.82	0.5774	56.00	58.80	-2.800
34	70	30	300	15	1	20.30	20.92	-0.6210	54.00	53.46	0.535
35	50	50	276	26	4	19.98	20.25	-0.2672	57.00	59.78	-2.780

3.3 Influence of SGB–BD Blend Ratios and Torrefaction Temperature on HHV and Energy Yield

Figures 4(a) and 4(b) display the 3D response surface plots showing how HHV and energy yield respond to changes in SGB and BD proportions, torrefaction temperature, and residence period. The HHV increased consistently with rising temperature, reaching its highest value at 300 °C. For example, increasing the SGB content from 50 wt.% to 60 wt.% and reducing BD from 50 wt.% to 40 wt.% at a particle size of 1 mm and a residence time of 23 min resulted in an HHV increase from 18.10 MJ/kg to 22.45 MJ/kg (Fig. 4a–b). In contrast, the energy yield behaved differently. At 200 °C, with a particle size of 5 mm and residence time of 15 min, the highest energy yield of 71% was recorded. The lowest value, 50%, occurred at 1 mm particle size, 300 °C, and 23 min residence time. Interaction effects between the blend components and temperature, as well as between temperature and residence time (X_3X_4), produced a slight increase in HHV. However, the interaction between temperature and particle size (X_3X_5) resulted in reduced energy yield.

(a)

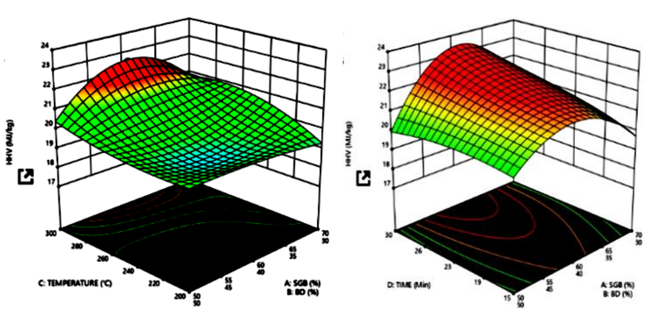

Figure 4a. 3D Surface plot illustrating the impact of temperature and duration on HHV

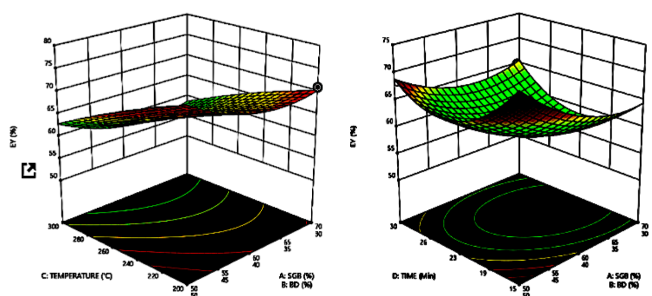

Figure 4b. 3D Surface plot illustrating the impact of temperature and duration on energy yield (EY)

The results indicate that the combined influence of temperature and residence time produced the highest HHV at 300 °C and 23 minutes of torrefaction (Fig. 4a). Beyond this temperature–time point, HHV began to decline steadily. In contrast, the highest energy yield was recorded at 200 °C with a residence time of 15 minutes. The increase in HHV during torrefaction is associated with the enrichment of fixed carbon in the SGB–BD blends. The slight reduction in HHV at more severe conditions is likely linked to the blend ratio and additional devolatilization of organic structures such as the breakdown of hydroxyl and methoxyl groups in the biomass (Yakub et al., 2017). The relatively high energy yield at lower temperatures is attributed to the dominance of primary thermal reactions at mild torrefaction conditions.

Yakub et al. (2017) described energy yield as the fraction of energy retained in the solid material following torrefaction. Their study showed that at roughly 300 °C, the energy yield declined to 53.41%, while HHV rose to 30.58%. This agrees with findings in (Oyebode et al., 2021), where energy yields for biochar subjected to severe torrefaction ranged between 50% and 79%. The reduction in solid mass leading to increased porosity, has been suggested as a key contributor to the observed drop in energy yield and energy density during torrefaction (Kasapoglu et al., 2020). In a similar study, Oladosu et al. (2024) reported that for torrefied Bambara groundnut shells (BBGS), increasing temperature and time enhanced HHV but simultaneously reduced energy yield.

Additional literature supports these observations. Torrefaction of Paulownia wood at 260 °C for 60 minutes while reducing particle size from 12 mm to below 0.3 mm resulted in a 5.41% decrease in solid product yield, while the heating value of the liquid product increased by 5.87 wt.% (He et al., 2023). Smaller particle sizes promote the outward movement of volatiles by lowering diffusion resistance, thus reducing secondary reactions and improving the energy content of the liquid fraction (Idoia et al., 2016 and Andrew et al., 202). Likewise, Lang et al. (2022) reported that larger particle dimensions negatively affected reactor performance when torrefying wood sawdust (0.25–2 mm). An increase in particle size corresponded with a decrease in the energy yield of the torrefied sample.

Thus, these results demonstrate that the interactions among blend composition, temperature, particle size, and residence time significantly influence HHV and energy yield during torrefaction of SGB and BD, especially at a 60:40 SGB–BD ratio. Larger particles slow heat penetration, while smaller particles permit faster heat transfer and consequently improve energy-related performance. Furthermore, longer residence periods up to 23 minutes tend to increase HHV while lowering energy yield, as shown in Fig. 4a–b, where the rise in HHV is accompanied by a reduction in EY.

3.4 Combustion and Mechanical Properties of SGB–BD Briquettes

Table 4 summarizes the thermal and mechanical properties of SGB–BD fuel briquettes, highlighting the effects of blend composition. Briquettes with a 60:40 (SGB:BD) ratio demonstrated the shortest ignition time (179 ± 9 s), compared with 232 ± 15 s for the 50:50 blend and (201 ± 12 s) for charcoal, indicating better flammability. The reduced ignition time of the optimal briquettes relative to the 9.23–17.00 min reported by Ferronato et al. (2022) is likely due to the lower binder content used in the formulation.

Table 4: Combustion Properties of the SGB–BD Fuel Briquettes

Parameters	Most Inferior Briquette Value	Optimal Briquette Value	Charcoal
Ignition time (s)	232± 15	179± 9*	201± 12
Water boiling time (s)	998± 52	847± 49	591± 24*
Fuel combustion rate (g/s)	0.039± 0.002	0.027± 0.003	0.019± 0.001
Compressive strength (MPa)	0.04	0.09	0.17*

*Reported best value

In terms of combustion rate, charcoal exhibited the slowest rate (0.019 ± 0.001 g/s), followed by the optimal briquettes (0.027 ± 0.003 g/s), while the 50:50 blend had the highest rate (0.039 ± 0.002 g/s). Cooking performance followed a similar trend: charcoal boiled 500 mL of water the fastest (591 ± 24 s), followed by the optimal briquettes (847 ± 49 s), whereas the 50:50 blend required 998 ± 52 s, approximately 55% longer than charcoal, suggesting limited suitability for practical cooking applications. Mechanical testing revealed that compressive strength increased with blend optimization. The optimized SGB–BD briquettes achieved a compressive strength of 0.09 MPa, compared with 0.04 MPa for the least desirable 50:50 blend, while commercial charcoal recorded 0.17 MPa. Although (Oyebode et al., 2021) reported standards of 0.38–2.56 MPa apply to briquettes produced using high-pressure industrial technologies, the manually operated press used in this study is designed for small-scale, community-level production and therefore yields lower-density briquettes intended for near-point use. The strength obtained aligns with the 0.08 MPa reported by Oladosu et al. (2023) for briquettes successfully deployed for domestic cooking, indicating that the optimized 60:40 (SGB:BD) formulation provides adequate durability for household handling and short-distance transport while offering improved combustion and energy performance.

4.0 Conclusion

Co-torrefaction of sugarcane bagasse and bamboo dust was successfully achieved, with process optimization showing that HHV and energy yield can be maximized by adjusting blend ratio, temperature, residence time, and particle size. The highest HHV (22.45 MJ/kg) was obtained at 300 °C, 23 min, and 1 mm particle size, while the maximum energy yield (71%) occurred at 200 °C, 15 min, and 5 mm. Statistical analysis confirmed the significance of quadratic and interaction effects (R^2 = 0.998 for HHV, 0.996 for EY). The optimized 60:40 (SGB:BD) briquette formulation exhibited faster ignition, slower combustion rate, and reduced fuel consumption relative to the least desirable formulation, offering improved cooking performance. Although traditional charcoal delivered slightly shorter boiling times and a lower combustion rate, the co-torrefied SGB–BD briquettes demonstrated competitive combustion behavior and practical suitability for household cooking.

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Declaration of Conflict of Interest

All authors contributed significantly to the conception, planning, and development of this article. They were actively involved in drafting the manuscript and provided critical revisions to enhance its scholarly quality. This work is original and has not been submitted to, nor is it under review by, any other journal or publication. The authors also declare that they have no financial or organizational affiliations, whether direct or indirect, that could be perceived as influencing the content of this study

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