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Research article

Development and optimization of rice husk composite briquettes as a sustainable cooking energy solution in Nigeria

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ABSTRACT

The processing of biomass into fuel briquettes is one of the sustainable measures widely advocated for curtailing deforestation and meeting the energy needs of about 3 billion people living in energy poverty. Improving the efficiency and durability of the briquettes is essential for their effectiveness as an energy source. This paper explores the production, evaluation, and optimization of rice husk briquettes using response surface methodology (RSM). The process variables considered are binder type and ratio, particle size, and dwell time, while the responses are relaxed density and compressive strength. The experiment was designed using Box Behnken design (BBD). Briquettes were produced in a low-pressure (4.5 MPa) hydraulic piston press utilizing 2 novel biomass binders (sweet potato peel and locust bean pulp) and cassava starch. In addition to the optimized responses, the briquettes were characterized for quality and thermal performance. The results range from 0.196 g/cm^3 to 0.306 g/cm^3 for relaxed density and from 20 kN/m^2 to 410 kN/m^2 for compressive strength. Under optimal conditions, 15% binder content, 0.5 min dwell time, and 1 mm particle size could yield briquettes with a relaxed density of 0.30 g/cm^3 and a transformed compressive strength of 0.032 m$^{0.5}$ s kg$^{-0.5}$, equivalent to 918 kN/m^2. The model's predictions were validated through confirmatory experiments, with the differences between the predicted and actual values being statistically insignificant at a 95% confidence interval. These findings suggest that rice husk briquettes with an optimal quality for domestic use can be efficiently produced under low pressure, offering a viable solution for energy sustainability and environmental conservation.

1. Introduction

Energy is an imperative aspect of socioeconomic development [1]. As a result of the population growth in most developing countries, the energy demand has outweighed the available energy resources and has persistently contributed to the rising energy cost [2]. With this, low-income earners find it difficult to access or afford the basic energy required for their primary needs. In contrast, the medium to high-income earners have overburdened the non-renewable fuels, making it unsustainable. As a result, more than a third of the world's population relies on solid fuels to meet their energy needs [3]. This has significantly increased the rate of deforestation, especially in Africa, where fuelwood and charcoal use is intense [4]. Through this, about 3.4 million hectares of forest land are lost annually in Africa [5]. Nigeria is among the top 10 countries globally with the highest deforestation rate of 5.0% (410,000 ha) per annum [6]. In the same vein, with an annual charcoal production capacity of 4,828,689.00 tonnes as of 2022, the country is the second-largest producer of charcoal in the world after Brazil [7]. This highlights the country's vulnerability to continued deforestation and climate change.

As part of measures to curtail deforestation and meet the energy needs of about 3 billion people living without access to clean and

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sustainable energy, producing energy from non-woody biomass has been encouraged [8]. This will serve as an alternative energy source and a source of livelihood [9]. Briquetting is one of the most advocated and practiced methods of harnessing energy from biomass [10]. It involves densifying raw biomass into a solid and more compact form. Through this process, the energy content and density of the biomass are improved, making it suitable as fuel and enhancing its storage and transportation potential. While the technology continues to diversify as a sustainable energy production method, its adoption and sustained use have been quite slow in Sub-Saharan Africa due to the high capital costs of setting up a commercial-scale production plant and its unavailability in local markets [11]. On this basis, small-scale or low-pressure (< 5 MPa) production methods have emerged to minimize costs and save energy [12]. This is particularly important as cost is one of the major factors that induce the use of traditional solid fuels like fuelwood and charcoal. With the low-pressure methods, households can now produce it themselves. However, the low-pressure technique typically requires binders as there are no provisions for heating systems [13,14]. Thus, selecting the appropriate type and ratio of the binder has been one of the most challenging aspects of producing low-pressure briquettes over the years. Hence, studies on briquette production have focused on developing new and sustainable binders [15]. Starch-based binders have been the most used in briquette production [16]. These binders are usually expensive as they are made from agricultural produce such as cassava, potato, corn, etc., which are major food sources in most parts of the world. Hence, their continuous use is not only uneconomical but could potentially influence food security and affect the sustainability of food-based raw materials. Thus, this study assessed potential binders in briquette production from selected biomass materials to save cost and conserve food and industrial raw materials. In addition to the type of binder, choosing the appropriate feedstock is also important. Because agricultural residues are the most abundant and easily accessible biomass, they have been the most used feedstocks in briquette production [17].

Rice husk is one of the most abundant biomass feedstocks globally. In Nigeria, about 2.4 million tons are produced annually. However, there is still no adequate strategy for utilizing this mammoth biomass [18]. Typically, rice husks are burned or landfilled, contributing to environmental degradation. With an energy content in conformity with the ENplus minimum for fuel production (≥ 16.56 MJ/kg) [19], rice husk is a good feedstock for briquette production [17]. However, rice husk has a high ash content rich in silica [20], which affects its thermal efficiency during combustion. To mitigate the high ash/silica content in rice husk and produce thermally efficient briquettes, measures such as pretreatment (e.g., carbonization and torrefaction), mixing or blending with low-ash biomass such as corncob and groundnut shell, or the use of additives could be employed. Due to the recalcitrance of rice husk, there are limited studies on rice husk briquette production. This includes but is not limited to the study of Lakshika et al. [21], where rice husk was bonded with starch, tree resin, and wastepaper pulp at ratios of 1:6, 1:7, and 1:5 under low pressure. The findings showed that briquettes of tree resin were found to have the highest energy content. In another study, rice husk was blended with citrus husks (orange, tangerine, and lemon) at varying ratios using a yellow potato peel binder, yielding briquettes with density, ash content, and energy value of 0.35–0.46 g/cm^3, 3.9%–4.9%, and 14.6–17.2 MJ/kg, respectively [22]. On optimization, several literature reported optimum values between $< 5\%$ and 15% for binder content and 6.86–122.7 MPa for compression pressure [10].

While this study acknowledges the recalcitrance of rice husk, it focuses more on its sustainability as an energy source in the study area, and its potential environmental benefits when processed into fuel briquettes as against the conventional felling of trees for energy production. To further ascertain the environmental benefit of rice husk briquette, the authors of this study have carried out (in a different study) a comparative life cycle assessment of rice husk briquette and charcoal, which revealed that rice husk briquette has the potential to mitigate climate change by 20%. Following the abundance of rice husks in Nigeria, it is perceived to be a sustainable feedstock for energy production. Hence, it was selected as the primary feedstock in this study. Processing rice husks into fuel briquettes would not only serve as an energy source and a waste management solution, but it would also help reduce dependence on fuelwood and charcoal, thereby mitigating deforestation.

Overall, there are limited studies on low-pressure briquette production from rice husk, as previous studies were focused on other biomass forms. The few studies that explored rice husk in briquette production used it as a blend with other biomass, such as the studies of Chukwuneke et al. [23], Yank et al. [24], and Magnago et al. [22]. Others, such as Lubwama and Yiga [25] and Suryaningsih et al. [26] used it in carbonized form, while some studies, such as Saeed et al. [27] employed a high-pressure press, which is not only energy-intensive but also expensive to set up. Although Lakshika et al. [21] used a low-pressure compression, a very high content of binder beyond the limit of ISO 17225-1 [28] for briquette production ($\leq 20\%$) was used. Low-pressure briquette production is less costly as the machines are simple and easy to construct, with less energy requirement. The production unit is often used with freely available or low cost feedstocks, which reduces the overall cost of production. Briquetting is a waste treatment technique that helps prevent environmental pollution, especially in rural areas where biomass is often landfilled or burned. Thus, it could be easily practiced and adopted in households, reducing energy poverty and deforestation. Similarly, studies that optimized the production process and quality metrics of rice husk briquette are limited. Against this background, this paper aims to optimize the process conditions and selected quality metrics of rice husk briquette production. In addition to employing rice husk in its uncarbonized form under low pressure, the paper's novelty lies in exploring the potential of some biomass materials as novel binders in briquette production, with sweet potato peel binder prepared using the locust bean husk extract. In addition, the study has determined the optimum process conditions for attaining the most efficient output utilizing this technology. In the same vein, quality metrics prediction models have been developed.

2. Materials and methods

The flowchart followed in the study is presented in Fig. 1, which ranges from feedstock collection to model prediction and validation.

2.1. Material preparation

The feedstocks which include rice husks and binding materials (sweet potato peel [PPL] and locust bean pulp [LBP]) were sourced from Zaria, Kaduna State, Nigeria at latitude 11°12′1.8″ N and longitude 7°33′23.2″ E, latitude 11°10′5.65824″ N and longitude 7°39′25.88832″ E, and latitude 11°6′37.1826″ N and longitude 7°43′40.48392″ E, respectively. The control binder (cassava starch [CSS]) was purchased from the market. Cassava starch was selected as the control because it is one of the commonly used binders in briquette production [10]. The selection of sweet potato peel and locust bean pulp was based on availability, ease of handling, projected performance (as evident from the preliminary evaluation), and because they have not been previously used in briquette production (novelty), which is part of efforts to develop new biomass binders.

All feedstocks were kept in a closed container to avoid moisture absorption. The sweet potato peel was washed, sun-dried at an average temperature and relative humidity of 29 °C and 65% for 5 days, and ground in an electric milling machine (Model 9z-23, Zhengzhou Shuliy Machinery Company, Ltd., China). Rice husk was milled to particle sizes of ≤ 2000 microns (2 mm) using a hammer mill (Model HR600, Henan, China) fitted with a 2 mm screen mesh and later sieved to obtain other particle size levels (i.e., 1.0 and 1.5 mm). However, locust bean pulp

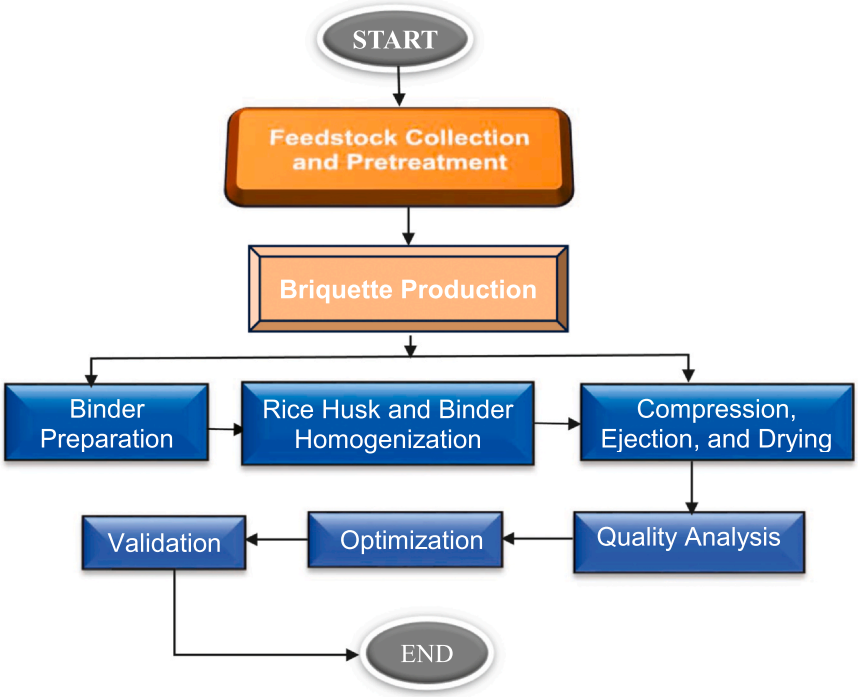

Fig. 1. Experimental process flowchart (Yunusa et al., 2024).

was collected in a pre-processed form, which does not require much processing. Thus, it was only mixed thoroughly to homogenize the lumps and then sieved through a 1 mm sieve to achieve particles ≤1 mm.

2.2. Briquette production

The production process began with binder preparation using the hot gelatinization method. The binder ratio was set at 3 levels, that is, 5%, 10%, and 15%, corresponding to 21 g, 42 g, and 64 g, respectively. The selection of binder ratio was guided by literature, standard, and preliminary tests. The contents of the binder were maintained between 5% and 15%, in compliance with the limit of ISO 17225-1 [28], which requires that additives (binders) should not exceed 20%. The raw binder was mixed with 100 ml of water at room temperature to homogenize appropriately in each experimental trial. This was followed by adding 500 ml of boiled water and 5 minutes of manual mixing to gelatinize. The binder was then mixed with rice husk, and 140 ml of water at room temperature was added and manually mixed for about 10 minutes to homogenize appropriately. The quantity of rice husk in each run was added based on the percentage of binder in the designed ratios, that is, 85% (360 g) rice husks to 15% binder, 90% (382 g) rice husks to 10% binder, and 95% (403 g) rice husks to 5% binder as shown in Table 1. A 200 g of the mixture was fed into the mold of a manually operated hydraulic piston press and densified per the residence time.

The press consists of 4 cylindrical molds of 8 cm in diameter and 16 cm in height. The samples were compressed at room temperature and a constant pressure of 4.5 MPa using a 5-ton hydraulic jack. Four (4) samples were produced per compression, and each run was replicated thrice.

Table 1
Briquette production mixing ratios

S/N	Rice husk (%)	Binder (%)
1	85	15
2	90	10
3	95	5

After ejection from the mold, the samples were sun-dried for 7 days. After drying, the samples were stored at room temperature for 3 weeks before evaluation. A pictorial view of the samples is shown in Fig. 2.

2.3. Experimental design

Box Behnken design (BBD) was employed in designing the experiment, using 3 numerical factors, 1 categorical factor, and 3 replicated central points. The actual and coded factors are presented in Table 2. 45 experimental runs were generated using Design Expert 13, with each binder type having 15 separate runs. Two responses, relaxed density and compressive strength, were considered. Response surface methodology (RSM) modeling was employed to optimize the production.

The number of experiments in a 3-level factorial design was estimated using Eq. (1) [29]:

$$N = 2k(k-1) + cp \tag{1}$$

where N is the number of experiments, cp is the number of central points, and k is the number of factors.

2.4. Briquette evaluation

2.4.1. Calorific value, proximate, and ultimate analysis

The gross calorific value was determined as per the method described in ASTM D5865-10a [30], using a Bomb Calorimeter (Model: 6100, Parr Instrument Company, USA). The moisture content was determined following the method described in ASTM D3173-87 [31], and estimated using Eq. (2):

$$MC\,(\%)wb = \frac{W_i - W_f}{W_i} \times 100 \tag{2}$$

where MC (%) wb is the moisture content (web basis), W_i is the initial weight of the sample (g), and W_f is the final weight of the sample (g)

The volatile matter was determined based on the modified procedure described in ASTM D3175 [32] for all sparking fuels, and the percentage of the volatile matter was estimated as the difference between the percentage weight loss and the moisture content as given in Eqs. (3) and (4) [32]:

Fig. 2. Briquette samples of (A) locust bean pulp (LBP) binder, (B) sweet potato peel (PPL) binder, and (C) cassava starch (CSS) binder.

Table 2
Actual and coded factors for experimental design

Factors	Code	Variation levels		
		Low (-1)	Medium (0)	High (+1)
Binder ratio (%)	A	5	10	15
Particle size (mm)	B	1	1.5	2
Dwell time (min)	C	0.5	1	1.5
Binder type	D	PPL	CSS	LBP

$$weight\ loss\,(\%) = \frac{a-b}{a} \times 100 \tag{3}$$

$$Volatile\ matter\,(\%) = c - m \tag{4}$$

where c is the weight loss (%), m is the moisture content (%), a is the weight of the oven-dried sample (g), and b is the weight of the sample (g) after heating in the furnace.

The ash content was determined following the procedure described in ASTM D3174-02 [33], and the percentage of ash was estimated using Eq. (5) [34]:

$$Ash\ content\,(\%) = M_{ash}/M_{oven-dry} \times 100 \tag{5}$$

where M_{ash} is the mass of the ash (g) and $M_{oven-dry}$ is the mass of the oven-dried sample (g).

The fixed carbon (FC) was estimated using Eq. (6) [35,36]:

$$\%FC = [100 - (\%Ash + \%VM)] \tag{6}$$

The carbon, hydrogen, and oxygen contents were determined from the result of proximate analysis with an accuracy of ± 2% using Eqs. (7) to (9) [37]:

$$Carbon\,(\%) = 0.635FC + 0.460VM - 0.095AC \tag{7}$$

$$Hydrogen\,(\%) = 0.059FC + 0.060VM + 0.010AC \tag{8}$$

$$Oxygen\,(\%) = 0.340FC + 0.469VM - 0.023AC \tag{9}$$

where FC is fixed carbon, AC is ash content, and VM is volatile matter.

2.4.2. Relaxed density

The relaxed density of the briquettes was determined 30 days after ejection from the mold [38], by measuring the mass and volume following the method described in ISO 3131 [39]. The mass was determined by weighing the samples on a digital weighing balance (Model: OPH-T3001, Optima Scale, USA) with an accuracy of ± 0.1 g, and the volume was obtained by measuring the length and diameter in 2 perpendicular directions using a digital vernier caliper with an accuracy of ± 0.01 mm. Thus, the density was estimated as the ratio of the mass per unit volume as given in Eq. (10) [40]:

$$\rho = \frac{m}{\pi/4 \cdot d^2 l} \tag{10}$$

where ρ is the density (g/cm^3), m is the mass of the briquette (g), d is the average diameter (cm), and l is the average length (cm).

2.4.3. Compressive strength

The compressive strength is the maximum crushing force that briquettes can withstand before failure [41]. This was determined using a universal test machine (SM1000-TecQuipment Ltd., Nottingham, UK) with a load cell capacity of 100 kN and a force measurement accuracy of ± 0.5% following the method described in ASTM D2166-06. Each sample briquette was placed between the plates as shown in Fig. 3 and subjected to uniform loading until failure. The peak load and nominal stress were automatically recorded every 0.5 seconds, with the maximum considered as compressive strength.

2.4.4. Thermal and emission analysis

The thermal analysis was conducted using the standard water boiling test (WBT) version 4.2.3 [42]. The test simulates the boiling time, specific fuel consumption (SFC), and burning rate of the various briquettes. The experimental layout of the analysis is presented in Table 3.

The test was conducted in a laboratory with an average temperature and relative humidity of 33.9 °C and 32%, respectively. It was carried out at a hot-start high-power phase with 150 g of each sample fuel employed in boiling 500 ml of water using an improved biomass cookstove. It commenced by determining the local boiling temperature (88 °C). A Camry digital scale balance (model: EK5350, China) with an accuracy of 1 g was used in weight measurements. A Smart Sensor (model: AR837, Hong Kong) was used to determine the ambient temperature and relative humidity. A mercury-in-glass thermometer was employed to monitor the temperature rise in the pot. An infrared thermometer was used to verify the readings from the glass thermometer, especially before steaming. While the time taken to boil was recorded using a stopwatch, the burning rate and specific fuel consumption were estimated using Eqs. (11) and (12) [42]:

$$r_{cb} = \frac{f_{cd}}{\Delta t_c} \tag{11}$$

Fig. 3. Determination of compressive strength of a briquette sample using the universal test machine.

Table 3
Experimental layout for thermal analysis

Sample	Sample ID	Binder ratio (%)	Particle size (mm)	Dwell time (sec)
CSS	CSS1	5	1.5	30
	CSS2	10	1.5	30
	CSS3	15	1.5	30
LBP	LBP1	5	1.5	30
	LBP2	10	1.5	30
	LBP3	15	1.5	30
PPL	PPL1	5	1.5	30
	PPL2	10	1.5	30
	PPL3	15	1.5	30

CSS = cassava starch briquette; LBP = locust bean pulp briquette; PPL = sweet potato peel briquette.

where r_{cb} is the burning rate (g/min), f_{cd} is the equivalent dry fuel consumed (g), and Δt_c is the time to the test (min).

$$SFC = \frac{f_{cd}}{W_{cr}} \tag{12}$$

where SFC is the specific fuel consumption, and W_{cr} is the effective mass of water boiled (lit).

The emission of gases was determined using an emission analyzer (model: NHA-506EN, Nanhua Instruments Co. Ltd.). Each sample was ignited in the cookstove and allowed to burn for about 5 minutes, for the flame to be established. The cookstove was covered with a duct comprising a central gas outlet. The analyzer probe was inserted into the outlet and allowed for about a minute until the readings were observed to have reached their maximum. The gases considered are CO_2, CO, HC, and NO.

2.4.5. Fourier transform infrared spectroscopy (FTIR) analysis

Fourier transform infrared spectroscopy (FTIR) was conducted to identify the functional groups in the samples [43]. It is an analytical method of determining the briquette's organic structure [44]. Through this, the bonding mechanism within the briquettes is known [45]. The analysis was done with a Cary 630 spectrometer (Agilent Technologies Inc., USA). The spectra for each sample were collected in the range of 650–4000 cm^{-1} with a resolution of 8 cm^{-1}, sample scans of 32, and background scans of 16.

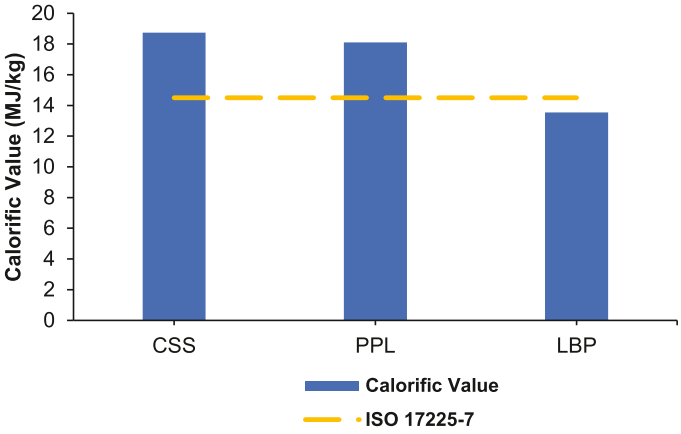

Fig. 4. Calorific value.

2.5. Statistical analysis and response equation

The data were analyzed statistically using analysis of variance (ANOVA) in Design Expert 13 (Stat-Ease Inc., MN, USA). The Tukey test was employed on response variables that are significantly different at 5% level based on binder type to identify the difference in group means. The responses as a function of the independent variables were predicted using a second-order polynomial equation (Eq. 13). Response surface methodology (RSM) was employed to optimize the process parameters and responses:

$$y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j \tag{13}$$

where y represents the response variable (relaxed density and compressive strength), $x_{,i}$ and x_j are the input variables, k is the number of factors, β_o is the intercept, β_i is the first-order model coefficient, β_{ii} is the quadratic coefficient, and β_{ij} is the linear model coefficient for the interaction between variables i and j.

3. Results and discussion

3.1. Calorific value, proximate, and ultimate analysis

3.1.1. Calorific value

The results of the calorific value are presented in Fig. 4. The calorific value shows the estimated energy content per unit mass of the briquette. The values range between 13.54 and 18.74 MJ/kg, with the CSS briquettes having the highest calorific value. The calorific values agree with the values (9.5–16.6 MJ/kg) obtained by Lubwama and Yiga [25] for briquettes developed from rice husk using cassava starch and clay binders, and conforms with the findings (9.66–19.23 MJ/kg) of Ndindeng et al. [11] for briquettes made from a blend of rice husk and bran. The values obtained for CSS and PPL also conform to the European Norm (ENplus) limit of 16.56 MJ/kg [19], and meet the limit (14.5 MJ/kg) reported in ISO 17225-7 [46]. This shows that the briquettes have adequate energy densities [15].

3.1.2. Proximate and elemental constituents

The results of the briquette's proximate and elemental constituents are presented in Table 4. The content of volatile matter ranges between 79.65% and 82.40%, consistent with the values (76.36%–89.18%) reported for briquettes made from rice husk using paper pulp, starch, and tree resin binders [21]. High volatile matter content, as obtained in this

Table 4
Proximate and major elemental constituents of the briquettes

	MC (%)	Ash (%)	VM (%)	FC (%)	C (%)	H (%)	O (%)
PPL	6.10	13.33	82.40	4.27	39.35	5.33	39.79
LBP	4.85	16.50	79.65	3.85	37.52	5.17	38.29
CSS	6.00	15.00	82.00	3.00	38.20	5.25	39.13

PPL = sweet potato peel briquette; LBP = locust bean pulp briquette; CSS = cassava starch briquette.

study, indicates good ignitability and combustion efficiency [47]. The ash content is between 13.33% and 16.50%, with LBP having the highest content. This agrees with the findings of Lakshika et al. [21] (7.11%–16.20%) and is lower than the values (17.64%–68.8%) reported by Ndindeng et al. [11] for briquettes produced from rice milling by-products. Overall, the ash content of uncarbonized rice husk briquette is generally high because rice husk is a recalcitrant biomass with a high ash content between 13% and 23%, as reported in ISO 17225-1 [28]. The content of fixed carbon is between 3% and 4.27%, with PPL briquettes having the highest content. The obtained values are low due to the high volatile matter recorded [36]. While fixed carbon is said to increase the energy content of the briquettes, lower values imply that the other forms of carbon (organic and inorganic) were volatilized.

With a carbon content between 37.52% and 39.35%, oxygen between 38.29% and 39.79%, and hydrogen between 5.17% and 5.33%, the major elemental constituents needed for combustion are adequately present in the briquette. The contents of carbon, oxygen, and hydrogen agree with the reported range by Lakshika et al. [21] and are lower than the values reported by Chou et al. [48].

3.2. Analysis of variance, model diagnostics, and equations

The analysis of variance (ANOVA) results is presented in Tables 5 and 6. The results depict the model's significance and the lack of fit relative to pure error. For both responses, the model has very low *P*-values < 0.0001 (< 0.05), indicating that there is only a 0.01% chance that large F-values (7.37 and 7.72) could occur due to noise. Additionally, the large *P*-values for the lack of fit (> 0.05) indicate that the model is significant and the lack of fit is insignificant.

Although the ANOVA results showed that the model used is statistically significant with an insignificant lack of fit, a transformation was recommended for compressive strength to improve the model's fitness and predictive capacity. As presented in the Box-Cox plot (Fig. 5), the model recommended an inverse square root transformation as the most suitable to improve data normality and stabilize variance. Hence, after applying the transformation, the lambda value eventually changed to -5 from an initial value of 1, indicating a significant improvement in the model fitness.

Additional fit statistics parameters are presented in Table 7. Therein, the obtained r-squared values (0.84 and 0.82) are in reasonable agreement with the adjusted r-squared values (0.73 and 0.71), as the differences between both are less than 0.2. Furthermore, the values of adequate precision for all the responses are desirable, as they are all greater than 4, indicating the model's adequacy in navigating the design space.

Based on the aforementioned, it means that there is a slight variation between the design or actual points and their predicted values (Fig. 6).

3.2.1. Model equations

The regression equations of relaxed density (ρ_r) and compressive strength (CS) for the independent variables (binder ratio [A], particle size [B], dwell time [C], and binder type) are presented in Equations 14 and 15, respectively.

a. Relaxed density

$$\rho_r = 0.2692 + 0.0134A - 0.0146B - 0.0014C - 0.0007D - 0.0096AB - 0.0055AC + 0.0006AD + 0.0011BC + 0.0108BD + 0.0012CD + 0.0007A^2 - 0.0147B^2 + 0.0028C^2 \quad (14)$$

b. Compressive strength

$$\frac{1}{\sqrt{CS}} = 0.1420 - 0.0353A + 0.0181B - 0.0157C + 0.0074D - 0.0030AB + 0.0067AC + 0.0063AD - 0.0126BC - 0.0192BD - 0.0325A^2 + 0.0203B^2 + 0.0057C^2 + 0.0299A^2C \quad (15)$$

Table 5
Analysis of variance result for relaxed density

Source	Sum of squares	df	Mean square	F-value	*P*-value	
Model	0.0150	17	0.0009	7.37	< 0.0001*	Significant
A-binder ratio	0.0035	1	0.0035	28.80	< 0.0001*	
B-particle size	0.0039	1	0.0039	32.89	< 0.0001*	
C-dwell time	0.0001	1	0.0001	0.6105	0.4422	
D-binder type	0.0001	2	0.0000	0.2347	0.7926	
AB	0.0009	1	0.0009	7.90	0.0097*	
AC	0.0003	1	0.0003	2.60	0.1202	
AD	0.0007	2	0.0003	2.85	0.0772	
BC	0.0000	1	0.0000	0.1100	0.7431	
BD	0.0012	2	0.0006	4.98	0.0155*	
CD	0.0008	2	0.0004	3.36	0.0515	
A^2	5.324E−06	1	5.324E−06	0.0444	0.8349	
B^2	0.0022	1	0.0022	17.96	0.0003*	
C^2	0.0001	1	0.0001	0.6330	0.4341	
Residual	0.0029	24	0.0001			
Lack of fit	0.0015	18	0.0001	0.3498	0.9610	Not significant
Pure error	0.0014	6	0.0002			

* Means significant at $P < 0.05$.

Table 6
Analysis of variance result for compressive strength

Source	Sum of squares	df	Mean square	F-value	*P*-value	
Model	0.1270	16	0.0079	7.72	< 0.0001*	Significant
A-binder ratio	0.0284	1	0.0284	27.63	< 0.0001*	
B-particle size	0.0079	1	0.0079	7.65	0.0101*	
C-dwell time	0.0001	1	0.0001	0.0999	0.7543	
D-binder type	0.0462	2	0.0231	22.47	< 0.0001*	
AB	0.0001	1	0.0001	0.1067	0.7464	
AC	0.0002	1	0.0002	0.2317	0.6341	
AD	0.0091	2	0.0045	4.41	0.0220*	
BC	0.0019	1	0.0019	1.85	0.1856	
BD	0.0105	2	0.0053	5.13	0.0130*	
A^2	0.0121	1	0.0121	11.76	0.0020*	
B^2	0.0044	1	0.0044	4.28	0.0483*	
C^2	0.0003	1	0.0003	0.3342	0.5680	
A^2C	0.0050	1	0.0050	4.88	0.0359*	
Residual	0.0277	27	0.0010			
Lack of fit	0.0257	21	0.0012	3.65	0.0571	Not significant
Pure error	0.0020	6	0.0003			

* Means significant at $P < 0.05$.

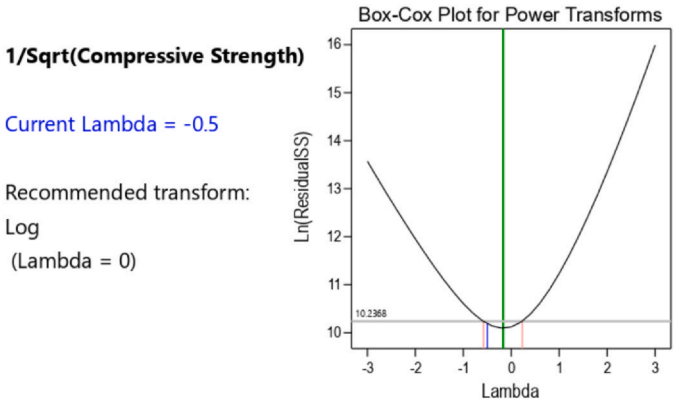

Fig. 5. Box-cox plot for power transforms of compressive strength to improve data normality and stabilize variance.

Table 7
Response model fit summary output for relaxed density and compressive strength

Indicators	R^2	Adjusted R^2	Predicted precision
Relaxed density	0.84	0.73	9.63
Compressive strength	0.82	0.71	9.56

3.3. Experimental design variables and quality parameters

The experimental design variables and responses are presented in Table 8. Each binder type was varied in fifteen (15) different experiments based on BBD. The response variables (relaxed density and compressive strength) were evaluated. The experimental data obtained were used in further modeling stages to determine the predicted values and optimal input and response variables. The values obtained range from 0.20 to 0.31 g/cm^3 for relaxed density and from 20 to 410 kN/m^2 for compressive strength, across varying process parameters (particle size, dwell time, binder type, and ratio). The findings are in agreement with those of Ajimotokan et al. [49] for briquettes made from rice husks and corncob under low pressure, a relaxed density between 0.42 and 0.78 g/cm^3, and a compressive strength between 39 kN/m^2 and 111 kN/m^2 were recorded. Similarly, the compressive strength meets the minimum standard of 350 kN/m^2 required for briquettes for domestic application [50].

3.3.1. Relaxed density

The results of the relaxed density are presented in Fig. 7. Although there was no significant difference between the 3 briquette types, CSS-bonded briquettes had the highest relaxed density. The obtained values are within the range of values previously reported for low-pressure briquettes [22,24,38]. These values are relatively low because rice husk is a low-density biomass (96–160 kg/m^3) [51], with low lignin reactivity. Therefore, it requires a longer residence time and medium to high pressure to consolidate properly into composites [52,53]. Additionally, the compression method employed in this study is a low-pressure (< 5 MPa) type. Moreover, the density of briquettes produced under low pressure with a hydraulic piston press is usually < 1000 kg/m^3 [54]. This is typically lower than those densified at high pressure. This indicates that the machine or briquette press also influences the quality performance.

3.3.2. Compressive strength

The compressive strength test results are shown in Fig. 8. The highest compressive strength was obtained in LBP-bonded briquettes at 15% binder, 1.5 mm particle size, and 1.5 minutes dwell time. This was followed by briquettes made from the combination of 15% LBP binder, 1.5 mm particle size, and 0.5 minutes dwell time. This shows that the ratio of binder is instrumental in obtaining compressive strength. Thus, the higher the binder ratio, the better the compressive strength [55]. However, this assertion may vary depending on other interacting process factors such as the blend of feedstocks used [49], material type, particle size, and compaction pressure [49]. The compressive strength values of LBP briquettes were significantly higher than those of PPL and CSS binders, indicating that the LBP binder could potentially perform better than CSS. Moreover, this superior performance of LBP may be attributed to its good textural density in raw and gelatinized forms, allowing it to be retained in the core layers even after densification and drying. However, the performance was inconsistent throughout the experiments, as briquettes made with PPL also showed higher compressive strength in several runs. This inconsistency could be due to the low precision in manual densification.

Though CSS-bonded briquettes exhibited better relaxed density, their compressive strength was below that of LBP and PPL in most runs. This shows that relaxed density does not translate to the total strength of the briquette, as it concerns the sample's mass per unit volume, not the sample's interparticle bond and core layer strength. Magnago et al. [22] also observed that the density of briquettes made from rice husks and citrus peel does not consistently change with compressive strength. Similarly, in the study of Yank et al. [24], it was observed that the briquette of rice husks and bran with the greatest density does not yield

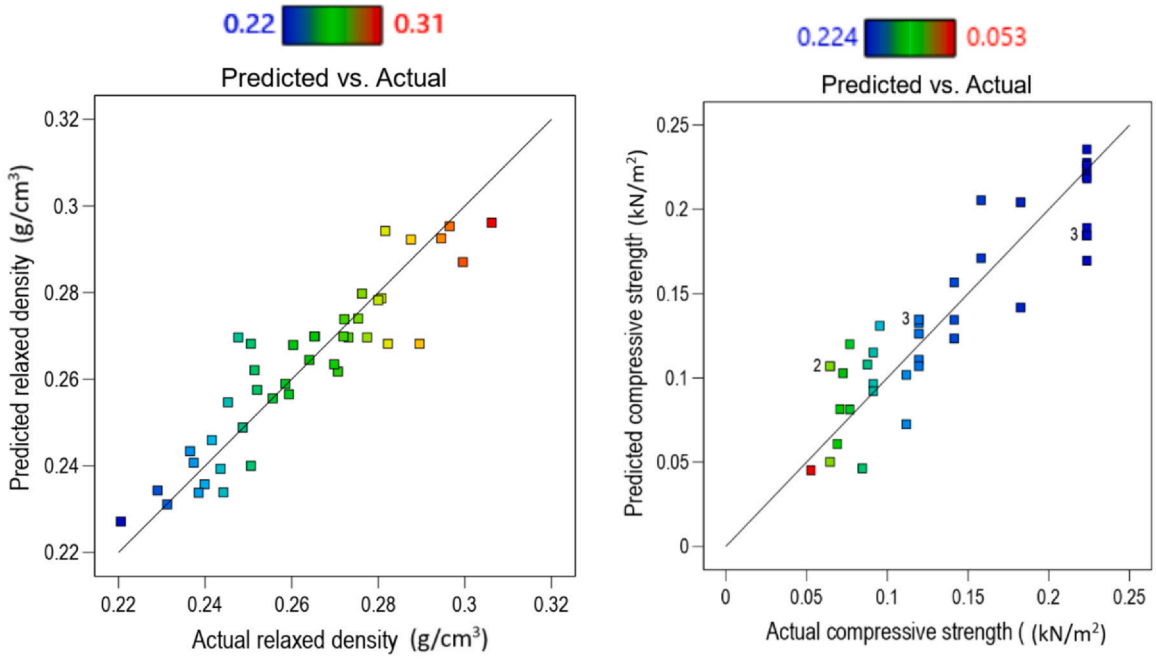

Fig. 6. Predicted versus actual plots showing the fitness of experimental data to the model. (a) Relaxed density and (b) compressive strength.

Table 8
Quality parameters as a function of input design variables

Std Run	A: BR (%)	B: PS (mm)	C: DT (min)	Responses					
				ρ_r (g/cm^3)			CS (kN/m^2)		
				CSS	LBP	PPL	CSS	LBP	PPL
1	5	1	1	0.240	0.259	0.242	20	50	80
2	15	1	1	0.306	0.258	0.281	110	140	210
3	5	2	1	0.229	0.221	0.249	20	30	50
4	15	2	1	0.259	0.238	0.237	190	120	70
5	5	1.5	0.5	0.251	0.252	0.260	40	30	200
6	15	1.5	0.5	0.288	0.282	0.295	170	360	240
7	5	1.5	1.5	0.196	0.270	0.271	20	50	120
8	15	1.5	1.5	0.296	0.280	0.264	50	410	120
9	10	1	0.5	0.251	0.300	0.275	20	70	130
10	10	2	0.5	0.244	0.244	0.216	20	20	20
11	10	1	1.5	0.272	0.276	0.245	20	170	80
12	10	2	1.5	0.256	0.231	0.237	40	20	70
13	10	1.5	1	0.273	0.265	0.251	20	70	70
14	10	1.5	1	0.248	0.272	0.282	20	70	240
15	10	1.5	1	0.277	0.265	0.290	20	70	240

BR = binder ratio; PS = particle size; DT = dwell time; CSS = cassava starch; PPL = sweet potato peel; LBP = locust bean pulp.

the highest compressive strength. Thus, compressive strength simulates the durability of the briquettes, indicating the total load a briquette can withstand during handling and storage [56]. While the density of briquettes may occasionally influence the compressive strength, it is important to note that compressive strength is not necessarily influenced by density, as density alone cannot fully account for the effectiveness of bonding [50]. This is evident in the correlation plot (Fig. 9), which shows a moderate positive correlation between the 2 responses, depicting that compressive strength is moderately influenced by relaxed density. Based on this, several samples yielded a low compressive strength despite having relatively good densities, with only a few meeting the minimum limit of > 350 kN/m^2 as recommended by Richards [50]. To improve compressive strength significantly, employing pretreatment measures such as hydrothermal carbonization on the raw rice husk before densification is recommended [57].

3.4. Response surface analysis

3.4.1. Relaxed density

The 3D surface response and contour plots of relaxed density are shown in Figs. 10 to 12. The color gradient illustrates the dynamics from lower relaxed density values (blue) through the medium values (green) to the region where relaxed density is highest (red). Relaxed density ranged between 0.22 and 0.31 g/cm^3, with the higher values mainly observed in briquettes bonded with LBP binder. The maximum relaxed density was recorded in the LBP-bonded briquettes at the interaction between particle size and binder ratio when dwell time is held constant at 1 minute (Fig. 10a). This indicates that after attaining the 30-day relaxation period, briquettes bonded with LBP binder have higher densities than those bonded with other binders, due to better gelatinization and improved binding of the core layer particles.

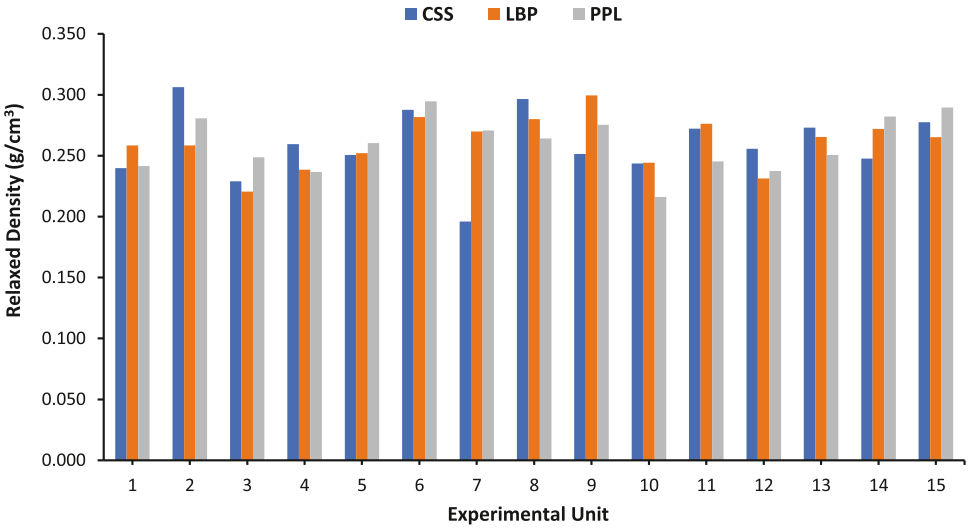

Fig. 7. Experimental results of relaxed density.

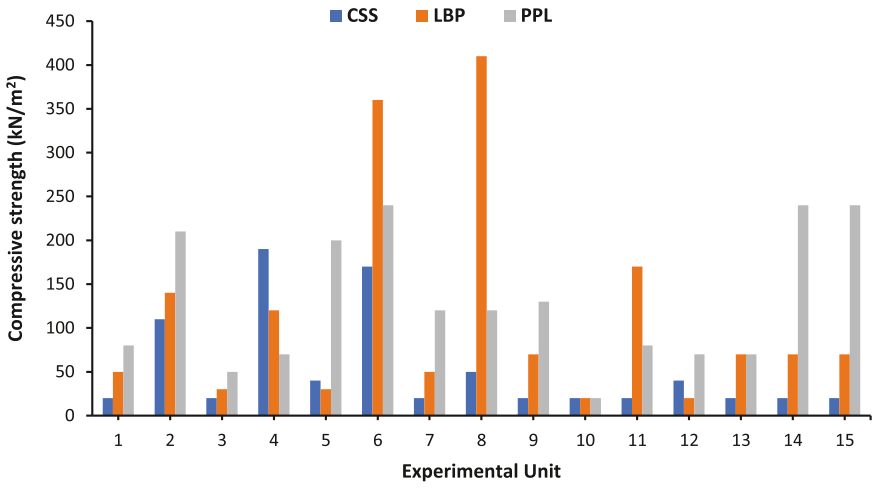

Fig. 8. Experimental results of compressive strength.

As shown in Fig. 11, relaxed density increases as dwell time increases and particle size decreases. This confirmed the assertion of Miao et al. [58], who reported that biomass with smaller particle sizes yields denser briquettes than those with larger sizes. Similarly, relaxed density increases as dwell time and binder ratio increase (Fig. 12). Because the dwell time is the period during which the mixture consolidates, the higher it is, the better the briquette density [10]. Similarly, binder content is very instrumental in low-pressure briquetting, as it aids compaction and solidification. Thus, as observed, the higher the binder, the better the relaxed density. These findings are consistent with those of Magnago et al. [22] and Onyango et al. [59], who also observed that briquettes with higher binder content have higher relaxed densities. Although the highest relaxed density was achieved with LBP-bonded briquettes, there is no significant difference with briquettes made from PPL and CSS binders.

3.4.2. *Compressive strength*

The 3D and contour plots of compressive strength are shown in Figs. 13 and 14. Due to the inverse square root transformation applied, these model graphs do not represent the actual values but the transformed outputs. The maximum compressive strength was noted at the region where binder content was maximum and dwell time between 0.5 and 1.1 minutes (Fig. 13). This is consistent with the findings of Magnago et al. [22], which noted that the compressive resistance of briquettes improves as the binder content increases. Overall, the highest compressive strength was observed in LBP-bonded briquettes. Previous studies, such as Jiao et al. [60], observed that an increase in dwell time enhances compressive strength at lower pressure and decreases it at higher pressure. Compressive strength measures the maximum force the briquettes can withstand before cracking or breaking [41], making it a critical factor in simulating load resistance during transportation and storage [56]. These findings show that LBP has good potential to yield briquettes with better compressive strength under low-pressure conditions. Similarly, as depicted in Fig. 14, the compressive strength increases as particle size decreases. While these findings agree with those of Zepeda-Cepeda et al. [61] for briquettes made from sawdust, it is contrary to the findings of Mitchual et al. [62], which report that compressive strength increases as particle size increases. This confirms that the quality metrics of briquettes are not consistently dependent on a single factor but a combination of varying factors such as material type, compaction pressure, and particle size, among others.

3.5. *Optimization*

The criteria used in the optimization phase were aimed at maximizing the responses while maintaining the process variables within the design range [63]. The predicted optimum parameters include a 15% binder ratio, 0.5 minutes dwell time, 1 mm particle size, and cassava starch binder. Chukwuneke et al. [23] also obtained a 15% optimal starch binder ratio for briquettes made from the combination of rice

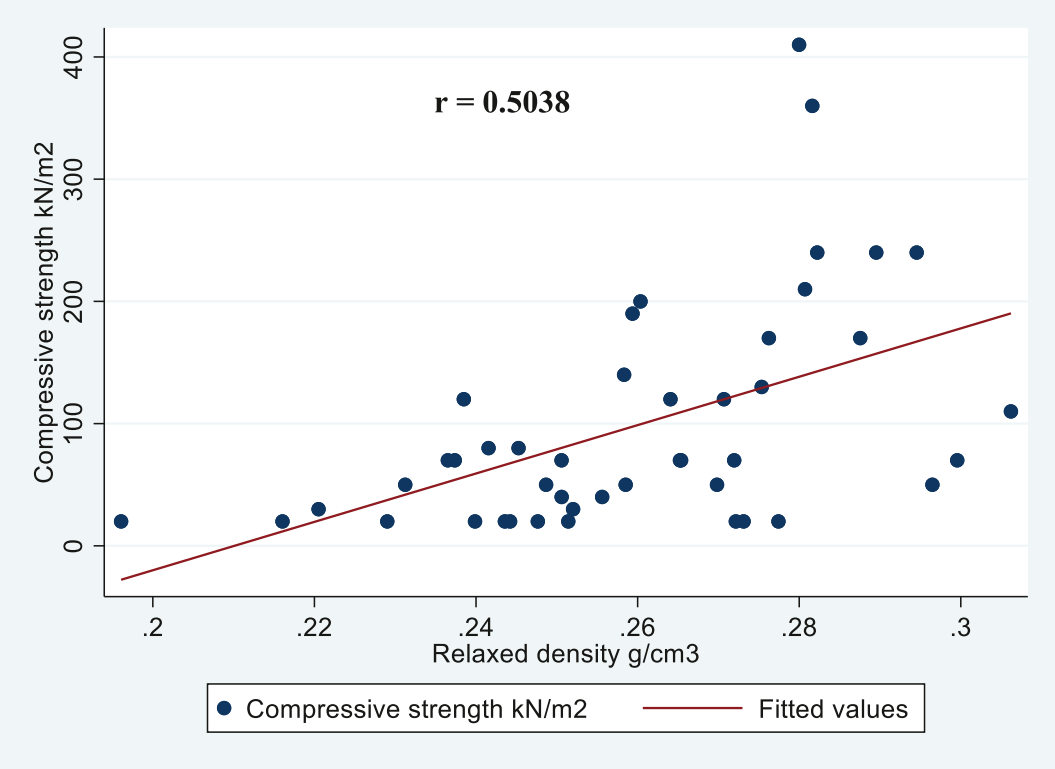

Fig. 9. The correlation between compressive strength and relaxed density.

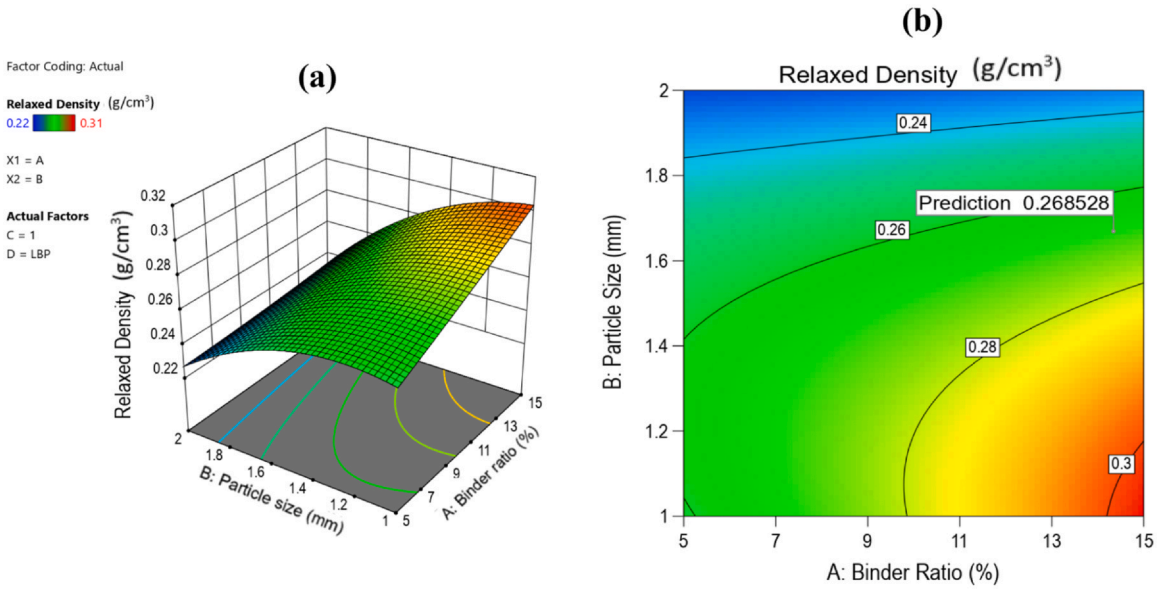

Fig. 10. (a) A 3D surface response and (b) contour plots, for the effect of interaction between BR and PS on relaxed density.

husks and sawdust. The 3D response surface and contour plots of the optimized responses are presented in Figs. 15 and 16. The model predicts an optimal relaxed density of 0.30 g/cm^3 (Fig. 15) and a compressive strength of 0.033 m$^{0.5}$ s kg$^{-0.5}$ (transformed), equivalent to 918 kN/m^2.

3.6. Validation

To confirm the veracity of the model predictions, a validation experiment was conducted based on the average of three (3) predicted solutions in the case of relaxed density. Because the compressive strength was transformed, the validation was done with 3 actual and predicted values. The results of the experimental and predicted values are summarized in Table 9. The percentage error obtained in both responses is $< 10\%$, depicting a minimal difference between the predicted and confirmatory experiments. Further analysis using a t-test was performed to assess the deviation between the means (Table 10). The *P*-value was 0.21 ($> 5\%$), indicating no significant difference between the experimental and predicted values.

3.7. Result of thermal and emission analysis

The result of the thermal analysis is shown in Table 11. The boiling time ranges between 3.1 and 9.3 minutes, with the samples made from cassava starch binder having the shortest boiling time. The result is

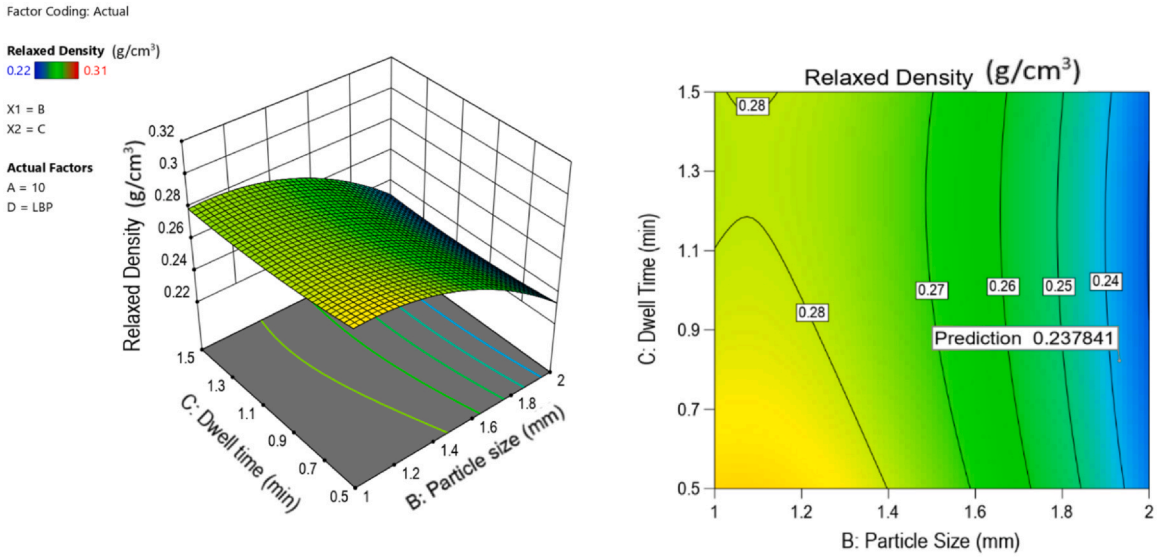

Fig. 11. (a) A 3D surface response and (b) contour plots, for the effect of interaction between PS and DT on relaxed density.

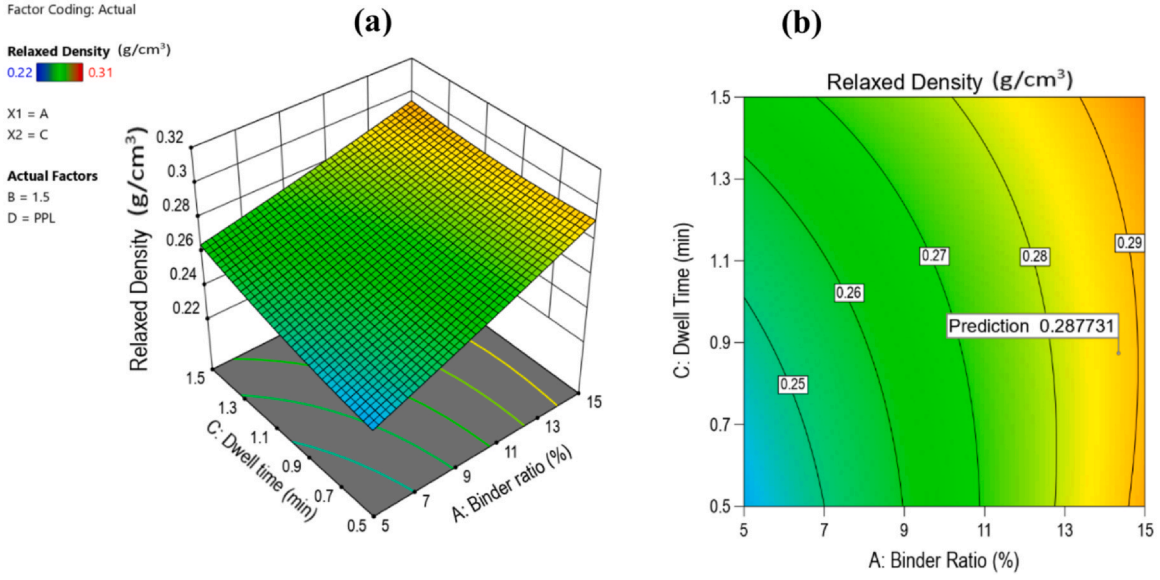

Fig. 12. (a) A 3D surface response and (b) contour plots, for the effect of interaction between BR and DT on relaxed density.

better than the control (charcoal), which took 15 minutes to boil. The short boiling time in briquettes is due to the high burning rate (10.22–37.10 g/min) recorded, which is occasioned by low density and high ignitability. This further influences the specific fuel consumption, which was higher in briquette (160.55–342.26 g/l) than in charcoal (179.29 g/min). The emissions recorded were between 1.26% and 2.89% for CO_2, 0.01–0.05% for CO, 4–14 ppm for HC, and 10–32 ppm for NO, respectively. Except for NO emission, which may have been induced by the binders, all other emissions were lower in briquettes than in charcoal. The result of CO_2 emission is consistent with the findings of Pilusa and Huberts [64], where 2.13% (21,332 ppm) was obtained from burning briquettes made from the mixture of spent coffee beans, paper pulp, coal fines, mielie husks, and sawdust. Overall, the emissions from PPL briquettes are lower except for NO, which the binder may have influenced. In this regard, a thorough life cycle analysis is the best approach to estimate the overall emissions and environmental impacts of the 2 product systems (briquettes and charcoal). Moreover, Mwampamba et al. [14] also observed that briquettes may have higher emissions characteristics due to the presence of binders.

3.8. ANOVA summary and post hoc analysis based on binder type

To distinctly assess the differences in briquette performance based on binder types, Table 12 summarizes the analysis of variance of all the quality, thermal, and emission performances evaluated in this study. From Table 12, the results show that the briquettes did not differ significantly except in the case of compressive strength, boiling time, and HC. Thus, to determine the specific groups that are statistically different, the Tukey test was applied on the 3 outcomes that showed significant difference from the analysis of variance (i.e., compressive strength, boiling time, and HC). The results of the post hoc test are presented in Tables 13 to 15. The outcome from compressive strength (Table 13) shows that the 3 briquette differ significantly, with briquettes made of CSS binder having the highest mean value. While briquettes made with LBP and PPL binders do not differ significantly in terms of boiling time (Table 14), the CSS briquettes with the shortest mean boiling time outperformed the 2. However, HC emission from LBP and PPL briquettes is significantly lower than that of CSS briquettes (Table 15).

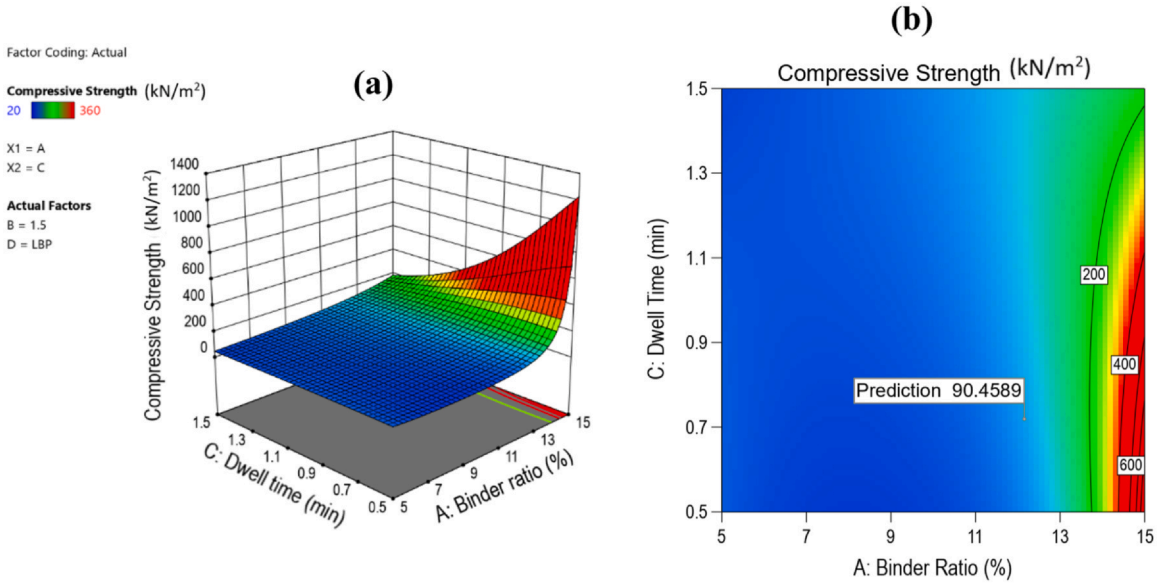

Fig. 13. (a) A 3D surface response and (b) contour plots for the effect of interaction between DT and BR on compressive strength.

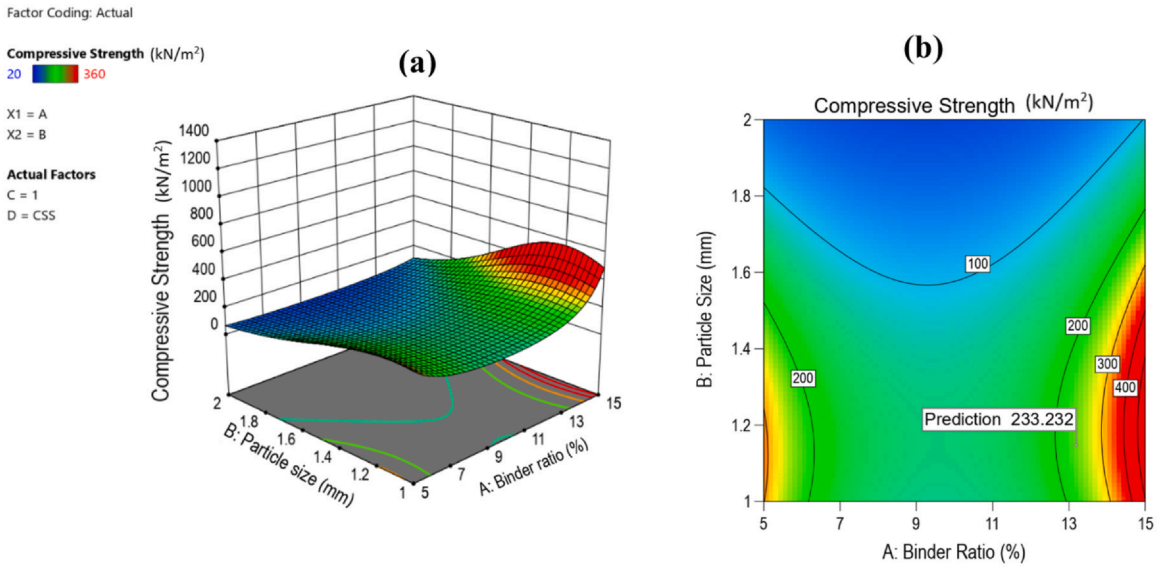

Fig. 14. (a) A 3D surface response and (b) contour plots for the effect of interaction between BR and PS on compressive strength.

3.9. Fourier infrared spectroscopy (FTIR) results

Fig. 17 presents the results of FTIR analysis for CSS, LBP, and PPL briquettes, respectively. Overall, more than 5 peaks were observed in the whole spectrum, indicating the presence of complex chemical bonds in the briquettes [65].

In the single bond region (2500–4000 cm^{-1}), the 3300–3700 cm^{-1} spectra show the stretch vibration of the phenolic hydroxyl group [45]. This peak is observed at around 3300 cm^{-1} in the 3 briquettes, which enhances adhesion between particles through lignin plasticity, thereby improving the mechanical integrity of the briquettes [66]. However, this is more typical in high-pressure densification as heat is required to soften the lignin. Thus, because the compression was at low pressure and room temperature, as the biomass increases, there is a tendency for weak binding or bond formation [45]. Similarly, Zhao et al. [67] noted that the phenolic hydroxyl bond is among the most stable functional groups, which could form a strong and stable conjugated structure. This could also improve the thermal stability of the briquette, resulting in slow and sustained combustion. The same peak stretched to 3300 and 3200 cm^{-1}, indicating hydrogen bonds in the briquettes. Hydrogen bonds improve the binding and structural integrity of the briquette [68]. However, this peak is insignificant in CSS briquettes, implying that the hydrogen bond is weaker in CSS briquettes than in PPL and LBP briquettes. There is no sharp intensity transmittance within the 3670 and 3550 cm^{-1} regions in the 3 briquettes. This implies the absence of oxygen-related bonds such as phenol [65]. In addition, no peaks were detected between 3200 and 3000 cm^{-1} in the 3 samples. This shows that the briquettes do not contain an aromatic structure, which implies a potential reduction in thermal stability [44]. A narrow band is observed around 2900 cm^{-1} in the 3 briquettes, indicating the presence of a C-C bond. Similarly, the peak is very shallow in CSS briquettes, showing a low proportion in CSS compared to PPL and LBP briquettes. C-C bond improves thermal and combustion efficiency and enhances the binding and durability of the briquette. However, no specific peak was detected between 2700 and 2800 cm^{-1} in the 3 briquettes, showing no aldehyde. Aldehydes are formed due to lignin decomposition, and their presence could improve ignition and flame intensity [68]. No peak is observed in the triple bond region (2000–2500 cm^{-1}). In the double bond region (1500–2000 cm), a shallow peak is observed between 1650 and 1600 cm^{-1} in the 3 briquettes, showing the presence

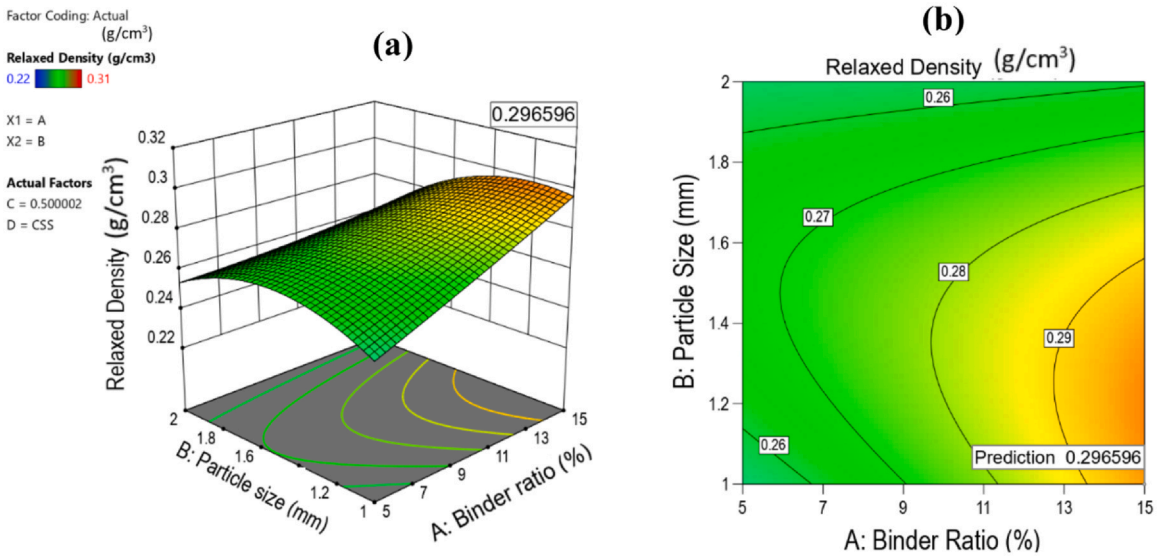

Fig. 15. (a) A 3D surface response and (b) contour plots of the optimized relaxed density.

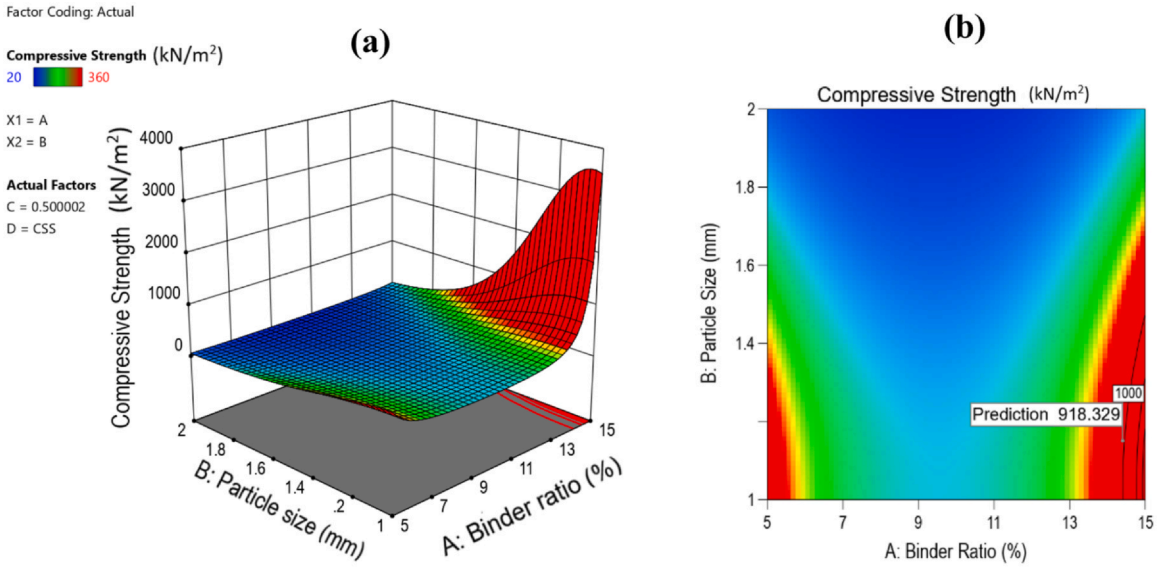

Fig. 16. (a) A 3D surface response and (b) contour plots of the optimized compressive strength.

Table 9
Experimented and predicted values

Variable	Experimental value	Predicted value	Error (%)
Relaxed density (g/cm^3)	0.30	0.30	
	0.29	0.30	
	0.29	0.30	
Average	*0.29*	*0.30*	*3.33*
Compressive strength (kN/m^2) m$^{0.5}$ s kg$^{-0.5}$	(277.8) 0.06	(82.6) 0.11	
	(20.7) 0.22	(30.9) 0.18	
	(20.7) 0.22	(17.4) 0.24	
Average	*0.17*	*0.18*	*2.65*

Table 10
Summary of t-test analysis

	Obs.	Mean1	Mean2	Dif.	St Err.	t value	*P*-value
EV-PV	2	0.23	0.24	0.008	0.003	3	0.21

Table 11
Result of thermal and emission analysis

Sample ID	Boiling time (min)	Burning rate (g/min)	SFC (g/l)	CO_2 (%)	CO (%)	HC (ppm)	NO (ppm)
CSS1	5.10	13.73	160.55	1.55	0.05	14.00	10.00
CSS2	3.80	23.95	236.98	1.90	0.01	14.00	11.00
CSS3	3.10	37.10	342.26	1.26	0.02	13.00	12.00
LBP1	9.30	10.22	233.99	1.68	0.02	9.00	22.00
LBP2	7.40	12.70	218.60	2.16	0.01	8.00	28.00
LBP3	7.40	10.41	180.75	2.03	0.01	4.00	31.00
PPL1	6.80	13.53	206.28	2.89	0.01	4.00	32.00
PPL2	6.10	13.44	194.31	1.31	0.01	7.00	22.00
PPL3	6.10	17.54	240.99	2.08	0.01	6.00	17.00
Charcoal	15	4.73	179.29	1.40	0.09	35.00	4.00

SFC = specific fuel consumption; CSS = cassava starch briquette; LBP = locust bean pulp briquette; PPL = sweet potato peel briquette.

Table 12
Summary of ANOVA results for quality and thermal performance based on binder type

Dependent variable	F value	Prob > F
Relaxed density (g/cm^3)	0.2347	0.7926
Compressive strength (kN/m^2)	22.47	0.0001*
Boiling time (min)	70.52	0.0008*
Burning rate (g/min)	3.78	0.1199
Specific fuel consumption (g/l)	0.32	0.7437
CO2 (%)	0.61	0.5877
CO (%)	2.0	0.2500
HC (ppm)	16.81	0.0113*
NO (ppm)	5.42	0.0727

Note: * Means significant at $P < 0.05$.

Table 13
Post hoc test for compressive strength

Compressive strength (kN/m^2)	Mean	Std. error	Tukey groups
CSS	129.33	19.44	B
LBP	90.71	20.12	AB
PPL	52	19.44	A

Note: Means sharing a letter in the group label are not significantly different at the 5% level.

Table 14
Post hoc test for boiling time

Boiling time (min)	Mean	Std. error	Tukey groups
CSS	4.00	0.52	B
LBP	8.03	0.52	A
PPL	6.33	0.52	A

Note: Means sharing a letter in the group label are not significantly different at the 5% level.

Table 15
Post hoc test for HC

HC (ppm)	Mean	Std. error	Tukey groups
CSS	13.67	1.04	B
LBP	7.00	1.04	A
PPL	5.67	1.04	A

Note: Means sharing a letter in the group label are not significantly different at the 5% level.

of some carbonyl double bond of amides or carboxylate functional groups. This bond improves binding, dimensional stability, and the durability of the briquettes. Adeleke et al. [69] attributed the peak around 1600 cm^{-1} to the presence of aromatic rings. Aromatic rings allow the formation of molecular forces that improve chemical bonding [70]. In the fingerprint region (600–1500 cm^{-1}), a strong signal was observed around 1000 cm^{-1} in all the briquettes, implying high cellulosic and hemicellulose content, and the presence of polysaccharides, which contribute to combustion stability and energy density. The content of cellulose and hemicellulose is influenced by the primary biomass (rice husk), which is highly lignocellulosic. However, this peak could also show the presence of a vinyl-related compound [65]. While there is no significant difference among the briquettes, the PPL briquette showed a higher peak, implying higher polysaccharides, cellulose, and hemicellulose content. A shallow peak around 790 cm^{-1} was observed in all the samples, indicating a few constituents of para-aromatic compounds. However, because the peak is relatively sharper in the CSS briquette, it shows that CSS has a higher content of para-aromatic compounds than LBP and PPL briquettes. Para-aromatic compounds are pivotal in energy efficiency, thermal stability, and durability of briquettes.

3.10. Policy relevance

Fuel briquettes, being an alternative and a potentially sustainable energy source from biomass, not only align with the Sustainable Development Goal (SDG) 7, which looks at ensuring access to clean and affordable energy, but also align with Nigeria's national focus on ensuring energy access, rural development, and climate change mitigation. With over 8 million tons of rice produced annually in Nigeria, more than 2 million tons of husk are generated but underutilized, as they are often landfilled and burned, contributing to environmental pollution [71]. In the same vein, the rate of energy-based deforestation keeps exacerbating, which induces climate change. Thus, to minimize these problems, there is a need for the government and relevant agencies to have actionable policies relating to energy sufficiency, climate change, and deforestation control. Harnessing energy from rice husk through briquetting will address some critical policy areas as outlined below:

i. With over 70% of households in Nigeria reliant on solid fuels like charcoal and firewood to meet their primary energy needs, rice husk briquette will serve as a sustainable, viable, and low-cost alternative, offering a viable solution to energy poverty, deforestation, and loss of biodiversity.
ii. The adoption and promotion of rice husk briquette production supports the circular economy principle, where waste is transformed into valuable energy products, offering a solution to environmental degradation.
iii. The use of rice husk briquette against charcoal and fuelwood reduces the emissions of greenhouse gases, which would culminate in mitigating climate change.
iv. The technology could serve as a source of livelihood, supporting small and medium enterprises, especially in the rural and peri-urban parts of the country.

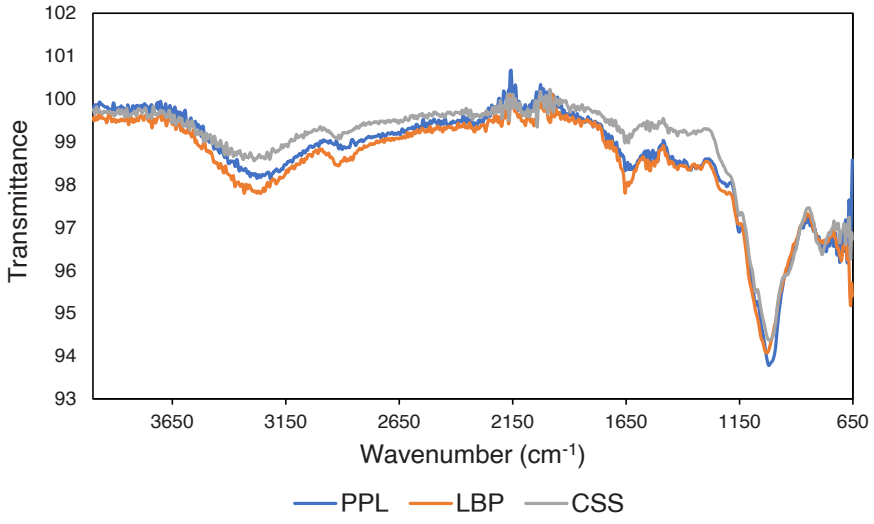

Fig. 17. FTIR spectra showing the chemical bonds and functional groups in the 3 types of briquettes.

4. Conclusion

The optimum process and response parameters of rice husk briquettes produced at low pressure using organic binders were determined. This is part of the measures to improve the production efficiency of low-pressure briquettes. The optimal relaxed density and compressive strength were obtained as 0.30 g/cm^3 and 0.032 m$^{0.5}$ s kg$^{-0.5}$ (918 kN/m^2), achieved with a binder content of 15%, particle size of 1 mm, and dwell time of 0.5 minutes. These predictions were verified through a confirmatory experiment, which did not show statistically significant differences between the experimental and predicted values, indicating that the model has adequately navigated through the design space. Additionally, to reduce overreliance on starch-based and inorganic binders in briquette production, the study discovered novel biomass binders (locust bean pulp and sweet potato peel) for use in briquette production. The quality of briquettes produced with these novel binders, especially how they outperformed the CSS briquettes in compressive strength, proves their potential as binders in briquette production.

The findings from this study provide a valuable reference for future research, especially aspects encompassing briquette production as optimum production conditions, quality prediction models, and novel binders have been determined. In addition, the study highlights the feasibility of producing briquettes from uncarbonized rice husks under low pressure. This is particularly relevant for low-income households that rely heavily on fuelwood and charcoal. Therefore, to reduce the overreliance on fuelwood and charcoal and address the energy deficit in Nigeria, rice husk briquettes can be sustainably produced at low pressure from the huge quantity of rice husks generated in the country. Furthermore, this would serve as an energy source and waste management strategy and contribute to climate change mitigation efforts.

As the study progresses, future studies should investigate a range of compression pressures through optimization to determine the optimum conditions for producing uncarbonized rice husk briquettes. Similarly, densifying rice husks at low to medium pressure without milling should be explored. Given the low density of rice husks, codensification with other biomass or using blends could improve the quality and thermal performance. Moreover, exploring pretreatment methods such as carbonization, hydrothermal treatment, or torrefaction could mitigate issues like slagging and fouling associated with high ash content. In addition, future studies should investigate the briquettes' surface and core morphology based on the binder types using microstructural analysis.

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CRediT authorship contribution statement

S.U. Yunusa: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **E. Mensah**: Supervision, Conceptualization. **K. Preko**: Supervision, Writing – review & editing. **S. Narra**: Writing – review & editing, Supervision. **A. Saleh**: Supervision. Safietou Sanfo: Supervision. **F. Dembele**: Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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