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Optimization of fuel briquette made from bi-composite biomass for domestic heating applications

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ABSTRACT

This study aimed at optimizing the fuel briquettes produced from flamboyant pod (FBP), and corn cob (CC) mixed with cassava starch (SB) as a binder using custom design methodology (CDM). The compressive strength, ash yield, and emission analysis of the briquettes produced were determined. The combustion efficiency parameters as well as CO, NO_2, $PM_{2.5}$, and PM_{10} of the emissions were compared to optimal fuel briquettes and charcoal fuel. The optimal combination of compressive strength and ash yield was obtained for the briquette fuel blend formulated from 30 wt.% flamboyant pod, 51 wt.% corn cob and 17 wt.% starch. While the water boiling time of the fuel increased by about 35–48% compared to charcoal fuel, the ignition time and the specific fuel consumption rate decreased by ~34% and 16%, respectively. Furthermore, the major air pollutants were reduced from 222 to 196 ppm for CO, 3.63–2.34 ppm for NO_2, and 0.21–0.09 ppm for $PM_{2.5}$. These properties of the briquette align with charcoal, thus supporting the use of flamboyant-corcob-starch (FBCS) briquettes as a supplementary source of energy to charcoal.

Introduction

Concerns over the supply limit of fossil fuels coupled with their environmental impacts have prompted extensive research and development of renewable fuels as alternatives. Consequently, densification of agricultural residues into briquettes has received attention in recent years due to its environmental friendliness, being entirely renewable and ease of implementation. The exponential increase in global population is putting pressure on its energy demand and economy [1]. Increased population enables higher fossil fuel consumption which consequently leads to source depletion [2]. To ameliorate these challenges, the search for clean energy has amplified in recent years. The fuels most commonly adapted for cooking in developing countries are wood, charcoal, kerosene, and cooking gas. However, the combustion of these cooking fuels brings about the release of hazardous greenhouse gases such as methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), and fluorinated gases (F–gases). These gases cause various environmental issues such as air pollution and global climate change amongst others [2,3].

Anxieties over the supply and impact of fossil fuels on the environment have prompted further research and development into

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renewable fuels, especially biofuel [4]. Globally, the demand for cleaner affordable cooking fuel alternatives is currently on the rise as the cost of cooking gas increases. However, the smoke emitted from the direct combustion of biomass is made up of particles and gaseous chemicals. Therefore, the study of waste biomass presents the means to reduce greenhouse emissions and produce cost-effective cooking fuels for low-income households. Biomass, in essence, is a "mass" of biological organisms. Biomass as a renewable source of energy, is one of the most cost-efficient and has the least carbon dioxide emissions [5]. Growing amount of air and land pollution from agricultural wastes has become a major concern around the world. Some of these available agricultural wastes can be converted to biofuels that enable cost-effective, energy-rich, and eco-friendly cooking fuels.

Maize (*Zeal Mays*), commonly known as corn-on-cobs, is one of major grain crops grown in Africa. For instance, according to [6], about 5.3 million hectares of the crop are cultivated yearly in Nigeria. Corn cobs are sparingly used as fuels because they are dense, relatively uniform and have higher heating value. Thus, conversion processes are required to enhance their fuel characteristics [7]. Unlike corn cobs, *Delonix Regia*, a royal Poinciana flamboyant tree, flame of the forests that is commonly grown in Nigeria has little or no economic value. While the pods have been grounded into fine particles (~75 μm) and applied as filler to enhance the mechanical and physical properties of polyester-based composite [8,9], no part of the tree, especially the seeds and pods, has been utilized as solid fuel. One process of enhancing the fuel properties is briquetting.

Briquetting is a densification process for improving the calorific value and physicochemical properties of raw biomass and it reduces the associated transportation, handling and storage costs [10,11]. Direct burning of biomass produces large amounts of ash content with consequent environmental and health hazards. Despite this, over 2.5 billion people in Africa depend on the use of biomass for cooking [12]. The quality of briquettes hinge on the physicochemical properties of the biomass (size and surface area) and process parameters such as compression rate, dwelling time, temperature, pressure and binder used [5,13]. Past studies have shown that biomass with higher cellulosic content exhibits a lower compaction ratio than those with a higher lignin content [14]. In addition, investigations shown that guar gum (extracted from cluster beans) and cassava starch are the most suitable binder for briquetting process.

In Africa, India and Malaysia, agricultural residues including plant litter, sawdust, and rice husk are utilized for making briquettes and used as clean energy, especially in rural communities where access to cooking gas is limited [15–17]. Current reviews have shown that biomass briquettes could meet the energy demands for domestic and heating applications in rural communities where biomass feedstock are in abundant [18]. Although, a limited number of studies have reported the combustion characteristics and emission analysis of biomass-based briquette compared to conventional fuel such as charcoal. According to reported study [19], biomass briquettes released about 112 g CO, 5.7 g NOx, and 2.0 g PM per kg of fuel when burnt under normal airflow which is lower than emissions from wood briquettes but higher than firewood. However, investigations on optimization of fuel briquettes made from flamboyant pod have not been reported. Therefore, this study optimized the fuel briquette made from combination of flamboyant pod, and corn cob mixed with cassava starch as binder in order to provide the exact composition of the fuel blends for obtaining the best briquettes for domestic use. Converting these residues' energy would not only contribute to reducing greenhouse gas emissions but assist in sustainable waste management strategy.

Materials and methods

Collection and preparation of materials

The FBP was harvested from the flamboyant tree located in the vicinity of Kwara State University, Malete, Nigeria. The CC was acquired from merchants in Ilorin-Malete axes whereas the charcoal and starch binder (SB) were purchased at the community main market in Ilorin. The FBP and CC were washed with clean distilled water to remove soluble impurities, and sun-dried for seven (7) days.

The proximate analysis such as moisture content, volatile matter and ash content of the FBP and CC were determined using ASTM D1762-84. The ultimate analysis including the percentage compositions of the carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and, sulphur (S) contents of the samples was evaluated using the elemental analyser CHNS-932 (LECO). The gross heating values of the samples were evaluated using Oxygen Bomb Calorimeter model [20].

Experimental design

Experimental design involves the selection of the minimum number of design parameters and experimental trials to build the most accurate regression models. Most experimental design techniques accommodate multiple factors such as process, mixture, and discrete

Table 1
Minimum and maximum values of experimental parameters.

Value Range	Mixtures			Factor
	FBP (%)	CC (%)	SB (%)	Dwelling time (%)
Minimum	30	40	5	30
Maximum	50	60	20	150

FBP-flamboyant pod, CC- corn cob, SB- starch binder.

factors while reducing experimental costs. The techniques are based on Euclidean space, Borel set, and Caratheodory theorems. Theoretical details are presented in an earlier reported investigation [21]. In this study, experiments were designed and optimized using optimal design under custom design methodology of design-expert (version 13, 2022) within the ranges of the process mixture such as FBP, CC and SB; and dwelling time required to formulate fuel briquette as shown in Table 1. The compaction pressure of 5 MPa was maintained for all the experimental runs [18].

Briquette sample preparation and fabrication

The dried flamboyant pods, which are separated manually from the seeds, and corn cob were initially crushed using an hammer, grinded to finer particles using an hammer mill (SG-16 Series), and sieved using the required 0.5 mm sieve to attain a homogenous biomass [22]. Cassava starch (20 g) was mixed with 40 mL of water inside a bowl to obtain the cassava paste and 100 mL of water at 100 °C was poured to the cassava paste to form the cassava gel for densification of the flamboyant-corncob-starch (FBCS) briquette [23]. The compaction of briquettes used in the present study was done at a pressure of 5 MPa for all the experimental runs using the briquetting machine available at the Forestry Research Institute of Nigeria (FRIN) located at Oyo state, Nigeria.

The mould and press were properly positioned on the machine and clamped securely to ensure good shape and texture. The bi-composite biomass mixture was fed into the lower part of the mould base according to the specified mix ratios (Table 2). The contents in the mould base were compressed into a densified shape by pressing the upper part of the mould downwards. The briquettes were formed between the dwelling time of 30 $s \leq DT \leq 150$ s [24]. The amount of briquette samples made are as determined by the experimental design based on the mixing weighted (~100%) and ratio as attained in Table 1 within the ranges of $30 \leq FBP \leq 50$, $40 \leq CC \leq 60$ and $5 \leq SB \leq 20$. The samples were produced in triplicates. Instantly, after the discharge of the briquettes from the moulds, the mass and dimensions of the briequettes were recorded using a vernier calliper and digital weighing balance.The resulting briquettes (Fig. S1) were sun-dried to a husk for two weeks to ensure internal stability, higher strength, lower moisture content and combustibility [25].

Bio-composite briequettes combustion analysis

Ignition test

This is the time taken to ignite (t_i) the selected briquetted flamboyant pod-corn cob mixture and charcoal, and it is measured using the stop watch. The ignition time of briquetted flamboyant pod-corn cob mixture, and charcoal are compared to determine the optimal and ideal substance

Table 2
Experimental trials and responses based on optimal combined design.

	A	B	C	D	Compressive Strength (MPa)			Ash Yield (%)		
Run	FBP (%)	CC %	SB (%)	DT (s)	Actual Value	Predicted Value	Residual	Actual Value	Predicted Value	Residual
1	38	49	13	90	0.0300	0.0300	−0.0000	25.00	24.89	0.1074
2	44	51	5	60	0.0400	0.0394	0.0006	15.00	15.76	−0.7580
3	39	56	5	30	0.0400	0.0402	−0.0002	20.00	19.82	0.1819
4	39	49	12	30	0.0300	0.0290	0.0010	25.00	23.93	1.0700
5	38	49	13	90	0.0300	0.0300	−0.0000	25.00	24.89	0.1074
6	50	42	8	90	0.0800	0.0802	−0.0002	10.00	9.520	0.4773
7	30	55	15	150	0.0800	0.0801	−0.0001	10.00	10.01	−0.0118
8	47	40	13	60	0.0500	0.0502	−0.0002	10.00	10.76	−0.7627
9	40	55	5	150	0.0600	0.0601	−0.0001	15.00	14.99	0.0070
10	30	50	20	30	0.0300	0.0290	0.0010	10.00	9.89	0.1141
11	42	40	18	150	0.0500	0.0501	−0.0001	15.00	15.09	−0.0940
12	30	60	10	90	0.0300	0.0298	0.0002	15.00	15.12	−0.1153
13	38	49	12	150	0.0300	0.0290	0.0010	12.30	12.16	0.1371
14	46	49	6	121	0.0500	0.0495	0.0005	19.00	19.28	−0.2808
15	35	45	20	120	0.0600	0.0595	0.0005	13.50	13.57	−0.0723
16	30	60	10	150	0.0400	0.0399	0.0001	11.00	11.01	−0.0082
17	35	45	20	60	0.0300	0.0290	0.0010	23.00	23.74	−0.7417
18	40	55	5	90	0.0300	0.0308	−0.0008	20.50	19.94	0.5600
19	30	60	10	90	0.0300	0.0298	0.0002	15.00	15.12	−0.1153
20	50	43	8	30	0.0300	0.0300	−0.0000	15.00	14.83	0.1749
21	30	50	20	90	0.0400	0.0404	−0.0004	16.50	16.21	0.2890
22	42	40	18	90	0.0300	0.0290	0.0010	17.50	16.96	0.5404
23	50	42	8	150	0.0400	0.0400	−0.0000	14.50	14.52	−0.0152
24	42	40	18	30	0.0400	0.0399	0.0001	10.00	9.73	0.2747
25	38	49	12	150	0.0700	0.0700	−0.0000	12.00	12.16	−0.1629
26	38	49	13	90	0.0300	0.0300	−0.0000	25.00	24.89	0.1074
27	30	60	10	30	0.0300	0.0299	0.0001	14.50	14.57	−0.0744
28	39	49	12	30	0.0300	0.0290	0.0010	23.00	23.93	−0.9331

Water boiling test

This was carried out on selected briquetted samples and charcoal to determine the optimal and ideal substance. A stopwatch was used to record the time (t_b) at which water boiling temperature, equal 100 °C from the time at which the substances ignite and a thermometer was used to take this temperature measurement.

Fuel burning rate

This test was carried out simultaneously with the water boiling test. The selected briquetted flamboyant pod-corn cob mixture, and charcoal of equal quantity used in the combustion tests were then separately placed in briquette stoves and ignited to compare and determine the optimal and ideal substance. The fuel burning rate (FBR) is the ratio of the mass burnt to the time taken as shown by Eq. (1).

$$\text{Fuel Burning Rate, FBR} = \frac{\text{mf}}{\text{t}} \tag{1}$$

Specific fuel consumption (SFC)

The specific fuel combustion (SFC) is the amount of fuel burnt for each unit of energy output. It is essentially the ratio of the mass of fuel used to the volume of water evaporated during the combustion tests according to [24] Eq. (2).

$$\text{Specific Fuel Combustion, SFC} = \frac{\text{mf}}{\text{mw}} \tag{2}$$

Shatter index

This test is to determine the durability and hardness of the briquette samples. The sample of size 70 mm × 35 mm was dropped at a height of 100 m on a concrete slab. The shatter index (X) is calculated using Eq. (3) [26].

$$\text{Shatter Index, } X = \frac{\text{WB} - \text{WA}}{\text{WB}} \times 100 \tag{3}$$

Compressive strength

The Compressive strength of the charcoal and briquetted FBCS samples were determined using the universal testing machine (UTM) of load cell 50 kN according to ASTM 2166–85 in order to compare the optimal and ideal biofuel based on its durability. The compressive stress was applied at a constant rate of 0.01667 N/mm^2/s until the charcoal and the briquette appeared to fail [27].

Numerical optimization using desirability approach

The desirability approach is a popular method that assigns a score to a set of responses and chooses factor settings that maximize that score. It combines multiple responses into a single dimensionless metric. The nature of each response goal might be in range, minimized, maximized, or target, and defines the desirability function. This study focuses on maximization of compressive strength and minimizing ash yield of the briquetted sample. Eqs. (4) and (5) give the desirability (d_i) for maximizing and minimizing the responses, respectively [28].

For maximization

$$d_i = 0 \text{ when } \text{Y}_i < Low_i$$

$$d_i = \left(\frac{\text{Y}_i - \text{Low}_i}{U_i - \text{Low}_i}\right)^{wt_i}$$

when $\text{low}_i \leq \text{Y}_i < \text{T}i$

$$d_i = 1, \text{ when } \text{Y}_i > T_i \tag{4}$$

For minimization

$$d_i = 1 \text{ when } \text{Y}_i < T_i$$

$$d_i = \left(\frac{\text{High}_i - \text{Y}_i}{\text{High}_i - \text{T}_i}\right)^{wt_i}$$

when $T_i \leq \text{Y}_i < \text{High}_i$

$$d_i = 0, \text{ when } \text{Y}_i > \text{High}_i \tag{5}$$

The global desirability (D) is determined by the geometric mean of the sole desirability of each response is given by Eq. (6) [29].

$$D = \left(\prod_{i=1}^{n} d_i \right)^{\frac{1}{n}} \tag{6}$$

where d_i is the desirability, $i = 1$ to n, Y is the response values, High and Low is the upper and lower limit of the response; T= target value of the response and *wt* is the weight with an assigned value of 1 and n is the number of response

Gas emission in the combustion of the FBCS briquette sample

To investigate the emission analysis, optimal FBCS briquette sample and charcoal were combusted in a cooking stove. Trace gas emissions were measured using Aeroqual series 500 sensors. The Aeroqual sensors measure CO (Model ECM), NO2 (Model ENW), PM $_{2.5,}$ and PM $_{10}$ (Model CD), by following a modified protocol according to [19]. The test was carried out at a pilot scale with the main focus of determining the energy performance and emission of the optimal FBCS briquettes and charcoal. In particular, four parameters were evaluated: ignition time, water boiling time, fuel burning rate, and specific fuel consumption. The results were compared amongst the selected fuels; most inferior briquettes, optimal briquettes sample and charcoal. Figure S2 shows the exploded view of the briquettes cooking stove.

Results and discussion

Maximization of compressive strength and minimizing ash yield of FBCS bio composite briquette

The briquetted combination of FBP and CC and starch binder at varying dwelling time based on Optimal Combined Design (Table 2) revealed that experimental Run 6 [FBP (50.0%), CC (42.0%), SB (8%)] and Runs 7 [FBP (30.0%), CC (55.0%), SB(15%)] with dwelling time of 90 s and 150 s, respectively, gave the best results as both have the highest compressive strength and lowest ash yield at 0.08 MPa and 10%, respectively. Since Run 5 [FBP (38.0%), CC (49.0%), SB (13%) Dt (90.0 s)] and Run 26 [FBP (38.0%), CC (49.0%), SB (13%), Dt (90.0 s)] are replicates of Run 1 [FBP (38.0%), CC (49.0%), SB(13%), Dt (90.0 s)], it can be inferred that Run1 [FBP (38.0%), CC (49.0%), SB(13%), Dt (90.0 s)] and Run 4 [FBP (39.0%), CC (49.0%), SB(12%), Dt (30.0 s)] produced the least desirable FBCS briquettes with both having compressive strength of 0.03 MPa and ash yield of 25%, respectively. Thus, shatter test was carried out to determine the best and inferior solution. The shatter index percentage of Run 1, Run 4, Run 6 and Run 7 were attained at 40%, 50%, 10% and 2%, respectively. Similarly, further investigations were also conducted to determine the HHV of the selected Runs. Run 4 resulted to the lowest HHV of (12.98 MJ/kg) while Run 7 gave best HHV of (19.22 MJ/kg). The relatively lower HHV of the Run 1, Run 4, and Run 6 has rendered the briquette samples inefficient and thus resulted to lower thermal efficiency and increase in air pollution of the fuel blend during combustion phase [30]. Therefore, it can be deduced that the best result is at Run 7 [FBP (30.0%), CC (55.0%), SB (15%), Dt (150.0 s)] and the most inferior sample is at Run 4 [FBP (39.0%), CC (49.0%), SB (12%), Dt (30.0 s)].

Physicochemical study of raw samples and bio-composite briquettes

The proximate and ultimate analyses of the raw FBP, CC, charcoal, for the best [Run7] and most inferior [Run4] briquetted samples were summarized in Table 3. The raw FBP contains moisture content (6.29 wt.%), CC (8.27 wt.%), charcoal (4.95 wt.%), Run 7 (8.45 wt.%), and Run 4 (8.50 wt.%). It was observed that Run 4 gave the highest moisture content, FBP, and CC, has an intermediate moisture content while charcoal gave the lowest moisture content. Thus, compare to raw biomass and Run 7 [FBP (30.0%), CC (55.0%), SB (15%), Dt (150.0 s)], Run 7 (8.45 wt.%) produced a preferable FBCS briquette fuel and it worthy to note that briquettes with a reduced moisture content have a higher calorific value. Thus by comparison with charcoal, Run 4 will take longer to heat up, have a lower calorific value and more of it will be consumed during combustion process [25,31]. For the volatile matter Run 4, FBP, and CC contains the most volatile matter within the range (73.30 −75.65 wt.%), Run 7 is intermediate at (68.40 wt.%), and charcoal contains the least volatile matter (48.67 wt.%). Briquettes with a high volatile-matter concentration are intended to ignite easily and to be highly reactive in combustion applications [27,32]. Thus, briquettes calorific value diminishes as their volatile matter concentration increases (Table 3). The fixed carbon contents of raw biomass and Run 4 briquetted fuel falls within the range (12.63–14.30 wt.%), Run 7, (22.95 wt.%) and charcoal (33.61 wt.%). It was observed that the calorific value of the samples increases with the fixed carbon contents.

Table 3
Proximate and ultimate analysis of FBP, CC and briquette samples.

Sample	MC (%)	VM (%)	AC (%)	FC (%)	C (%)	H (%)	N (%)	S (%)	O (%)	HHV (MJ/Kg)
Raw FBP	6.29	73.30	1.78	12.63	45.02	5.61	0.37	0.58	48.12	14.20
Raw CC	8.27	74.39	2.42	13.90	42.71	6.49	0.25	0.15	50.40	16.13
Raw Charcoal	4.95	48.67	5.40	33.61	71.50	22.21	1.55	0.80	3.39	22.70
Run 4- 39:49:12	8.50	75.65	2.20	14.30	46.58	5.98	0.22	0.01	42.50	12.98
Run 7- 30:55:15	8.45	68.40	1.53	22.95	58.35	6.20	0.07	0.06	38.35	19.22

MC-moisture content, VM-volatile matter, AC-Ash content, FC-fixed carbon, FBP-Flamboyant pod, CC-corn cob.

The ash yield and compressive strength of the charcoal, for the best [Run 7] and most inferior [Run 4] FBCS briquettes samples were presented in Table 4. It was observed that charcoal gave both the maximum compressive strength and ash yield at 0.12 MPa and 5.40%, respectively, Run 4 gave the intermediate ash yield (2.2%) but the least compressive strength of (0.03 MPa). While the best desirable FBCS briquettes (Run 7) produced average compressive strength (0.08 MPa) and the least ash yield (1.53%). The difference between the compressive strength of the charcoal and Run 7 briquette was relatively small (0.04 MPa) whereas a significant reduction was observed in the ash yield of FBCS sample compared to charcoal . Thus making FBCS compete favourably with charcoal and could therefore be used in domestic cooking and generation of steam in themal palnt stations

Experimental results and model analysis

The experimental results of Table 2 were fitted to quadratic models to independently establish the relationship between the responses, (compressive strength and ash yield) as a function of the FBP, CC, SB and dwelling time (see Eqs. (7) and (8)).

$$\textbf{Compressive strength} = +0.1129A + 0.0702B + 0.1727C - 0.2361AB - 0.1467AC - 0.0793AD - 0.3807BC - 0.0378BD - 0.4406CD + 0.2661ABD + 1.11ACD + 0.7708BCD - 0.0114AD^2 - 0.0277BD^2 + 0.3480CD^2 + 0.1700ABD^2 - 0.9730ACD^2 - 0.2648BCD^2 \quad (7)$$

$$\textbf{Ash Yield} = -34.90A - 57.42B - -174.66C + 290.55AB + 507.94AC - 1.20AD + 599.89BC - 17.89BD - 38.58CD - 1153.16ABC + 55.71ABD + 89.69\ ACD + 126.54BCD + 141.15AD^2 + 269.19BD^2 + 708.58CD^2 - 473.26ABCD - 938.47ABD^2 - 1800.04ACD^2 - 2246.20BCD^2 + 4831.37ABCD^2 \quad (8)$$

where;, A is Flamboyant pod, B = corn cob, C = starch binder, and D= dwelling time The value of the coefficient of determination (R^2) and adjusted R^2 for the compressive strength model are 0.9996 and 0.9981, respectively and 0.9931 and 0.9732 for ash yield model. The models F values and standard deviation obtained for the compressive strength are 660.90 and 0.008, respectively and 50.2 and 1.27 for ash yield (Tables 1–2 S) clearly implies that the models are accurate and a correlation between the prediction and actual results of the models was strongly robust [33]. The interaction parameters such as AB (FBP and corn cob), AC (FBP and starch), BC (corn cob and starch), BD (corn cob and DT), and CD (starch and DT) are significant models terms at 99% ($p < 0.01$). This indicate that they have significant effects on the durability and rate of ash production of the fuel briquettes

The p-value is the most crucial parameter in the ANOVA analysis. The maximum p-value for a model should be 0.05, and models with p-values higher than 0.05 are not significant [9,34]. The data points on the plot of the responses were reasonably distributed close to the straight line (Fig. 1a—b), showing a good correlation between the experimental and projected values of the responses as well as the suitability of the basic premises used in the previous analysis. Given that the proportions of the three components and the process factor in the FBCS mixtures can be changed

Influence of processing conditions on the strength and ash yield of briquettes

The impacts of the three fuel mixture components (flamboyant pod, corn cob, starch binder) and dwelling time factor on the compressive strength and ash yield of the briquetted fuel are illustrated in Figs. 2 and 3, respectively. The compressive strength of the briquetted fuel significantly increased to 0.08 MPa upon increases of corncob fraction from 50 to 55 wt.% and decrease of starch binder fraction from 20 to 15 wt.% at FBP 30 wt.% and at dwelling time of 150 s (Fig. 2a). The compressive strength of 0.03 MPa was obtained upon decreasing the corncob from 57 to 42 wt% and increase of starch from 5 to 10 wt% at FBP 38 wt.% and compaction duration at 90 s (Fig. 2b). The reason for the lower quality of FBCS briquette produced could be attributed to the lower concentration of starch binder in the mixture components. According to reported study [35], the higher the binder concentration and compaction pressure the better the briquette which resulted in higher quality of briquette for hadling, storage and transportation.

The impacts of three fuel mixtures of flamboyant pod, corn cob, starch binder and dwelling time factor on the ash yield of briquetted fuel are illustrated in Fig. 2 (c—d). As can be observed, ash yield decrease with increase in percentage composition of starch up to 15% and then further increase in ash yield when composition of starch in the fuel mixture was in range 16–20%. For instance, 15 wt % of ash yield was obtained at 5% starch content in the fuel mixtures compared to 10 wt.% ash yield when the starch content at 15%. Contrarily, ash yield increase to 20 wt% at 18% composition of starch in the mixtures. The ash yield of the briquetted fuel decreased from 25 to 10% upon decrease of corncob fraction from 60 to 55 wt.% and increase of starch binder fraction from 10 to 15 wt.% at FBP 30 wt.% and at dwelling time of 150 s (Fig. 2c). However, upon decreases of the corncob from 57 to 49 wt% and increase of starch from 5 to 13 wt% at FBP 38 wt.% and at compaction duration of 90 s lead to increase in the ash yield of 25 wt.%. The reason for the variation in ash deposition of the FBCS briquetted fuel produced could be attributed to the combustible element found in starch binder and

Table 4
Ash yield and compressive strength of charcoal and FBCS briquette samples.

Sample	Ash yield (%)	Compressive strength (MPa)
Raw Charcoal	5.40	0.12
Run 7- 30:55:15	1.53	0.08
Run 4- 39:49:12	2.20	0.03

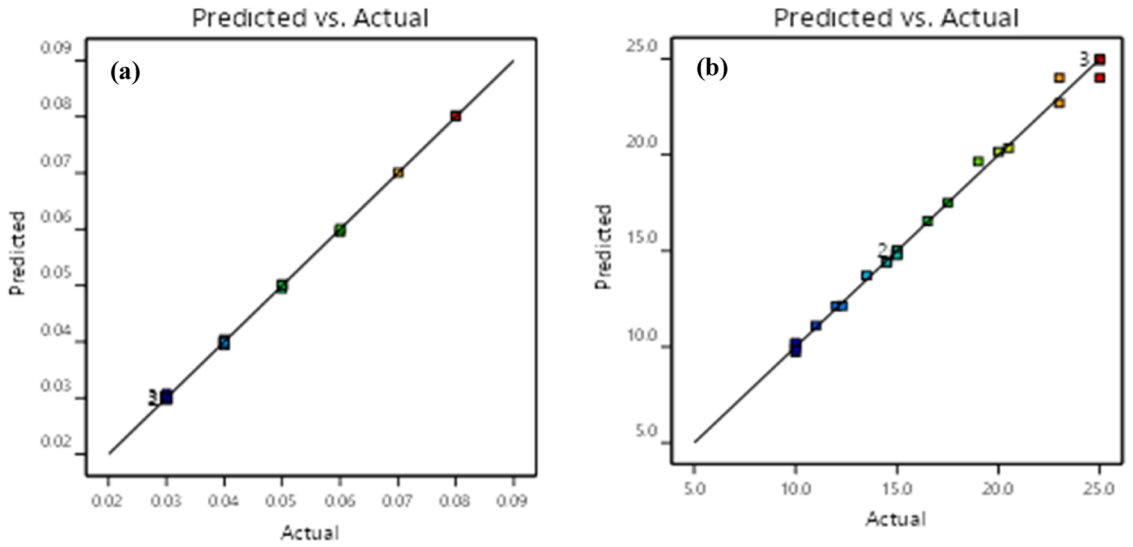


Fig. 1. Comparison of actual and predicted values of the responses for (a) compressive strength, (b) ash yield.

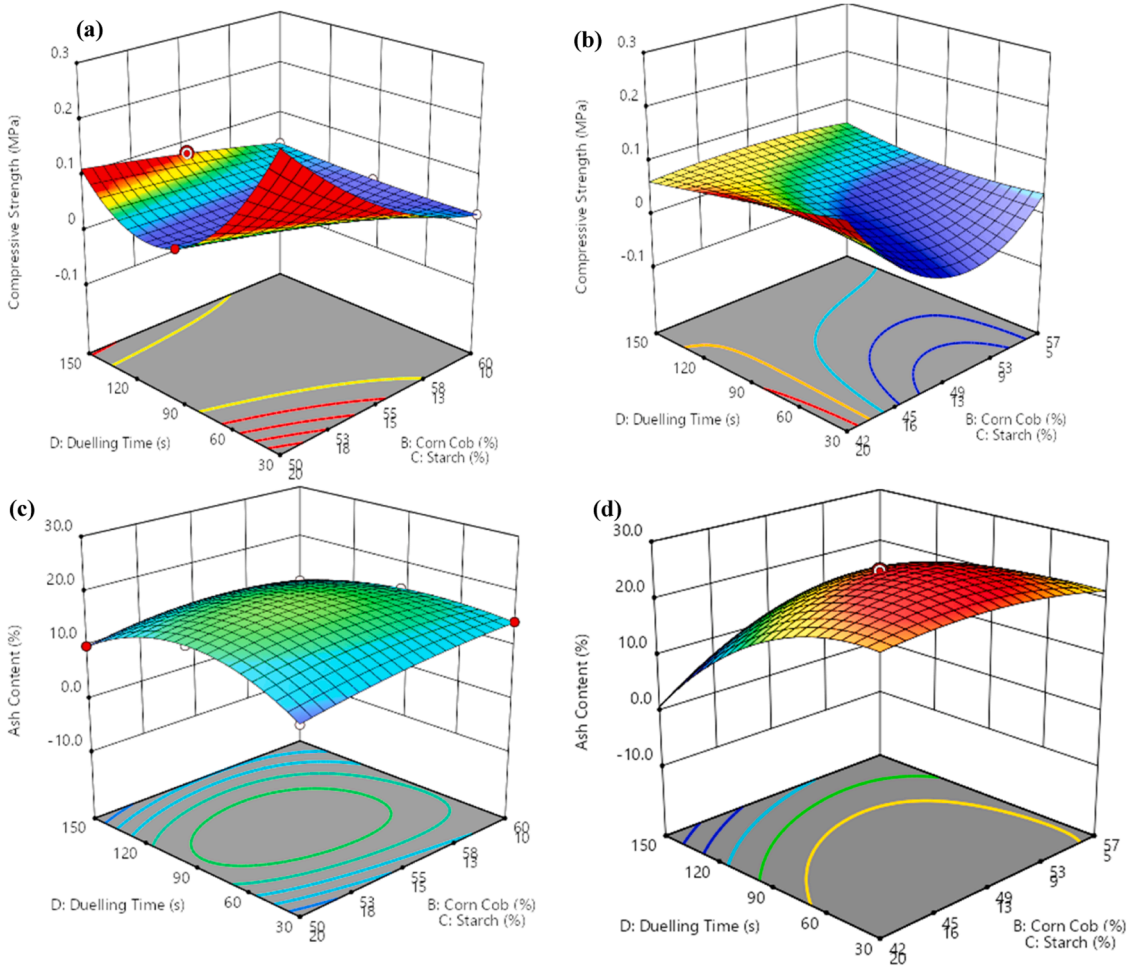


Fig. 2. 3D response surface plot showing the effect of CC and SB, on compressive strength and ash yield.

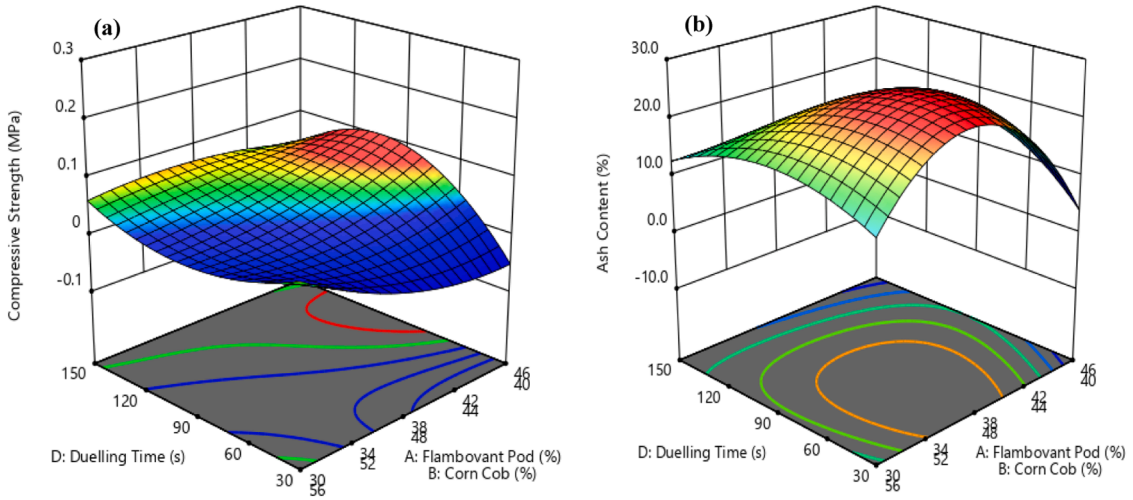


Fig. 3. 3D response surface plot showing the effect of FBP and CC on (a) compressive strength and (b) ash yield.

disparity in biomass mixture as well as way of briquette burning technique [35].

As can be acknowledged in Fig. 3a, the compressive strength of the briquetted fuel significantly increased to 0.08 MPa upon decrease the flamboyant fraction from 46 to 30 wt.% and increase of corncob fraction from 40 to 56 wt.%, keeping dwelling time and starch fraction at 150 s and 15 wt.%, respectively. In addition, the ash yield of the briquetted fuel significantly decreased from 25 to 10% upon decrease of flamboyant fraction from to 46–30 wt.% and increase of the corncob fraction from 40 to 56 wt.% while keeping the dwelling time and starch fraction at 150 s and 15 wt.%, respectively (Fig. 3b). This implies that the percentage of ash yield are within the reported range which emphasised that the difference in ash yield of the briquetted samples could probably due to variation in biomass mixed componenets and way of briquette burning approach [35].

Numerical optimization

The optimization is based on chosen desired goal ("in range", "maximization" and "minimization") for each input and response parameter. Table 5 presents the criteria for the optimization to attain minimum value of ash yield and maximum value of compressive strength. The default weight value of ("1″) was assigned to each goal to adjust the shape of certain desirability functions. The importance value of ("3″) was selected to allow equal importance to all goals. Table 6 shows the numerical optimization for the input and response parameters. The fuel mixtures of flamboyant pod (30 wt.%), corncob (52 wt.%), with starch (18 wt.%) and dwelling time at (52 s) are considered for optimum quality of the briquettes having the maximum desirability of 0.9980. Fig. 4 depicts the desirability of all constraints for the most desirable solution post-optimization via a bar graph

Validation

The confirmation test was carried out at an optimal value of flamboyant pod (30 wt.%), corn cob (52 wt.%), with starch (18 wt.%) and dwelling time at (52 s). The percentage errors of the selected solution are within the tolerance and confirm the accuracy of the prediction model (Table 6). The graphs of predicted results are also shown in Fig. S3.

Combustion and emission analysis of bio fuel

The combustion analysis of the boiling time for 500 ml of water (Figs. 5a—b), shows that charcoal took 660±41 s to reach the boiling point. A longer period was obtained for the most inferior FBCS briquettes 1260 ± 65 s while combustion at an optimal value of flamboyant pod (30 wt.%), corncob (52 wt.%), with starch (18 wt.%) and dwelling time at (52 s), recorded 930 ± 52 s, Therefore, on

Table 5
Criteria of optimization.

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Flamboyant Pod	in range	30	50	1	1	3
B:Corn Cob	in range	40	60	1	1	3
C:Starch	in range	5	20	1	1	3
D:Dwelling Time	in range	30	150	1	1	3
Compressive Strength	maximize	0.03	0.08	1	1	3
Ash Content	minimize	10	25	1	1	3

Table 6
Confirmation test results for FBCS briquettes fuel.

Number	FBP	CC	SB	DT	Compressive Strength	Ash Yield
1 Selected	**30.26**	**51.84**	**17.88**	**51.99**	**0.086**	**8.68**
2	48.88	46.12	5.00	31.49	0.073	10.00
3	33.10	50.22	16.67	150.99	0.071	10.00
Confirmation test	**30.26**	**51.84**	**17.88**	**51.99**	**0.091**	**8.52**
Error (%)	–	–	–	–	0.016	−2.10

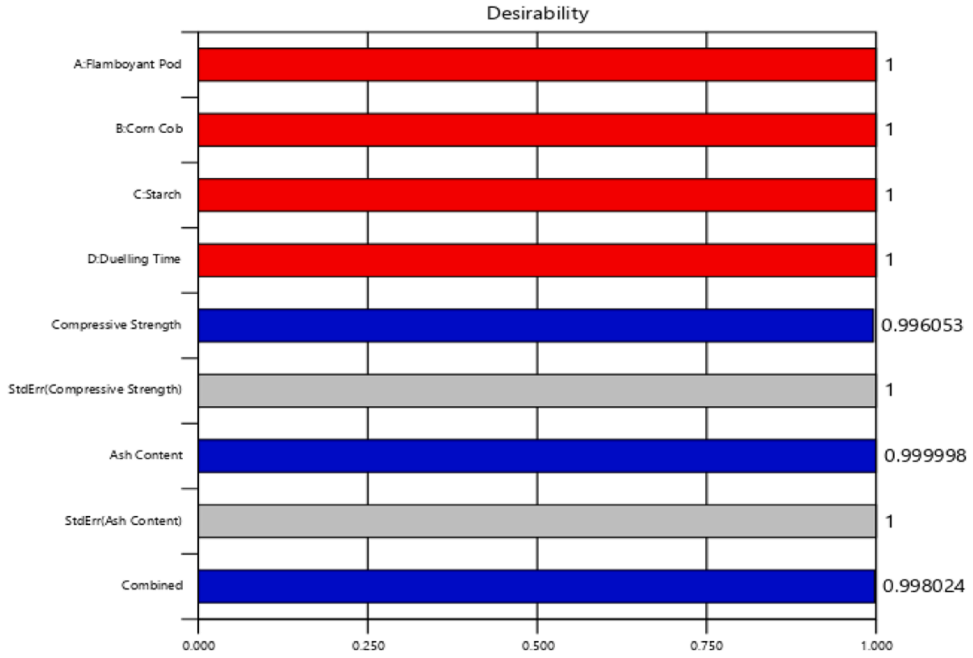


Fig. 4. Desirability of all constraints for most desirable solution post optimization through a bar graph.

balance, the most inferior briquette (39:49:12) at 30 s dwelling time increases the boiling time by about 420–600 s, compared to charcoal based fuel, which is ~ 45–55%. In specific, the optimal FBCS briquettes and charcoal appears to be more appropriate for cooking purposes, while the mixture component of flamboyant pod (39 wt.%), corncob (49 wt.%), with starch (12 wt.%) and dwelling time at (30 s) are not best for cooking compared to charcoal since the boiling time could be on high side

Broad results of the combustion and emission analysis are reported in Table 7. It can be inferred that charcoal is the best fuel only in terms of water boiling time and fuel burning rate, decrease by about (48%) and (51%), respectively which are directly interrelated: the rapid combustion process is connected to the rapid energy consumption rate. On the other hand, charcoal expressed the highest emissions in terms of CO, NO_2, $PM_{2.5}$ and PM_{10} (Table 7). Therefore, briquettes have better combustion and lower emissions compared to charcoal. As can be observed FBCS briquettes fuels allow for improving all the parameters except water boiling time and fuel burning rate. It can be inferred that at optimal conditions, briquettes performed best in terms of ignition time and specific fuel consumption rate. Similarly, it obtained the lowest level of CO emission, NO_2, $PM_{2.5}$ and PM_{10} emissions, while compared to the most inferior briquettes and charcoal. Therefore, FBCS briquettes combustion at an optimal value of flamboyant pod (30 wt.%), corncob (52 wt.%), with starch (18 wt.%) and dwelling time at (52 s), reduces emissions and improves thermal efficiency during the combustion phase.

Fig. 6a reports the results of the CO emission analysis. In terms of emission parts per million (ppm), charcoal generates the highest value of 222 ± 19 ppm, while lowest emission values were obtained for the optimum FBCS briquettes, with 196 ± 12 ppm and the most inferior briquettes recorded emission value of 205 ± 16 ppm. The reasons for the maximum value of CO emissions compared to FBCS briquettes could probably be due to the shape of the fuel, nature of the charcoal, and lack of oxygen available for the burning phase [36, 37]. The lowest emission for the optimum FBCS briquettes can be inferred that it has more access to oxygen and thus improved performance during combustion process and reduce the amount of CO emitted [38].

Results of the $PM_{2.5}$ and PM_{10} emissions analysis were reported in Fig. 6b. In terms of emission part per million, charcoal has an average $PM_{2.5}$ emission value equal to 0.21 ± 0.06 ppm, and most inferior briquettes have an intermediate value of 0.18 ± 0.02 ppm (Fig. 6b). The lower $PM_{2.5}$ values were obtained for briquettes at the optimum condition with 0.09 ± 0.01 ppm. These lowest $PM_{2.5}$ emissions could probably be due to improved performance during the combustion phase and the higher volatile matter contents of FBCS at the optimal value as compared to charcoal and the most inferior briquettes. Similar results were obtained in terms of PM_{10}

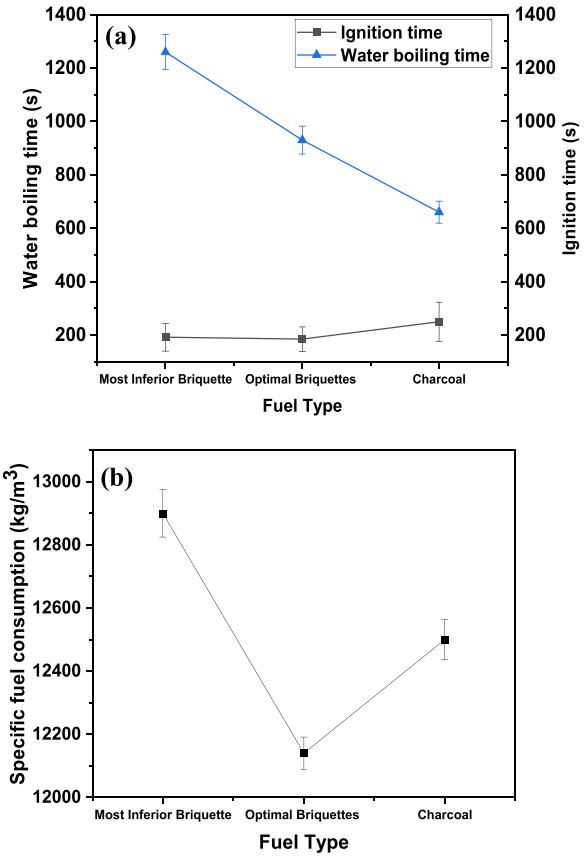


Fig. 5. Combustion analysis comparison (a) water boiling time (b) specific fuel consumption.

Table 7
Comparison of fuels based on parameters assessed.

Parameters	Most Inferior Briquette Value	Optimal Briquettes Value	Charcoal
Ignition time (s)	192 ± 17	185 ± 9*	250 ± 15
Water boiling time (s)	1260 ± 65	930 ± 52	660 ± 34*
Fuel Burning Rate (g/s)	0.045 ± 0.002	0.032 ± 0.003	0.022 ± 0.001*
Specific Fuel Consumption (kg/kW·hr)	13,500 ± 35	11,340 ± 52*	12,500 ± 96
CO (emission (ppm)	205 ± 16	196 ± 12*	222 ±19
NO_2 (emission (ppm)	2.62± 0.04	2.34 ± 0.05*	3.63 ± 0.06
$PM_{2.5}$ (emission (ppm)	0.18 ± 0.02	0.09 ± 0.01*	0.21 ± 0.06
PM_{10} (emission (ppm)	0.51 ± 0.04	0.33 ± 0.02*	0.79 ± 0.07

* Reported best values.

emission part per million (Fig. 6b). Charcoal achieved PM_{10} emission of 0.79 ± 0.07 ppm. Lower $PM_{2.5}$ emission values were obtained at optimal mixture FBCS with 0.33 ± 0.02 ppm. The most inferior briquettes recorded an average quantity of PM_{10} emission with the value of 0.51 ± 0.04 ppm.

Conclusion

The optimization of fuel briequettes made from bio-composite biomass for domestic heating application has been examined. The fuel mixtures of flamboyant pod (30 wt.%), corn cob (52 wt.%), starch (18 wt.%) and dwelling time at (52 s) is considered for optimum quality of the briquettes with the highest desirability of 0.9980. The adequacy of model was validated by a confirmation test with an error in prediction of 2%. The briquettes fuel blend proposed that the water boiling time increase by about 35–48% compared to charcoal fuel. On the other hand, at the optimal value, the briquettes performed best in terms of ignition time and the specific fuel consumption rate by decrease to ~ 35%, and 16%, respectively. Furthermore, air pollutants reduce compared to charcoal, from 222 ppm CO to 196 ppm CO, and from 3.63 ppm NO_2 to 2.34 ppm NO_2 as well as $PM_{2.5}$ decreased from 0.21 ppm $PM_{2.5}$ to 0.09 ppm $PM_{2.5}$. These results suggest that FBCS can serve as a dependable source of fuel briquettes that aid in combustion. Thus, producing briquettes

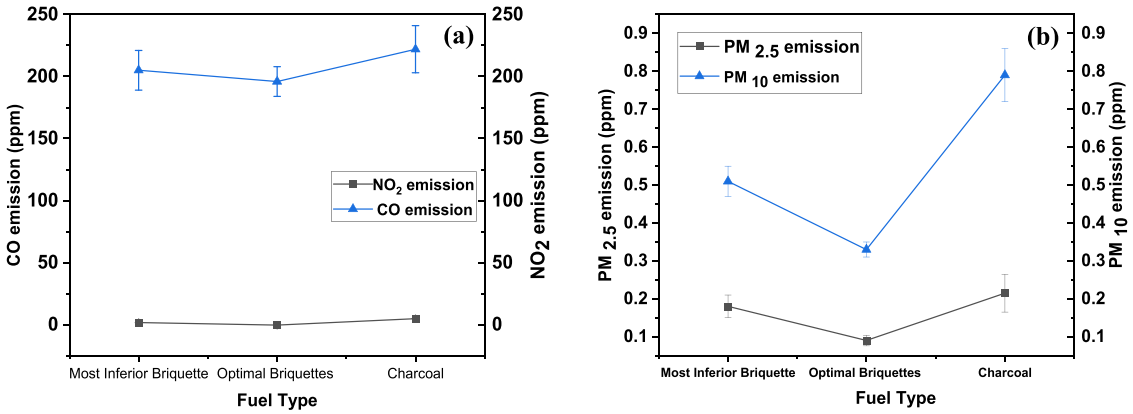


Fig. 6. Combustion analysis comparison (a) CO, & NO_2 emission (b) $PM_{2.5}$ and PM_{10}.

from flamboyant pod, corn cob, and cassava starch provides renewable, clean, and sustainable energy as an alternative to charcoal while also minimizing the effects on forests.

CRediT authorship contribution statement

K.O. Oladosu: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing, Writing – original draft. **S.A. Babalola:** Data curation, Methodology, Software, Supervision, Validation. **M.W. Kareem:** Formal analysis, Methodology, Validation, Visualization, Writing – review & editing, Writing – original draft. **H.A. Ajimotokan:** Methodology, Resources, Supervision, Validation, Visualization, Writing – review & editing. **M.Y. Kolawole:** Investigation, Methodology, Validation, Visualization, Writing – review & editing, Writing – original draft. **W.A. Issa:** Methodology, Project administration, Validation, Visualization, Writing – review & editing. **A.S. Olawore:** Methodology, Software, Validation, Visualization, Writing – review & editing. **E.A. Ponle:** Methodology, Supervision, Validation, Visualization, 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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sciaf.2023.e01824.

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