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Article

Development of torrefied and pelletised hybrid solid fuels from corncob and African birch wood

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Abstract: The development of solid fuels from biomass plays a pivotal role in the global transition toward sustainable energy systems. Hence, optimizing production processes and understanding the influence of key parameters on fuel quality are essential for enhancing performance and sustainability. This study examined the development and process optimisation of combined torrefied and pelletised hybrid solid fuels derived from corncob and African birch wood (ABW). Residues of corncob and ABW blends were prepared gravimetrically and evaluated in both raw and torrefied forms to determine optimal combinations with enhanced combustion characteristics. A Box–Behnken experimental design was employed to investigate the effects of key operating parameters on physic-mechanical properties of the pellets. The statistical modelling demonstrated strong linear correlations, with coefficients of determination (R^2) of 0.9362 for density, 0.9796 for shatter index, and 0.9736 for water uptake capacity. Analysis of variance confirmed that all continuous variables exerted statistically significant effects on the response variables. Optimal process parameters were identified at a torrefaction temperature of 259.39°C, particle size of 0.5 mm, binder content of 15%, and compacting pressure of 140 MPa. Under these conditions, the model predicted a pellet density of 1466.54 kg/m^3, shatter index of 93.69%, and water uptake capacity of 2.37%. These experimental values compared favourably with the predicted outcomes, achieving a desirability factor of 1.00, thereby validating the robustness, reliability, and accuracy of the predictive model. They underscore the potential of combining corncob and ABW residues in the production of high-quality hybrid solid biofuels, with optimised processing conditions significantly enhancing their physic-mechanical performance.

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1. Introduction

Rapid industrialisation, economic and technological advancements have driven a surge in global energy demand, in particular within industrial sectors, with fossil fuels such as coal consumption projected to rise

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despite recent global slowdowns. Notably, the demand for coal is projected to rise by 4.5%, despite a decline in global economic activity and energy consumption due to the COVID-19 pandemic [1]. This trend is expected to contribute significantly to carbon dioxide emissions above 2019 levels and most significantly to global warming, due to its high emission rate as the principal by-product of hydrocarbon-based combustion systems [1]. To mitigate the environmental impacts of coal consumption, increasing the production and use of clean energy through anthropogenic interventions has emerged as a promising approach, and one such strategy involves the development of energy from biomass sources [2–4]. As a sustainable alternative, biomass fuels are gaining traction.

Historically, forestry residues have served as a major source of biomass and are now recognised as one of the most promising alternatives for energy generation, given their improved combustion characteristics, sustainability potential, and ecological compatibility [3–6]. Woody biomass, such as African birch wood, is commonly generated during furniture manufacturing, pruning, and sawmilling processes. Owing to its economic viability and potential to mitigate global temperature rise, African birch wood has gained popularity as a renewable energy source, particularly in conventional boiler applications [7]. However, the use of woody-based biomass poses sustainability concerns, including deforestation, soil erosion, and biodiversity loss. To address these challenges, integrating abundant agricultural residues – such as corncobs into biomass fuel production is a viable solution [8]. Corncobs are readily available due to their short growth cycle, and their use in energy production raises fewer environmental concerns [9]. Nevertheless, corncobs exhibit inferior combustion properties compared to woody biomass, necessitating careful consideration of blending ratios to ensure combustion quality is not compromised [2]. Developing an optimal blend of woody and agricultural residues is therefore essential to harness the benefits of both feedstocks effectively.

Raw biomass is generally associated with several limitations, including low thermal efficiency, hydrophilic behaviour, heterogeneous composition, high handling costs, and limited market acceptance [3, 10]. To overcome these drawbacks and enhance the economic and social feasibility of biomass-based energy solutions, pre-treatment processes such as torrefaction are crucial [4, 10, 11]. Torrefaction is a mild pyrolysis technique in which biomass is thermally decomposed under inert conditions at temperatures ranging from 200°C to 300°C. This process improves fuel properties by reducing moisture content and increasing energy density, resulting in a product with coal-like attributes suitable for co-firing in existing coal-fired systems [12,13]. Despite its benefits, torrefaction can negatively affect certain physico-mechanical properties of biomass, including solid yield, density, shatter index, and compressive strength. To address these issues, densification or pelletisation is often employed [9]. This process involves compressing biomass with or without binders under high pressure, enhancing mechanical durability and energy density [14, 15]. However, the effect of torrefaction on pellet quality is complex and depends on multiple interacting variables [16, 17].

Several studies have investigated the impact of torrefaction on biomass such as corncob and African birch wood. Ajimotokan et al. [2], for instance, examined the combustion characteristics of torrefied and raw corncob and African birch wood, confirming both as viable energy sources, with African birch wood consistently exhibiting superior combustion performance. However, the study did not explore combustion and densification characteristics of blended biomass in both raw and torrefied forms. In a related study, Bruno et al. [18] produced biogenic pellets by co-pelletising sugarcane bagasse with pinewood sawdust and peanut shell in a 50:50 ratio to analyse the effects of a blend of sugarcane bagasse with either pinewood sawdust or peanut shell residues. The authors reported that the blending has significant improvements on the pellet quality, with blends of sugarcane bagasse with pinewood sawdust consistently exhibiting superior combustion performance.

Ibitoye et al. [19] evaluated briquettes made from corncob and rice husk blends. The author remarked that, fuel produced from mix of two sources had an improved quality and the 80:20 blend of corncob to rice husk exhibited the highest compressive strength and water resistance. Bulcha et al. [20] pelletised mixed torrefied corncob and khat stem to enhance the physicochemical and thermal properties of hybrid solid fuels. The authors reported improved physicochemical properties of fuel by blending torrefied corncob and khat stem in a 25:75 ratio, with process optimisation enabling the production of fuel with ideal properties. In research conducted by Zawiślak et al. [21] using combined birch sawdust and pea residues in a 1:1 ratio, the authors observed that the resulting pellets had superior mechanical strength and density compared to pellets produced from individual feedstocks.

A review of highlighted existing literature indicates a gap in determining the ideal blending ratio of corncob and African birch wood for solid fuel development. Furthermore, optimisation of process parameters for torrefied corncob and African birch wood blends has received limited or no attention. Therefore, this study aims to investigate the development and process optimisation of combined torrefied and pelletised hybrid solid fuels derived from corncob and African birch wood residues, with the goal of producing high-quality, sustainable biofuels.

2. Materials and Methods

Samples of corncob were obtained from the University of Ilorin farm in Ilorin, Kwara State, Nigeria (latitude 8.4799 N and longitude 4.5418 E) and African birch wood (ABW) from Gbugbu community, Kwara State, Nigeria, (latitude 8.7854 N and longitude 5.2971 E). Fine residues of pulverised corncob and ABW were oven-dried at 105°C for 2 hours to reduce their moisture content and stored in a Ziplock nylon bag for further analysis. The dried samples were pulverised to reduce the particle sizes and their raw samples were characterised by proximate analysis and determination of their higher heating value. Thereafter, the establishment of the optimal blend of raw samples for solid fuel development based on ISO-17225-2 were carried out, followed by their torrefaction in a fixed bed reactor. The torrefied samples were pelletised under varying conditions. A Box–Behnken design was used to investigate the influence of four independent variables: torrefaction temperature, particle size, binder content, and compacting pressure. Responses measured included pellet density, shatter index, and water uptake. The optimum parameters were achieved using response surface methodology in tandem with Box-Behnken design.

2.1. Preparation of Feedstocks

Corncob and ABW residues were collected, oven-dried, and milled. The raw samples of corncob and ABW and their blends were designed using Minitab 19 statistical software – a robust statistical software for experimental design. Table 1 presents the experimental design layout in different ratios. Blends were gravimetrically prepared using these different ratios to establish optimal blends at different processing parameters for a detailed characterisation.

Table 1. Experimental design layout.

Sample ID	Corncob	ABW
S1	0	100
S2	25	75
S3	50	50
S4	75	25
S5	100	0

2.2. Torrefaction Process

A fixed bed reactor was used to perform the torrefaction experiments. The cylindrical reactor has inner diameter of 84 mm and a total length of 745 mm. The torrefaction reactor was externally heated with the help of heaters. The reactor temperature was monitored using K type thermocouple. Inert atmosphere of the inner chamber of the reactor was attained and maintained by introducing Nitrogen gas (carrier gas) at 100 mL/min flowrate to perform the experiments. The inert gas was introduced into the chamber from the bottommost part of the reactor, and a condensing unit was incorporated to the reactor, which allows vapours from torrefaction to pass through condensing unit. The temperature of the chamber with the different samples of the same composition of the optimal blends were maintained at 240°C, 260°C, and 280°C at residence time of 60 minutes. After the reaction has been halted, the flushing of the reactor was continued to cool down the reactor and to avoid initiation of an oxidative reaction. Each operating temperature was considered as separate experiment, and all experiment were conducted in triplicate to ascertain the consistency of the results obtained. The schematic of the fixed bed reactor is shown in Figure 1.

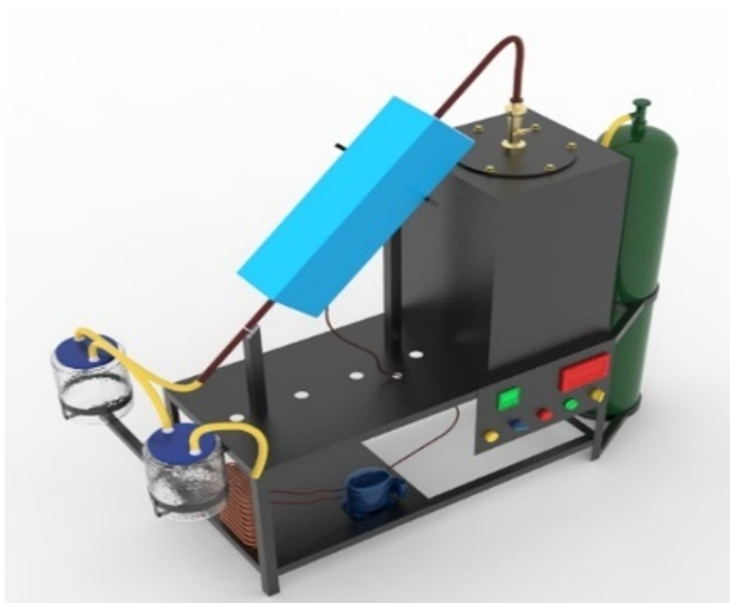

Figure 1. The fixed bed reactor for torrefaction.

2.3. Pelletisation Procedures

The torrefied blends of corncob and ABW residues were pulverised into fines for co-pelletisation and screened to 0.5 mm, 0.75 mm, and 1.0 mm particle sizes, respectively based on BS EN 15149-2 method [22]. 135 ml of clean water at boiling point was employed to gelatinised a thoroughly mixed 65 g of starch with 90 ml clean and portable water to produce a starch gel with a uniform jelly-like. The mould and the die were fabricated from commercial hollow pipe of inner diameter 12 mm and a rod of 11.6 mm diameter, respectively. The length of the mould and die is 8 cm and 9.8 cm, respectively. A laboratory-scale compression testing machine (STYE-2000 model, analogue type by Okchard Machine Tools Limited), rated 2,000 kN maximum capacity was used to exert pressure through the die inserted into the mould. Hybrid torrefied pellets were generated employing different processing parameters, which include torrefaction severity (240°C–280°C), particle size (0.3–1.0 mm), binder content (5%–15%, by weight), and compacting pressure (100–140 MPa). The holding time for each pellet was 120 seconds. The produced torrefied hybrid fuel pellets were cooled to ambient temperature and stored in a zip-lock nylon bag for further analysis. A schematic illustration of the pellet mould and die for pelleting is shown in Figure 2.

(a) (b)

Figure 2. (a) The die and mould and (b) densification machine.

2.4. Analytical Methods

The analytical methods carried out were the combustion analysis (i.e., higher heating values, ash contents, energy density and solid yield) and physico-mechanical analysis (i.e., density, shatter index and water uptake tests).

2.4.1. Higher Heating Values

The higher heating value (HHV) test was carried out using oxygen bomb calorimeter with model IKA C3000, located at Central Mechanical Research Institute, Durgapur, India based on ASTM standard test method ASTM D5865-13 to determine the energy content of the raw samples of corncob and ABW and their blends [23]. One gram of each sample was filled into the bomb calorimeter's sample holder, which was then transferred to the capsule made of steel to determine the HHV for all samples.

2.4.2. Ash Contents

The ash contents of the samples were determined based on standard test method ASTM D3174-12 [24]. One gram of each sample was put in a crucible and placed in a furnace (at 600°C for 5 hours). Thereafter, the crucible was removed from the furnace and placed in the desiccator for 1 hour. This process of heating and cooling, allowing removal of the volatiles and unburnt carbon, was repeated until constant weight is obtained. The crucible and ash generated was cooled and weighed to the nearest 0.1 mg and the weight was recorded.

2.4.3. Energy Density

Energy density is expressed as the ratio of higher heating value of torrefied sample to its raw higher heating value as expressed as follows

$$E_d = \frac{HHV_{torrefied\ sample}}{HHV_{raw\ sample}}, \tag{1}$$

where E_d and HHV are the energy density and higher heating value, respectively.

2.4.4. Solid Yield

Solid yield is a parameter that is used to express the fraction of feedstock recovered after thermochemical pretreatment as presented in Equation 2.

$$MY = \frac{\text{Weight of torrefied biomass}}{\text{Weight of raw biomass}} \times 100, \tag{2}$$

where MY denotes the solid yield of the sample.

2.4.5. Density

The relaxed density is widely accepted as a known property of densified pellets and recognised as a vital parameter that has close link to the effective packaging and transportation of solid biofuels. In this study, the density of the hybrid pellets was obtained using Equation 3.

$$\rho = \frac{m}{v}, \tag{3}$$

where ρ is the relaxed density measured in kg/m^3; m is the mass in kg and v is the volume in m^3. Furthermore, v can be calculated using Equation 4.

$$v = \frac{\pi d^2 h}{4}, \tag{4}$$

where d is the diameter of the pellet and h is the height of the pellet.

2.4.6. Shatter Index Test

The shatter index of the pellet was determined by dropping pellet from a 1.85 m height onto a flat steel plate for four times. The shatter index is the ratio of the final weight of the produced pellet retained after four drops to the initial weight [22]. The shatter index was computed as presented in Equation 5.

$$\text{Shatter index} = \frac{\text{Weight of the sample in plate after 4 drops}}{\text{Initial weight of the sample}} \times 100. \tag{5}$$

2.4.7. Water Uptake Capacity

The water uptake capacity of the generated pellets was determined by immersing the pellet in a distil water of volume 200 ml at 30 $\pm$ 2°C for 30 minutes. The pellets were removed, cleaned to reduce water on its surface. The percentage increase in weight was taken as the water uptake capacity [25]:

$$\text{Water uptake} = \frac{W_2 - W_1}{W_1} \times 100, \tag{6}$$

where W_1 is the initial weight before immersion and W_2 is the final weight.

2.5. Experimental Design and Optimisation

Response surface methodology, a robust mathematical modelling technique, in conjunction with Box-Behnken design was adopted for the experimental design because they offer higher efficiency than both three-level full factorial and central composite designs [26]. Also, because the designed experiment was based on quality attributes that largely depend on variables like the type of biogenic feedstock, degree of pretreatment and process parameter [26]. Minitab 19 was used for the analysis and subsequently to optimise process variables for the production of torrefied hybrid pellets. In this investigation, the variables (independent factors), i.e., torrefaction severity, particles size, percentage binder, and compacting pressure were designated as X1, X2, X3 and X4, respectively. Table 2 present the Box-Behnken design variables and their respective levels. As presented in Table 2, three different levels were assigned in the coded factors as -1, 0, +1, translating to lower, middle and upper level, respectively.

Table 2. Box-Behnken design variables and their levels.

Variables	Symbol	-1	0	+1
Torrefaction severity (°C)	X1	240	260	280
Particle size (mm)	X2	0.5	0.75	1.0
Binder (%)	X3	5	10	15
Compacting Pressure (MPa)	X4	100	120	140

The optimal number of runs was estimated using Equation 7:

$$N = 2v(v-1) + p_o, \tag{7}$$

where N represent the total number of experiments, v is the number of independent variables that was adopted in this work, and p_o represent the number of center points, which is 5 within the context of this study. Hence, a total of 29 experimental runs were conducted in an unrandomized manner. After rigorous analysis of different models consisting of liner, 2FI, quadratic and cubic, a linear equation was fitted to come up with the correlation between the independent factors and their corresponding output value. To assess the effects of multiple independent variables systematically on a set of output variables related to physical properties of hybrid torrefied pellets, Box-Behnken response surface approach was adopted to comprehensively design the experiment.

2.6. Statistical Modelling

In this research, statistical modeling was conducted using Response Surface Methodology in Minitab 19 software to evaluate and optimize the relationship between continuous variables and the response variable. Experimental runs were designed using a suitable response surface design in tandem with Box-Behnken Design to ensure efficient data collection across the experimental domain. The data obtained were analyzed using multiple regression analysis to fit the model and assess the influence of each variable. Analysis of Variance (ANOVA) was used to evaluate model significance, adequacy, and the contribution of individual terms.

3. Results and discussion

Table 3 presents the results of Higher Heating Value (HHV) and ash contents of all the samples under investigation. It could be observed that the HHV of the blends increases with rise in African birch wood (ABW) residues. The highest HHV that was recorded was 16.82 MJ/kg while the least was 14.21 MJ/kg. The high HHV that was observed in African birch wood could be alluded to the established fact that ABW has higher lignin content compare to corncob making it a more superior fuel in terms of energy value [2]. Also, the ash content of the hybrid samples increases with the rise in corncob content. The ash content is the fraction of non-combustible residues in biomass after combustion. As expected, sample S_{optimal} had the least percentage of ash content of 2%, while sample S2 takes second position with ash content of 2.31. Sample S5 which contain 100% corncob residue had the highest ash content which might have been occasioned by the high mineral content in corncob as speculated by Ajimotokan et al. [2]. An excellent fuel attributes is that the fuel does not leave excessive amount of ash during combustion.

Table 3. Local solution.

Sample ID	%ABW	%CC	HHV (MJ/kg)	Ash (%)	Composite Desirability
$S_{optimal}$	88	12	16.82	2.00	1.00
S2	75	25	16.30	2.31	0.00
S3	50	50	14.54	3.23	0.00
S4	25	75	14.32	3.38	0.00
S5	0	100	14.21	3.46	0.00

*CC – Corncob

Figure 3 presents the optimal blends with desirability factor of 1.

According to ISO-17225-2, it states that the minimum HHV for solid fuel is 16.5 MJ/Kg and the ash content should not exceed 2%, which is the basis for optimisation criteria. Based on the response optimizer, the ideal blend was obtained as 88% of African birch mixed with 12% corncob, with an HHV and ash content value of 16.8 MJ/kg and 2.0% respectively. These findings were validated and they compare favourably with the predicted values.

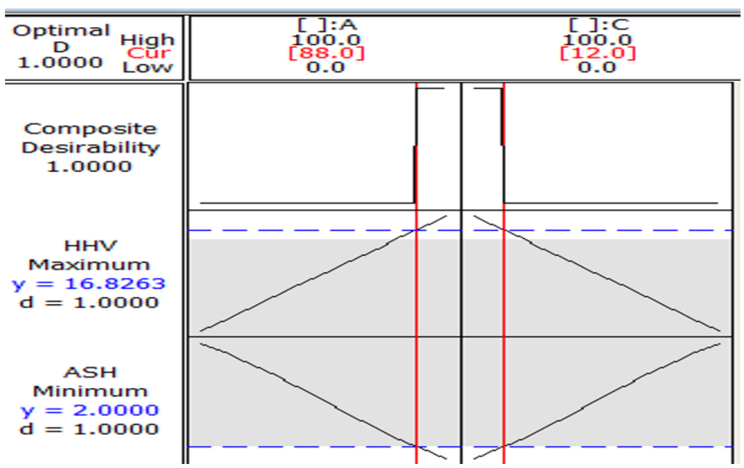

Figure 3. Response optimizer plot.

3.1. Torrefied products of optimal blend

The results of HHV, ash content and solid yield of the raw and torrefied optimal blend was presented in Table 4. The solid yield of torrefied samples under varied treatment conditions is presented. It could be observed that the solid yield of torrefied samples and their blends decreases with the rise in severity of torrefaction, and the observed solid yield could be alluded to devolatilization process and thermal cracking that had occurred during the torrefaction processes. Also, as presented in Figure 4, the color changes with the rise of torrefaction could be alluded to the thermal effect on physicochemical properties. The main contributor to the low solid yield observed at 280°C is the thermal degradation of some short-chain lignin content and hemicellulose. Also, with the growth of torrefaction severity, the loss of chemically bonded water and compounds with low-melting point decreased which contributed to the low solid yield that was experienced with the rise in torrefaction severity [27,28]. The energy density is a parameter used to determine how energy dense a particular fuel is. It could also be observed from Table 4 that from all the samples considered, torrefied sample (280°C) had the highest energy density due to its rise in HHV occasioned by the torrefaction process. Therefore, to produce solid fuel with excellent properties, hybrid torrefied pellet was produced from all the torrefied hybrid samples [29].

Table 4. HHV of raw and torrefied.

Sample ID	M_{feed} (g)	$M_{product}$ (g)	Sy	HHV_{raw} (MJ/kg)	$HHV_{torrefied}$ (MJ/kg)	Energy Density
88ABW12CC (280°C)	120.00	77.15	64.29	16.80	22.75	1.35
88ABW12CC (260°C)	120.00	86.42	72.01	16.80	20.69	1.23
88ABW12CC (240°C)	120.00	93.69	78.05	16.80	19.46	1.15

88ABW12CC is 88% of African birch wood mixed with 12% of corncob

(a) (b) (c) (d)

Figure 4. Samples of raw and torrefied blends of corncob and African birch wood residues (a) raw blends of CC and ABW (b) torrefied blend at 240°C (c) torrefied blend at 260°C (d) torrefied blend at 280°C.

Table 5. Box-Behnken Design and Experimental Results.

Run	X1	X2	X3	X4	Y1	Predicted Y1	Y2	Predicted Y2	Y3	Predicted Y3
1	240	0.50	10	120	1335.70	1369.56	91.15	92.0168	3.01	2.9595
2	280	0.50	10	120	1027.80	1009.84	82.08	82.1884	2.11	2.1345
3	280	1.00	10	120	1263.90	1207.21	88.56	88.2468	3.12	3.0978
4	280	1.00	10	120	863.32	847.49	77.22	78.4184	2.32	2.2728
5	260	0.75	5	100	779.80	837.14	80.03	78.7718	2.83	2.8012
6	260	0.75	15	100	1094.30	1087.11	82.41	83.0418	2.81	2.7345
7	260	0.75	5	140	1193.20	1129.94	88.10	87.3934	2.51	2.4978
8	260	0.75	15	140	1351.50	1379.91	92.48	91.6634	2.50	2.4312
9	240	0.75	10	100	1194.40	1141.99	86.06	85.8209	3.13	3.1803
10	280	0.75	10	100	797.30	782.27	76.41	75.9926	2.39	2.3553
11	240	0.75	10	140	1393.94	1434.78	94.03	94.4426	2.84	2.8770
12	280	0.75	10	140	1154.71	1075.06	85.01	84.6143	2.07	2.0520
13	260	0.50	5	120	1099.41	1064.72	85.02	84.9676	2.51	2.5803
14	260	1.00	5	120	827.62	902.36	82.06	81.1976	2.73	2.7187
15	260	0.50	15	120	1270.81	1314.69	90.07	89.2376	2.49	2.5137
16	260	1.00	15	120	1108.32	1152.33	84.26	85.4676	2.58	2.6520
17	240	0.75	5	120	1192.39	1163.40	87.01	87.9968	3.10	3.0620
18	280	0.75	5	120	798.40	803.68	77.61	78.1684	2.31	2.2370
19	240	0.75	15	120	1492.63	1413.37	93.36	92.2668	3.08	2.9953
20	280	0.75	15	120	1073.11	1053.65	82.87	82.4384	2.13	2.1703
21	260	0.50	10	100	990.82	1043.31	82.27	82.7918	2.64	2.6987
22	260	1.00	10	100	895.60	880.95	79.03	79.0218	2.80	2.8370
23	260	0.50	10	140	1312.01	1336.10	90.74	91.4134	2.41	2.3953
24	260	1.00	10	140	1103.64	1173.74	87.58	87.6434	2.45	2.5337
25	260	0.75	10	120	1134.28	1108.52	85.18	85.2176	2.61	2.6162
26	260	0.75	10	120	1154.61	1108.52	84.97	85.2176	2.63	2.6162
27	260	0.75	10	120	1016.15	1108.52	85.07	85.2176	2.61	2.6162
28	260	0.75	10	120	1119.30	1108.52	84.94	85.2176	2.57	2.6162
29	260	0.75	10	120	1108.24	1108.52	85.73	85.2176	2.58	2.6162

3.2. Statistical Analysis and Model Fitting

Table 5 presents a complete matrix design with experimental and predicted values from the Box-Behnken response surface approach adopted in comprehensively designing the experiments.

The coefficients of regression equation are vital in determining the response variables, and those coefficients with positive signs shows a favourable impact, whereas, negative values indicate an unfavourable impact. Multiple regression analysis was applied meticulously to assess and analyse the independent variables considered in this study and their respective impact on all responses under study. Thereafter, a linear model was accurately formulated to represent the complex interactions. Equation 8 to 10 represents the models developed for response variable in coded factor. To assess the significance and accuracy of the developed model, analysis of variance (ANOVA) was employed to study the main effects that influence the output related to density, shatter index, and water uptake capacity.

$$Y_1 = 2562 - 8.993x_1 - 324.7x_2 + 25x_3 + 7.32x_4, \tag{8}$$

$$Y_2 = 124.62 - 0.2457x_1 - 7.54x_2 + 0.427x_3 + 0.2155x_4, \tag{9}$$

$$Y_3 = 8.748 - 0.020625x_1 + 0.2767x_2 - 0.00667x_3 - 0.007583x_4. \tag{10}$$

Table 6 presents the compilation of all the p-values obtained from analysis of variance (ANOVA) employed to assess the significance of the developed model and study the main effects that influence the outputs as regards density, shatter index, and water uptake capacity. All of the values were found to be below the critical significance level of 0.05. The results obtained in this work demonstrates a high statistical significance of the linear models developed. These findings pointed out the role of the variables in explaining the observed response in the three output which are density, shatter index and water uptake capacity.

Table 6. ANOVA of the experimental results in this study.

		Y1		Y2		Y3	
Source	**DF**	**F-Value**	**P-Value**	**F-Value**	**P-Value**	**F-Value**	**P-Value**
Model	4	88.04	<0.001	287.74	<0.001	221.06	<0.001
X1	1	149.91	<0.001	546.66	<0.001	755.87	<0.001
X2	1	30.54	<0.001	80.43	<0.001	21.25	<0.001
X3	1	72.39	<0.001	103.18	<0.001	4.94	0.036
X4	1	99.32	<0.001	420.67	<0.001	102.18	<0.001
R-sq		0.9362		0.9796		0.9736	
R-sq (adj)		0.9256		0.9762		0.9692	
R-sq (pred)		0.9058		0.9683		0.9593	

The R-sq. values obtained for the three responses were 0.9362, 0.9796, and 0.9736 for Y1, Y2, and Y3, respectively, as presented in Table 6, indicating that the developed models correctly captured the observed data, which compared favourably with the output variables. Therefore, based on these obtained values, it is viable to employ the linear model for discovering and navigating the design to correctly predict the response variable of interest. Overall, terms with a p-value greater than 5% (0.05) are considered significant and notable factors. It can be seen that all input variables had negative effects on the density except compacting pressure. Out of the four factors considered, severity of torrefaction was determined to be the most impactful variable on all the three responses namely; density, shatter index and water uptake capacity due to their F-value of 149.91, 546.66 and 755.87 respectively. Next on influence is compacting pressure with an F-value of 99.32, 420.67 and 102.18 respectively, followed by the binder and particle size. It is clear that all the input variable with high F-value has corresponding low p-value. Following this, all the input variable were statistically significant on the response variable.

3.3. Effects of Operating Parameters on the Pelletisation Process

The effect of operating parameters and their interactions on the response variable of interest.

3.3.1. Effect of Operating parameters on the Density of Pellets

Figure 5 presents the response surface plots of pellets density at different levels of torrefaction severity, particle size, percentage binder content and compacting pressure. The complex interplay was presented graphically and the assessment of impact of continuous factors on response variable could be visually observed. It could be observed that torrefaction severity has more effect on the pellet density. This could be attributed to the loss of chemically bonded water and compounds with low-melting point (i.e., volatiles) which would have added to the binding effect during pelletisation. Therefore, as the severity of torrefaction increases, density tends to reduce [30]. Also, the reduction in mass of the produced pellets resulting from generation of brittle dust that ultimately led to reduction in the pellet density as the severity increases were also alluded to the observed trend. Compared to the pellets of torrefied corncob that was reported in our previous work [9], the density of the hybrid pellets produced in this current study is observed to be higher. This is due to the complementary effect of the woody and agro-residue. On the other hand, the effect of particle size on density shows that increase particle size results to low pellets density. This is due to the increase in distance of the inter-particles and decrease in the inter-particle contact area as the particle size increases which negatively contribute to the solid bridge development between adjacent particles. Furthermore, higher value of density that was observed in low particle size could be alluded to the enhance mobility of feedstock in the mould during densification which birth the penetration of smaller particles into the void section of feedstock [31]. Based on the percentage binder, torrefied pellets density increases with increase in percentage binder content. The highest value of density in this study was (1492.63 kg/m^3) which occur at a percentage binder of 15%. Therefore, increasing the binder content within a reasonable range as a positive effect on density. This could be ascribed to the cohesive structure that was reinforced by the binding agent which eliminate the gaps and voids in pellets particles. Compacting pressure played a significant role during pelletization because alike binder, the degree of pelletizing force used in the densification promotes the rearrangement of particles which consequently increase the density [32]. Other plots in Figure 5 shows the interactions of the continuous variables on the pellet density as depicted.

3.3.2. Effect of Operating Parameters on Shatter Index of the Produced Pellets

The shatter index of solid fuels is broadly regarded as a vital parameter that requires meticulous attention in the context of their production and application. Substantial losses of mass due to the brittle nature of torrefied biomass and their corresponding harmful effect such as high risk of explosions during handling and storage makes it important to investigates their effect in solid fuel development. In addition, low shatter index may cause problems in boilers due to their high dust emissions [26]. Therefore, the effects of continuous variables on shatter index of hybrid pellets as presented in Figure 6. Figure 6a displayed the effects of torrefaction severity and particle size and their interactions on the pellet shatter index, while the binder and compacting pressure were fixed at the middle level. The results showed that torrefaction severity directly affected the shatter index of the produced pellets. Reduction in shatter index of torrefied pellets with the rise of torrefaction severity indicated the presence of solid bridges between the particles of torrefied biomass, which could be due to several reasons. Firstly, torrefaction results in the release of extractives and the decomposition of hemicellulose content, which reduced its bonding capability and consequently create

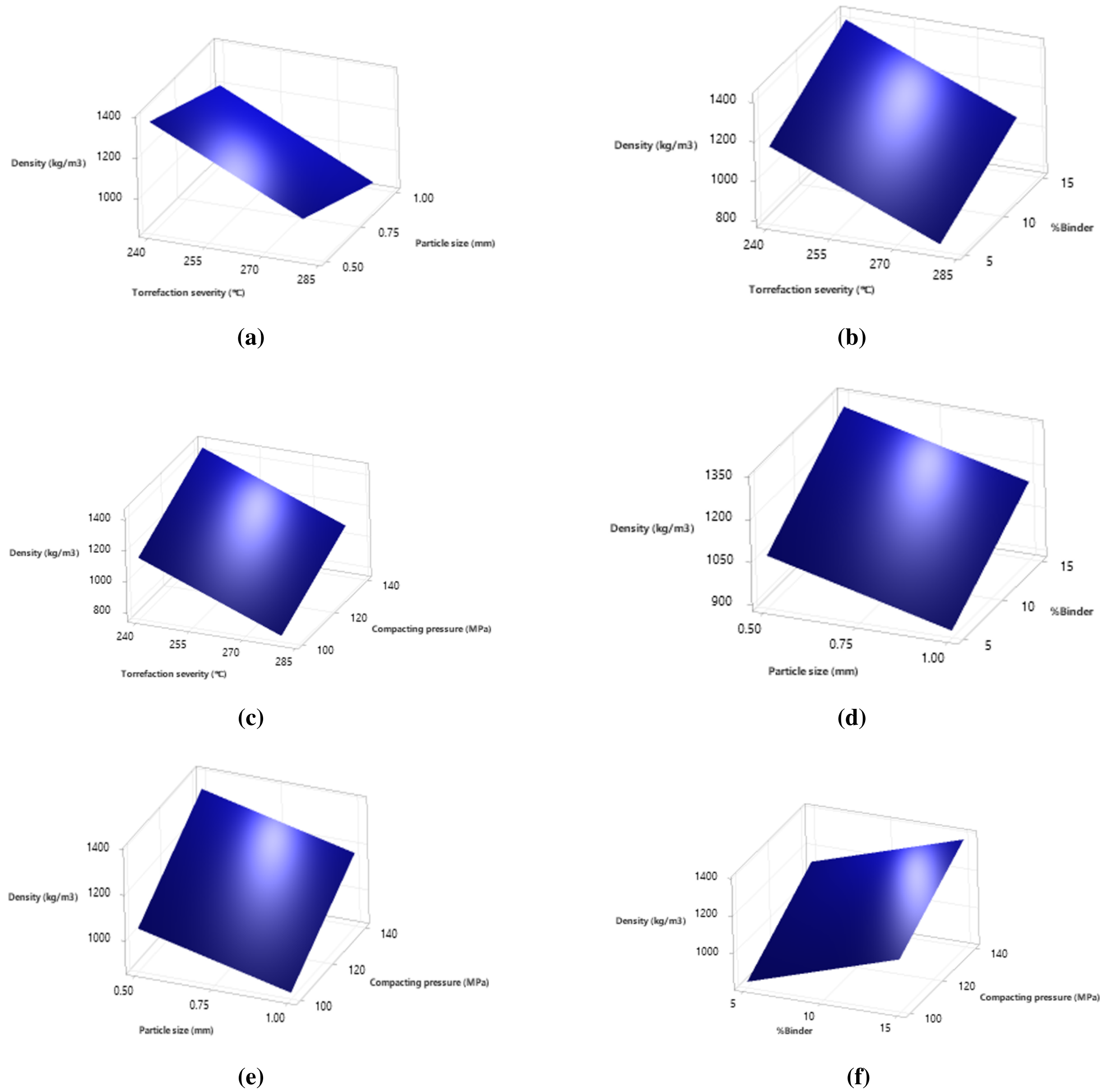

Figure 5. The response surface of pellet's density considering (a) torrefaction severity and particle size; (b) torrefaction severity and binder; (c) torrefaction severity and compacting pressure; (d) particle size and binder; (e) particle size and compacting pressure; and (f) binder and compacting pressure.

gaps and voids in the produced pellets. This phenomenon leads to the lower shatter index by promoting the relative movement of particles [31, 33]. Also, the improved grindability and brittle nature of torrefied biomass makes it easy for the pellet to break easily during shatter index test. Other possibilities include the inability of torrefied biomass to absorb moisture, which leads to the reduction of weak hydrogen bonds sites during densification. Although, improved shatter index of pellets produced from 240°C was observed compared to their torrefied pellets counterparts in this study. However, torrefaction above 260°C poses a relatively low shatter index. This was supported by the work of [31]. In their work, they ascribed the cause of this observation to the removal of fatty compounds during torrefaction at low temperature. Also,

Figure 6b shows the direct relationship between the rise in percentage binder content and shatter index of pellets. This could be alluded to the cohesive structure that was reinforced by the binding agent which eliminate the gaps and voids in pellets particles. Alike binder, compacting pressure also shows a positive trend on shatter index of the pellets. With an increase in particle size, the shatter index reduces. This is because higher particle sizes serve as fissure points for breakage. This finding is in line with what was reported in other studies.

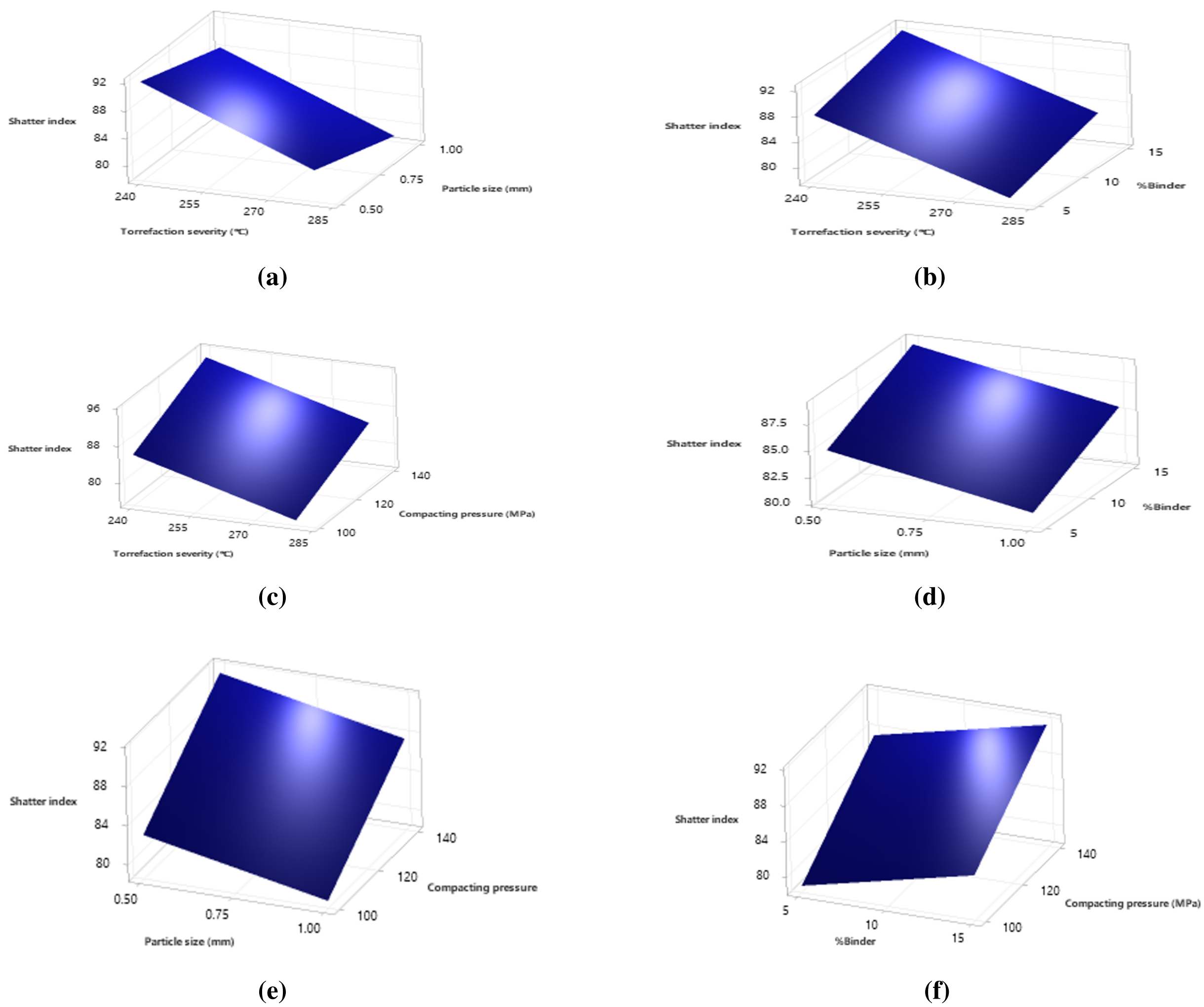

Figure 6. The response surface of pellet's shatter index considering (a) torrefaction severity and particle size; (b) torrefaction severity and binder; (c) torrefaction severity and compacting pressure; (d) particle size and binder; (e) particle size and compacting pressure; and (f) binder and compacting pressure.

3.3.3. Effect of Operating parameters on Water Uptake of Pellets

Figure 7 depicts the effects of independent variables on the water uptake of the hybrid torrefied pellet made from corncob and African birch wood residues. The effect of torrefaction and compacting pressure and their combined effect on water uptake by setting particle size and binder content at middle level as shown in figure Figure 7c. It could be noted that torrefaction severity exerted a positive influence on water uptake because as the severity increases hydrophobic property increases. Compacting pressure on the other hand shows a similar behaviour. The observed impact of torrefaction severity on water uptake could be ascribed to the breaking down of OH groups which in turn cause the biomass to lose the capacity of forming the hydrogen bonds [31, 34]. Therefore, based on the observation in this study, hydrophobicity property was noticed to increase with the severity of torrefaction. This observation was supported by findings in other studies [31, 32, 34, 35]. Similarly, findings in this study clearly shows that the role of compacting pressure on water uptake is analogous to that of torrefaction severity. This is because the densification improves the rigidity and bonding mechanism which also assist in retarding the water uptake rate of the torrefied pellets [31]. Meanwhile, Figure 7d shows the effect of particle size and percentage binder on the observed response. It could be noted that these two parameters and their combined effect has little influence on water uptake.

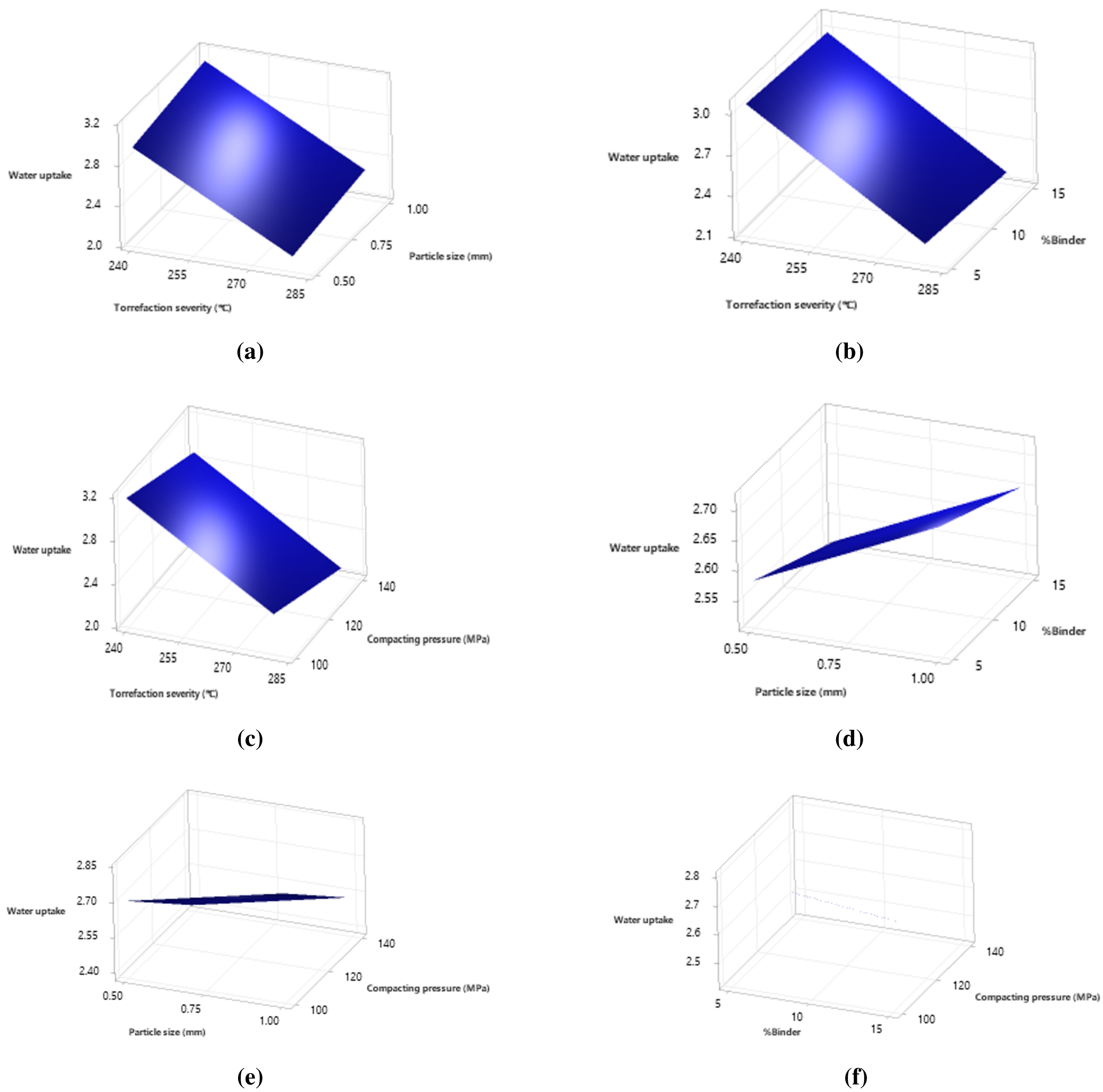

Figure 7. The response surface of pellet's water uptake considering (a) torrefaction severity and particle size; (b) torrefaction severity and binder; (c) particle size and binder; (d) torrefaction severity and compacting pressure; (e) particle size and compacting pressure; and (f) binder and compacting pressure.

3.4. Optimisation of Process Parameters of Torrefied Hybrid Pellets

One of the advantages of optimizing process parameters, in particular when those parameters influence the responses interdependently is its ability to give a set of conditions of the continuous factors that would simultaneously yield optimal values for the response. Minitab software was used to perform this task and all continuous variables used are within their ranges. After the process, the optimal conditions for the production of torrefied hybrid pellets of high quality from torrefied corncob and African birch wood residues were determined successfully. These conditions include setting torrefaction temperature at 259.39°C, employing a particle size of 0.5 mm, utilizing a binder content of 15%, and applying a compacting pressure of 140 MPa. The corresponding predictive values based on these conditions were determined for density, shatter index, and water uptake, which were 1466.5 kg/m^3, 93.69%, and 2.37% respectively. The regression model validity was examined by carrying out an experiment at the optimal conditions. The results are as presented in Table 7.

Table 7. The results of the verification test on optimal parameters.

Response	Goal	Predicted	Experimental
Y1 (kg/m^3)	Maximised	1466.50	1449.32
Y2 (%)	Maximised	93.69	92.75
Y3 (%)	Minimised	2.37	2.29

4. Conclusions

Process optimization of combined torrefied and pelletised hybrid solid fuels from corncob and African birch wood residue were carried out in order to produce solid fuels that could be used for sustainable development. The physicochemical properties of raw corncobs, African birch wood residues and their blends were assessed to investigate the blend with a better energy value and the optimal blend was used to produce torrefied feedstock for solid fuel development. Irrespective of the degree of torrefaction, torrefaction had a significant effect on the overall fuel properties of the samples torrefied. Experimental study using four key continuous variable which include torrefaction severity, particle size, percentage binder and compacting pressure was conducted. The response variable that was analysed to assess the efficiency of the optimization process include density, shatter index and water uptake. Regression model with high R^2 values of 0.9362, 0.9796, and 0.9736, respectively was obtained, depicting a strong affinity between the developed models and the experimental data. After rigorous analysis of the experimental data, an optimal condition required for producing torrefied hybrid pellets with high quality was established using multi-response optimization. Findings revealed that the continuous factors needed to be carefully controlled. This includes torrefaction severity (259.39°C), particle size (0.5 mm), percentage binder (15%), and compacting pressure (140 MPa). Corresponding predicted response value of density yielded 1466.54 kg/m^3, shatter index of 93.69%, and water uptake of 2.37%. With a desirability factor of 1.00, the experimental values obtained under the optimal condition were in par with the predicted variable.

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