Optimizing Ash Yield in the Co-Combustion of Palm Kernel and Cashew Nut Shells with Kaolin Additives Using Optimal Combined Design

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Abstract
High ash yield (AY) from the co-combustion of palm kernel shells (PKS) and cashew nut shells (CNS) presents significant challenges for efficient biomass combustion in a grate furnace. This study aimed to optimize AY from co-combustion of PKS, CNS and kaolin additive (KA) in a tubular furnace. Optimization of the components' mixture, and of factors such as temperature, particle size (PS) and residence time (RT), was conducted utilizing an optimal combined design within Design Expert software (version 13). AY of PKS-CNS fuel mixture, with and without KA, was then analysed using X-ray Diffraction (X-RD), to identify mineral phase compounds within the ash. Optimized composition consisted of PKS (69.6%), CNS (23.3%) and KA (7.1%), at 900 °C, with PS of 1.00 mm and RT of 120 min. This composition resulted in the lowest AY of 10.10% and higher heating value of 21.34 MJ/kg. X-RD analysis revealed a decrease in K-Na-Ca-Mg-Fe-Al compounds, and a significant increase in SiO_2, along with disappearance of potassium chloride peaks. This suggests that optimizing PKS-CNS mixture with KA and adjusting combustion parameters significantly reduced AY and improved fuel's energy content.

Keywords: Ash yield; cashew nut shells; kaolin additive; optimization; palm kernel shells.

Introduction•

Industries frequently utilize combustion of agricultural residues for heat and power generation. However, standalone biomass combustion often faces challenges such as reduced boiler efficiency and slagging on auxiliary equipment due to low combustion efficiency. Palm kernel shell (PKS), a by-product of oil palm industry with a high calorific value of 15.7 kJ/g, is commonly used to fuel boilers for steam and electricity generation [1]. Co-firing biomass with additives emerges as a viable solution to these issues [2]. Despite its benefits, PKS's high alkali content can lead

•The abbreviations list is in page 363.

to bed agglomeration during fluidized bed combustion. Nonetheless, PKS ashes find use in engineering applications, such as concrete reinforcement in construction [2]. Cashew nut shells (CNS), often discarded or burned in fields, pose environmental risks if their liquid leaches into soil or water bodies due to their toxicity. De-oiled CNS, which accounts for about 50% of raw nut's weight (with kernels making up 25% and natural cashew nut shell liquid (CNSL) remaining 25%), offer significant biomass waste once CNSL is removed. With a calorific value of 4252 kcal/kg, CNS are utilized for charcoal production through carbonization and steam generation [3]. Both PKS and CNS present versatile opportunities for energy generation, biomass fuel production, and incorporation into animal feed formulations [4].

In tropical regions like Nigeria, annual cashew nut production is approximately 220,000 metric tons, with CNS making up 60% to 70% of total nut weight. This results in an annual yield of around 132,000 to 154,000 metric tons of CNS [5, 6]. Nigeria is also a leading palm oil producer, generating over 1.03 million metric tons of PKS annually. These residues, characterized by low bulk density and varying sizes and shapes, are often disposed of by open-air burning or landfill deposition, releasing greenhouse gases such as CO_2, CH_4 and N_2O. PKS and CNS typically contain higher volatile contents and minimal ash contents compared to coal, but have relatively high levels of alkali metals like potassium and chlorides [7-9]. These alkali substances, particularly sulphates and chlorides, contribute to issues like corrosion, bed agglomeration, slagging and fouling in combustion devices [10]. At high temperatures, potassium is released as gaseous K_2SO_4, KCl and KOH, which can condense and deposit on cooler boiler surfaces. Interactions between these potassium species and silicon lead to the formation of low-melting silicates such as K_2SiO_3 and $K_2O{\cdot}4SiO_2$ [11-13].

Co-combustion of biomass residues, such as CNS and PKS, could offer several advantages over individual combustion of each biomass. This approach of co-firing enhances combustion efficiency, reduces pollutant emissions and mitigates operational challenges associated with individual biomass combustion. For instance, blending biomass with coal has been shown to reduce unburned carbon in ash, indicating more complete combustion. A study reported that 60% coal and 40% poplar sawdust blend resulted in 94.57% improvement in combustion efficiency compared to pure coal combustion [9, 12, 14].

Using smaller kaolin particles enhances thermal interaction, as they heat up and react more quickly, helping to stabilize flame and temperature. Their fine size also allows better dispersion within the combustion zone. This improves contact with volatile gases, leading to more efficient combustion.

Researchers have explored additives to mitigate issues of ash melting and slagging due to alkali species. Additives can convert low-melting temperature elements in biomass fuels into higher melting point substances, trap fine particulates via physical adsorption onto porous additive particles and increase ash melting temperatures [15-17]. This study aimed to optimize ash yield (AY) in co-

combustion of PKS-CNS mixed with kaolin additives (KA). Results have significant implications for sustainable waste management practices, and may be applicable to similar biomass sources.

Materials and methods

Samples collection and preparation

PKS and CNS were sourced from Olam Company (Nigeria) LTD in Ilorin, Nigeria. Kaolin, chosen for its ability to reduce ash build-up during combustion, was obtained from a reputable local distributor [18]. KA was milled to fine particle size (PS) of 1 mm [17]. Proximate and ultimate analyses were performed on PKS and CNS, with measurements conducted in triplicate using E-871 ASTM standard. A bomb calorimeter (XRY-1-A) was employed to determine Higher Heating Value (HHV) according to standard procedures.

Experimental design and torrefaction procedures for PKS and CN biomass

In experimental design, selecting minimal number of design parameters and trials is crucial for constructing most precise regression models. Most techniques for experimental design account for various factors, including process variables, mixtures and discrete elements, while also aiming to minimize experimental costs. These methods are grounded in principles such as Euclidean space, Borel sets and Carathéodory's theorem [19]. In this study, experiments were planned and optimized using optimal combined design (OCD) within custom design methodology provided by Design-Expert software (version 13, 2022). Considered variables included PKS, CNS and KA, along with heating temperature, particle size (PS) and residence time (RT) necessary for ash reduction during combustion process, as summarized in Table 1.

Torrefaction of PKS and CNS was conducted using a locally designed and constructed fixed bed pyrolytic apparatus. Prior to experiments, biomass was sun-dried for two weeks. Each sample of dried biomass was placed in fixed-bed reactor, where nitrogen gas was introduced at a flow rate of 3 mL/min, to maintain an inert atmosphere and prevent combustion. Torrefaction process was carried out at 250 °C with a RT of 30 min for PKS and CNS. This pre-treatment step is essential to enhance fuel properties of biomass, making it more suitable for combustion applications [19, 20].

Table 1: Minimum and maximum values of experimental parameters.

Value range	Mixtures			Factor		
	PKS (%)	CNS (%)	KA (%)	Temp (%)	PS (mm)	Time min
Minimum	50	40	5	30	1	60
Maximum	50	60	20	150	3	120

Numerical optimization via desirability function

Desirability approach is a widely used method that assigns a score to a set of responses, selecting factor settings that maximize this score. This approach

combines responses into a single dimensionless metric. Each response goal can vary, such as being within a range, minimized, maximized, or targeting a specific value, which defines desirability function. The present study aimed to minimize AY for combustion of PKS, CNS and KA mixtures. Eqs. (1-2) provide desirability (*D*) for minimizing AY [21]. D is determined by its sole geometric mean for each response, as given by Eq. (2) [22].
Thus, to minimize $d_i = 1$, when $Y_i < T_i$:

$$d_i = \left\{\frac{High_i - Y_i}{Low_i - T_i}\right\}^{w_i} \quad (1)$$

$$D = \{\prod_{i=1}^{n} d_i\}^{\frac{1}{n}} \quad (2)$$

where d_i is desirability ($_i$ = 1 to η), Y is response value, High and Low is upper and lower limit of response, T is target value of response, w is weight with an assigned value of 1 and η is response number.

Results and discussion

Proximate and ultimate analysis of PKS and CNS fuel samples

Proximate analysis was performed on fuel samples of PKS and CNS. As shown in Table 2, analysis determined that PKS contains 5.40% moisture content (MC), 4.76% ash content (AC), 23.87% fixed carbon (FC), and 65.97% volatile matter (VM). In comparison, CNS exhibited 7.2% MC, 6.85% AC, 22.14% FC and 63.76% VM. These results differ slightly from previously reported values [23], which may be due to variations in soil type or climatic conditions affecting biomass used in different studies.

Table 2: Proximate and ultimate analysis of PKS and CNS fuel samples.

Analysis	Fuel's components	PKS	CNS
		Composition	
Proximate	MC	5.40	6.20
	AC	5.76	7.85
	FC	24.87	22.14
	VM	64.97	62.76
Ultimate	C	51.46	48.73
	O	43.97	44.95
	H	5.02	5.92
	N	0.68	0.81
	S	0.03	0.02
	HHV	21.57	19.46

AY minimization in PKS-CNS co-combustion with KA

PKS-CNS co-combustion with KA at varying conditions, based on OCD (Table 3), revealed that experimental runs 7 (with 60.50% PKS, 25.6% CNS and 13.9% KA, for PS of 3.00 mm) and 46 (with 69.60% PKS, 23.3% CNS and 7.1% KA, for PS of 1.00 mm), both at 900 º C and RT of 120 min, gave best results, as they had lowest AY at 10.10%. However, runs 15 (with 69.60% PKS, 23.2% CNS and 7.2% KA, at 775 °C, for PS of 3.00 mm and RT of 60 min, and 24 (with 50.0% PKS, 35.0% CNS and 0.0% KA, at 700 °C, with PS of 2.00 mm, and RT of 120 min) rendered least desirable results, with highest AY of 14.9%.

Table 3: Experimental trials and corresponding responses using OCD.

	A	B	C	D	E	F	AY		
Run	PKS (%)	CNS (%)	KA (%)	Temp. (°C)	PS (mm)	Time (min)	Actual value	Predicted value	Residual value
1	69.4	30.6	0.0	789	2	118	14.50	14.63	-0.1275
2	67.0	33.0	0.0	790	3	87	13.00	13.19	-0.1871
3	58.8	35.0	6.2	900	1	120	11.90	11.91	-0.0144
4	69.0	23.6	7.4	900	2	60	11.40	11.33	0.0734
5	70.0	15.0	15.0	700	3	71	13.20	13.21	-0.0070
6	70.0	15.0	15.0	700	2	60	13.50	13.43	0.0700
7	60.5	25.6	13.9	900	3	120	10.10	10.05	0.0466
8	50.0	35.0	15.0	700	3	60	14.10	14.08	0.0156
9	58.4	35.0	6.6	700	1	97	13.90	13.91	-0.0127
10	70.0	27.3	2.7	793	3	116	14.80	14.36	0.4393
11	58.5	34.5	7.0	700	2	60	14.60	14.60	-0.0039
12	60.2	25.9	13.9	700	1	120	13.90	13.88	0.0199
13	50.0	35.0	15.0	700	2	120	14.70	14.72	-0.0199
14	59.0	35.0	6.0	788	2	119	12.10	12.08	0.0165
15	69.6	23.2	7.2	775	3	60	14.90	14.38	-0.0760
16	70.0	15.0	15.0	900	1	60	12.60	12.55	0.0517
17	60.3	25.4	14.3	700	2	60	13.50	13.52	-0.0207
18	69.5	23.4	7.1	900	3	97	11.10	11.33	-0.0321
19	69.7	23.1	7.2	812	2	119	11.80	11.99	-0.1861
20	50.0	35.0	15.0	900	3	120	11.00	10.99	0.0071
21	70.0	15.0	15.0	900	1	120	11.20	11.26	-0.0610
22	58.0	35.0	7.0	790	3	87	11.90	11.70	0.2009
23	69.3	23.5	7.2	700	1	120	13.60	13.54	0.0645
24	50.0	35.0	0.0	700	2	120	14.90	14.95	-0.0450
25	68.2	31.8	0.0	900	3	120	13.80	13.86	-0.0607
26	70.0	23.2	6.8	707	2	87	13.60	13.84	-0.2394
27	70.0	15.0	15.0	820	2	70	13.50	13.90	-0.4020
28	68.4	24.3	7.3	700	1	60	13.60	13.62	-0.0172
29	60.2	25.5	14.2	700	3	97	14.00	13.96	0.0353
30	58.5	35.0	6.5	897	2	87	11.80	11.80	-0.0015
31	70.0	15.0	15.0	700	3	98	13.40	13.43	-0.0294
32	69.6	23.4	7.0	812	1	87	13.50	13.63	-0.1301
33	70.0	23.2	6.8	707	2	87	14.20	13.84	0.3606
34	70.0	15.0	15.0	896	2	87	13.40	13.28	0.1218
35	58.2	34.7	7.1	900	3	120	11.50	11.48	0.0195
36	68.2	23.9	8.0	700	3	120	14.20	14.39	-0.1871
37	70.0	15.0	15.0	790	2	119	13.80	13.60	0.2028
38	50.0	35.0	15.0	790	2	61	13.00	13.05	-0.0526
39	60.3	25.3	14.3	78 9	1	87	12.80	12.63	0.1656
40	50.0	35.0	15.0	900	3	60	11.00	10.99	0.0142
41	59.0	33.9	7.1	900	3	60	11.70	11.70	-0.0037
42	50.0	35.0	15.0	700	1	83	13.80	13.80	-0.0035
43	70.0	15.0	15.0	790	1	87	13.60	13.42	0.1759
44	60.7	25.7	13.6	900	1	60	11.90	11.86	0.0400
45	60.2	25.8	14.0	900	1	120	11.20	11.20	0.0016
46	69.6	23.3	7.1	900	1	120	10.10	10.03	0.0676
47	58.7	34.7	6.6	823	1	60	12.10	12.08	0.0164
48	60.1	25.7	14.2	790	2	120	12.80	12.87	-0.0662
49	68.0	32.0	0.0	900	1	120	13.10	13.06	0.0356
50	67.7	32.3	0.0	825	1	60	13.50	13.55	-0.0495
51	68.2	31.8	0.0	900	3	60	14.10	14.11	-0.0105
52	68.5	31.5	0.0	897	2	87	12.30	12.30	-0.0031
53	60.3	25.5	14.3	820	3	60	12.40	12.39	0.0094
54	50.0	35.0	15.0	900	1	60	13.30	13.28	0.0156
55	67.6	32.4	0.0	700	2	60	13.60	13.58	0.0215

	A	B	C	D	E	F	AY		
Run	PKS (%)	CNS (%)	KA (%)	Temp. (°C)	PS (mm)	Time (min)	Actual value	Predicted value	Residual value
56	58.9	35.0	6.1	700	3	120	12.90	12.68	0.2235
57	54.0	31.0	15.0	792	2	90	13.70	13.55	0.1479
58	70.0	30.0	0.0	842	2	72	12.50	12.10	0.4034
59	60.3	25.0	14.6	892	2	87	11.60	12.10	-0.4966
60	60.3	25.0	14.6	892	2	87	13.90	13.86	0.0394
61	67.7	32.3	0.0	700	1	98	11.60	11.70	-0.0991
62	58.0	35.0	7.0	790	3	87	12.50	12.55	-0.0481
63	70.0	15.0	15.0	900	3	120	12.30	12.33	-0.0346
64	50.0	35.0	15.0	897	2	93	12.90	12.87	0.0338
65	60.1	25.7	14.2	790	2	120	12.80	12.71	0.0890
66	70.0	15.0	15.0	822	3	60	11.90	12.00	-0.1005
67	67	50.0	35.0	15.0	700	2	120	11.60	11.60
68	50.0	35.0	15.0	825	1	120	11.70	11.78	-0.0818
69	70.0	15.0	15.0	700	1	120	12.40	12.63	-0.2344
70	60.3	25.3	14.3	789	1	87	12.67	12.69	0.0438

To further evaluate performance, HHV of selected runs was assessed. Run 24 resulted in lowest HHV of 14.75 MJ/kg, while 46 gave best of 21.34 MJ/kg. Relatively lower HHV of runs 7, 15 and 24, of 15.10, 14.98 and 14.75 MJ/kg, respectively, rendered biomass samples inefficient, leading to lower thermal efficiency, and increasing air pollution during combustion phase [24]. Therefore, it can be deduced that best result was from run 46 (with 69.60% PKS, 23.3% CNS and 7.1% KA, at 900 °C, with PS of 1.00 mm and RT of 120 min), while worst sample was from run 24 (with 50.0% PKS, 35.0% CNS and 0.0% KA, at 700 °C, with PS of 2.00 mm and RT of 120 min).

Experimental results and model analysis

Experimental data presented in Table 3 were analysed using quadratic models to determine the independent relationships between AY and the influencing mixture components; PKS, CNS, and KA and the process factors, such as temperature, PS, and RT. These relationships are expressed in Eq. (3).

$$Ash\ yield = -8.26AB - 17.97AC + 7.83CD + 7.58CF - 10.93ACD - 10.67ACF - 21.90BCD - 13.84BCF + 2.26BDF - 5.44AD^2 + 3.86BD^2 - 4.28BE^2 + 7.80ABE^2 \quad (3)$$

In this model, variables are defined as follows: A is PKS, B is CNS, C is KA, D is temperature, E is PS and F is RT. Significance of each coefficient was determined through probability (p) values and residual least square error analysis. As shown in Table 4, quadratic models effectively captured experimental data, since p-values were less than 0.01. R^2, and adjusted R^2 values for AY were 0.9820 and 0.8643, respectively. Model's F-value for AY was 8.32, with a standard deviation of 0.4064, indicating significance at 99% confidence interval and minimal chance (0.01%) of occurrence due to noise. Significant terms included interactions between PKS and CNS (AB), PKS and KA (AC), PKS, KA and temperature (ACD), and CNS, KA and Time (BCF), all showing p-values less than 0.01, highlighting their substantial impact on ash deposition during combustion. Additionally, lack of fit was deemed insignificant, suggesting that the model fits well with low probability of error.

Table 4: ANOVA of AY using OCD.

Source	AY				
	Sum of square	**Df**	**Mean square**	**F-value**	**p-value (Prob> F)**
Model	81.08	59	7.628×10^{-3}	30.42	< 0.0001 *
Linear Mixture	8.36	2	0.055	219.17	< 0.0001*
AB	0.6092	1	9.705×10^{-3}	*38.71*	< 0.0001*
AC	0.7436	1	1.450×10^{-3}	5.78	0.0202*
CD	1.53	1	5.601×10^{-5}	0.22	0.6387
CF	2.05	1	4.320×10^{-4}	1.72	0.1957
ACD	0.7724	1	1.414×10^{-3}	5.64	0.0217*
ACF	1.30	1	1.108×10^{-4}	0.44	0.5095
BCD	3.02	1	3.113×10^{-7}	1.242×10^{-3}	0.9720
BCF	1.74	1	1.099×10^{-3}	4.38	0.0417*
BDF	0.6085	1	1.616×10^{-4}	0.64	0.4260
AD^2	1.794	1	1.794×10^{-3}	7.15	0.0103*
BD^2	0.8944	1	1.343×10^{-3}	5.35	0.0251*
BE^2	1.03	1	4.839×10^{-4}	1.93	0.1713
ABE^2	0.5557	1	8.608×10^{-5}	0.34	0.5607
Residual	1.49	9	2.507×10^{-4}		
Lack of fit	0.7717	4	2.705×10^{-4}	0.034	0.3502**
Pure error	0.7150	5	2.301×10^{-4}		
Cor Total	82.57	68			

Influence of processing conditions on AY during combustion of PKS-CNS KA

Effects of three fuel mixture components (PKS, CNS and KA), along with temperature, PS and RT, on AY of biomass fuels are depicted in Figs. 1 and 2, respectively. AY of biomass mixtures significantly decreased to 10.10 wt.% when PKS increased from 61.70 to 69.6 wt.%, and KA decreased from 15 to 7.1 wt.%, at CNS concentration of 23.3 wt.%, temperature of 900 °C, PS of 1 mm and RT 120 min (Fig. 1a).

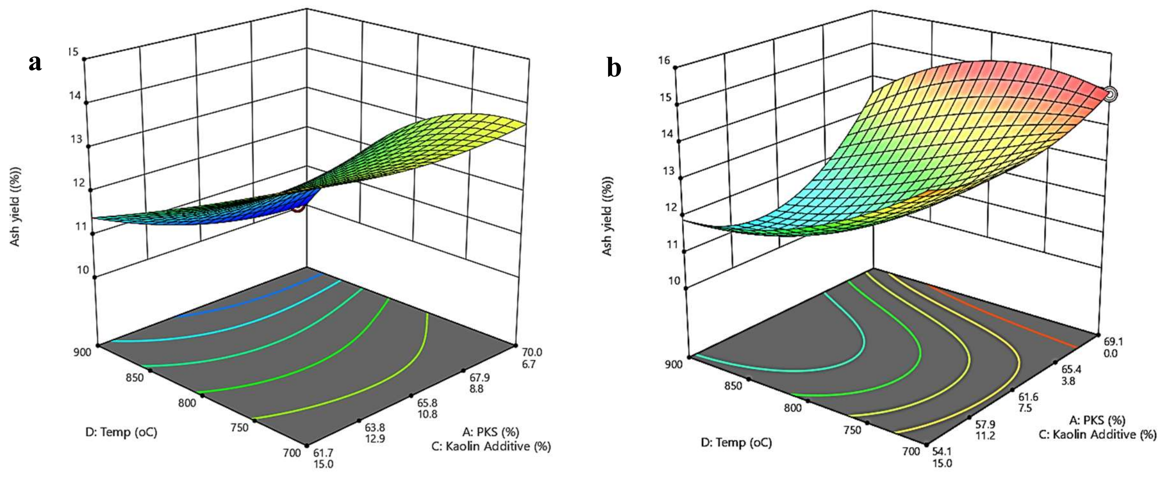

Figure 1: 3D response surface plot showing effect of PKS and KA on AY.

Conversely, AY of 14.9 wt.% was observed when PKS decreased from 69.6 wt.% to 50.0 wt.% without KA, at CNS concentration of 35 wt.%, temperature of 700 °C, PS of 1 mm and RT of 120 min (Fig. 1b). Increased AY in the absence of KA suggests that this played a significant role in reducing it. According to previous studies [25, 26], additives such as KA can increase melting temperature of ash beyond levels typically encountered in steam power plants.

Fig. 2 illustrates that AY of biomass mixture significantly reduced to 10.10 wt.% when PKS increased from 57.9 to 69.6 wt.% and CNS decreased from 35.0 to 23.3 wt.%, while maintaining temperature of 900°C, PS of 1.00 mm and RT of 120 min. Conversely, AY increased significantly from 10.10 to 14.9 wt.% when PKS was reduced to 50.0 wt.% and CNS was increased to 35.0 wt.%, without KA, while maintaining temperature of 700°C, PS of 2 mm and RT of 120 min. This indicates that variation in AY at different biomass ratios is likely due to species' composition of biomass components, heating temperature and presence of additives.

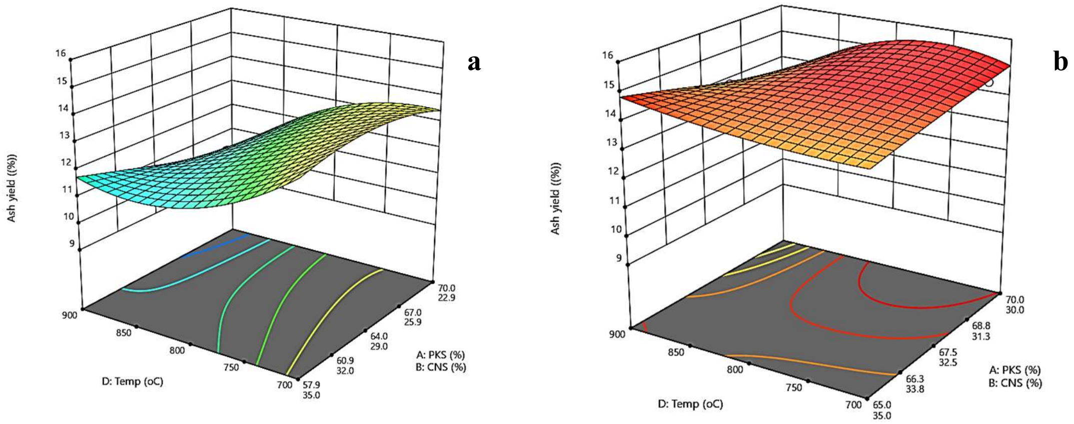

Figure 2: 3D response surface plot showing effect of PKS and CNS on AY.

Numerical optimization

Optimization is based on chosen desired goal ("in range", and "minimization") for each input and response parameter. Table 5 presents criteria for optimization to attain minimum AY value. Default weight value of "1" was assigned to each goal to adjust the shape of certain desirability functions. Importance value of "3" was selected to allow equal standing to all goals. Table 5 shows numerical optimization for input and response parameters. Fuel mixtures of 70 wt. % PKS, 22.87 wt. % CNS and 7.1 wt. % KA, at 874 ºC, PS of 1.84 mm and RT of 120 min, were selected for optimum quality of AY, with maximum desirability of 0.98926.

Table 5: Criteria of optimization.

Name	Goal	Lower limit	Upper limit	Lower weight	Upper weight	Importance
A: PKS	in range	50	70	1	1	3
B: CNS	in range	15	35	1	1	3
C: KA	in range	0	15	1	1	3
D: temperature	in range	700	900	1	1	3
E: PS	in range	1	3	1	1	3
F: time	in range	60	120	1	1	3
AC	minimize	10.1	14.9	1	1	3

Validation

Confirmation test was carried out at optimal value of 70 wt.% PKS, 22.87 wt.% CNS and 7.12 wt.% KA, at 874 ºC, PS of 1.84 mm and RT of 120 min. Percentage errors of selected mixture are within tolerance and confirm accuracy of prediction model (Table 6).

Table 6: Confirmation test results for PKS-CNS biomass.

Selected numbers	PKS	CNS	KA	Temp	PS	Time	AY
1	70.00	22.87	7.12	874	1.84	120	10.15
2	67.91	25.15	6.92	898.12	1.38	118.05	10.02
3	67.836	25.445	6.719	897.489	1.934	112.948	10.077
Confirmation test	70.00	22.87	7.12	874	1.84	120	9.98
Error (%)	-	-	-	-			-0.17

Fig. 3 depicts desirability of all constraints for most desirable solution post-optimization via bar graph.

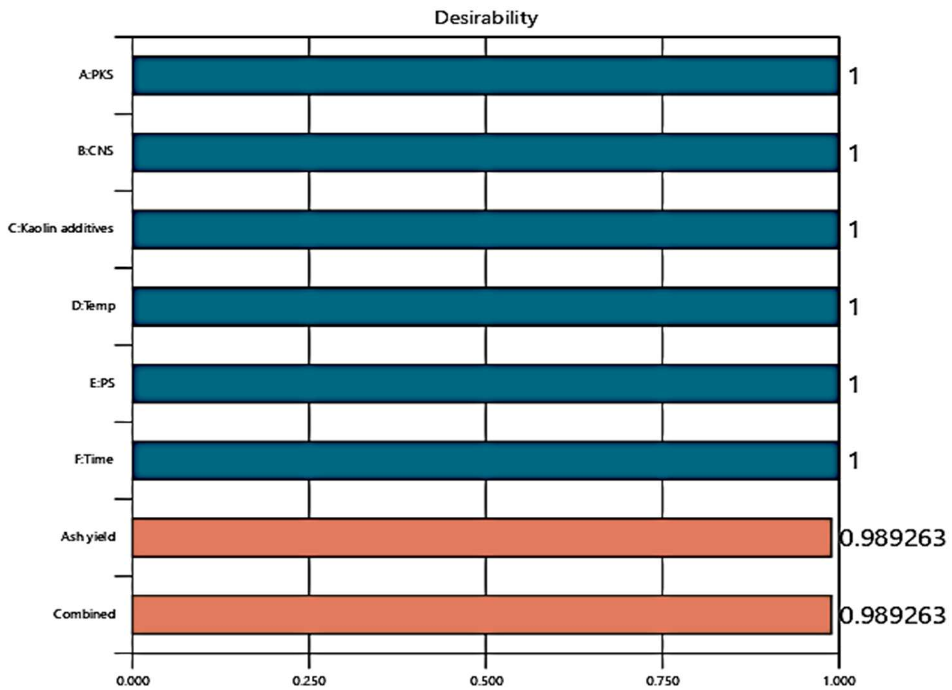

Figure 3: Desirability of all constraints for most desirable solution post optimization through a bar graph.

X-RD analysis

X-RD spectra of ash from mixtures of PKS and CNS, with and without KA, at temperatures of 700 and 900 °C, are presented in Figs. 4a and 4b.

Main crystalline phases detected at mixture ratio of 50% PKS, 35% CNS and 0% KA, at 700 °C, include graphite (C), sylvite (KCl), osumilite (K-Na-Ca-Mg-Fe-Al-S) and quartz (SiO_2). At optimal process parameters (Table 1), with 70% PKS, 23% CNS and 7% KA, at 900°C, amounts of C and K-Na-Ca-Mg-Fe-Al-S decreased gradually, while SiO_2 increased significantly, as shown in Figure 4b. Notably, peak for KCl disappeared with inclusion of KA. Presence of SiO_2 in ash indicates a reduced extent of reaction between K salts and chlorides. SiO_2 in co-combustion ash plays a crucial role in improving slagging and fouling behavior, as it can react with other compounds to form high melting point compounds and increase ash fusion temperature. KCl contributes to formation of other problematic species as temperature increases. As it was further stated by [27-30], co-combustion with additives during combustion process, through chemical binding mechanism, is a preferred strategy for mitigating ash-related issues in a grate furnace.

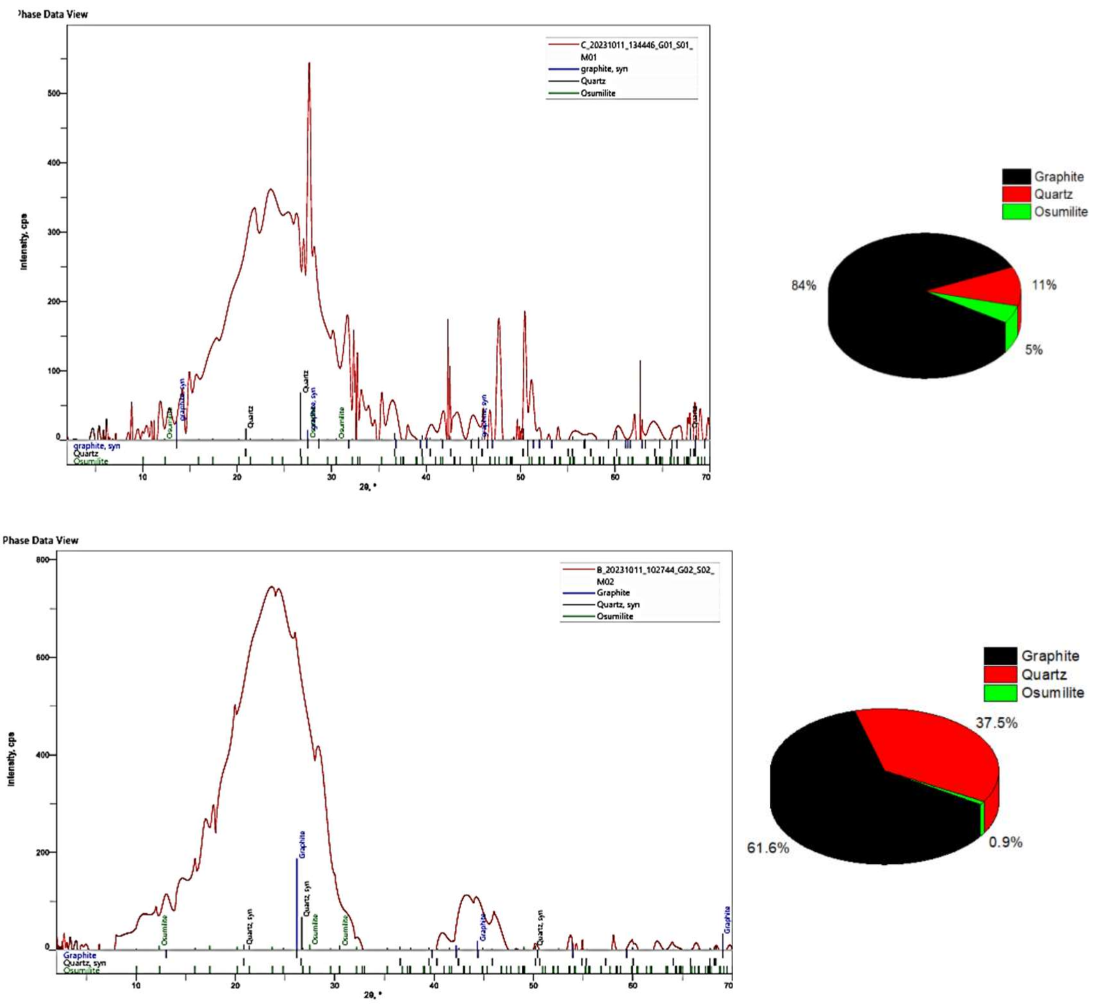

Figure 4: X-RD spectra of ash resulting from a mixture comprising - **(a)** 50% PKS, 50% CNS and 0% KA, at 700 °C and **(b)** 70% PKS, 23% CNS and 7% KA, at 900 °C.

Conclusions

Optimization of AY from PKS-CNS co-combustion with KA was conducted in a tubular furnace. Optimized composition consisted of 69.6% PKS, 23.3% CNS and 7.1% KA, at 900 °C, with PS of 1.00 mm and RT of 120 min. This composition resulted in the lowest AY of 10.10% and HHV of 21.34 MJ/kg. Mathematical models developed for AY using OCD demonstrated a strong fit, with coefficients of determination (R^2) and adjusted R^2 values of 0.9820 and 0.8643, respectively. These refined models show great potential for application in thermal power plants, aiming to reduce AY during biomass combustion in a grate furnace.

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Authors' contributions

K. O. Oladosu: conceptualization; experimentation; validation; original writing. **A. G. F. Alabi**: methodology; supervision; resources; review and editing. **M. W. Kareem**: methodology; original writing; review and editing. **A. O. Alade**: data analysis; writing; validation.

Abbreviations

AY: ash yield
CNS: cashew nut shells
HHV: higher heating value
KA: kaolin additive
OCD: optimal combined design
PKS: palm kernel shells
PS: particle size
R^2: coefficients of determination
RT: residence time
X-RD: X-ray diffraction

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