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Investigating impacts of ammonium phosphate on ash yield from co-combustion of sugarcane bagasse and banana leaves

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ABSTRACT

High ash yield from the co-combustion of sugarcane bagasse (SGB) and banana leaves (BL) presents significant challenges for efficient biomass combustion in a grate furnace. This study aimed to explore the potential of ammonium phosphate ($NH_4H_2PO_4$) as an additive to reduce ash yield during the co-combustion of SGB and BL in a muffle furnace. An I-Optimal design of the Combined Methodology (OCD), embedded in Design Expert (version 13.0.5), was employed to design experiments for optimizing ash yield, considering various particle sizes, additive concentrations, and temperatures. The $NH_4H_2PO_4$ additive was most effective at concentrations between 4% and 7%, beyond which ash yields increased significantly. The optimal composition was determined to be 75% SGB, 20% BL, and 5% $NH_4H_2PO_4$ at 950°C, resulting in the lowest ash yield of 6.46% and HHV of 22.4MJ/kg. The presence of $NH_4H_2PO_4$ in the biomass mixture significantly reduced ash yield. The input and output relationship of the biomass additive mixture was modeled using OCD, resulting in R^2 and adjusted R^2 values of 0.9825 and 0.9099, respectively, indicating accurate determination of the model coefficients. This study demonstrates that ammonium phosphate additive has great potential in mitigating ash-related problems in biomass combustion.

INTRODUCTION

Energy is fundamental to life and a crucial driver of sustainable development. Since ancient times, humanity has concentrated its efforts on energy production to support ongoing development (Nusbaumer *et al.*, 2023). Scholars argue that without substantial energy deployment, no country can effectively address the challenges of economic growth and poverty alleviation. According to Lawal (2021), population growth and energy consumption are closely interconnected; as a nation's population increases, so do its energy needs. Biomass energy refers to any thermal energy generated from organic materials that are not fossil-based. It can be derived from land, freshwater, and ocean environments. According to Daniyanto *et al.* (2015), biomass energy sources include wood from forests, crops, agricultural residues, ethanol made from corn or sugarcane, and methane extracted from landfills. These sources are organic materials from biological origins, predominantly plant biomass, which is the most abundant renewable material globally. Ajala *et al.* (2021) predicted that the annual worldwide production of these materials will reach 1,010 million tonnes.

With numerous advantages, biomass presents significant potential as a feedstock to replace conventional fossil fuels partially or entirely as the primary global energy source (García *et al.*, 2019). Sugarcane bagasse is one of the most abundant waste products globally. It is a lignocellulosic biomass with high energy content, offering a potential solution to the world's energy crisis and environmental challenges (Adeniyi *et al.*, 2021). Annually, approximately 1.6 billion tons of sugarcane are produced worldwide, resulting in 279 million metric tons of sugarcane byproducts (Chen et al., 2016; Bostrom et al., 2011). Processing such a large quantity of sugarcane inevitably generates significant waste. Sugarcane bagasse typically contains high levels of lignin (21%), cellulose (44%), hemicellulose (28%), ashes (5%), and extractives (2%) (Ajala et al., 2021). Sugarcane bagasse only becomes a high thermal value fuel once dried. Raw bagasse has a low heat of combustion, approximately 5.4 MJ/kg. Typically, 270 tons of bagasse are produced for every 100 tons of raw sugar extracted from cane; of this, 67.5 tons, or 25%, are surplus waste (Oladosu et al., 2022). Bananas are the second most widely produced fruit in the world (Bianca et al., 2017). Each banana plant takes 10 to 12 months from planting to harvesting and yields fruit only once in its lifetime. After harvesting, the banana tree is typically cut down, leaving the lower stem and rhizome intact to allow a new plant to sprout. For every tonne of bananas harvested, approximately 100 kg of fruit are discarded, and 4 tonnes of waste are generated, meaning that the waste produced is four times the amount of the harvested fruit. Banana waste includes rotten fruit, peels, pseudo-stems, rhizomes, leaves, and empty fruit bunches (Noeli *et al.*, 2016). Bananas have versatile uses, ranging from food to waste management. The fruit can be eaten raw, cooked, or processed into products like candy or alcohol. Rotten fruits and peels can be used as animal feed for pigs, chickens, and other livestock. Leaves serve as meal wrappers, while pseudo-stems can be processed into crafts, paper, ropes, fabrics, and boards (Noeli et al., 2016). Additionally, some vegetables benefit from compost made from banana waste. Banana waste can also be utilized for energy production. It can be compressed into briquettes, fermented to produce ethanol, or biochemically converted to methane gas through anaerobic digestion. Moreover, burning leaves and pseudo-stems directly can generate power (Li *et al.*, 2019). Bianca *et al*. (2017) noted that Nigerian farmers typically harvest bananas for consumption and use fresh leaves for wrapping food, discarding the rest of the plant. This results in a significant accumulation of pseudo-stems, posing a disposal challenge. Transforming these wastes into energy could address Nigeria's agricultural waste disposal issues in an environmentally friendly manner. Banana waste holds considerable potential as a feedstock for energy production, which could help solve the country's waste management problems. Banna leaves, however, come with certain difficulties, unlike other biomass products. Their composition varies greatly, which greatly affects how they burn (Manatura *et al.,* 2018). Moreover, they include large concentrations of ash-forming species, including silicon, phosphorus, nitrogen, chlorine, and alkali and alkaline-earth species. These elements can raise gaseous emissions of particulate matter (PM), such as sulfur and nitrogen oxides. This may result in issues with fouling, corrosion, slagging, and agglomeration during the burning process, among other operational issues, thereby leading to a further restriction of the use of biomass as a renewable energy source (Zhu *et al.,* 2021). Co-combustion of sugarcane bagasse and banana leaves in a grate furnace offers several advantages such as enhancing fuel efficiency by utilizing two readily available agricultural residues, reducing reliance on fossil fuels and lowering energy costs (Eveline et al., 2013). This synergy maximizes the energy output due to the complementary properties of bagasse and banana leaves. Sugarcane bagasse, being rich in cellulose and hemicellulose, burns relatively easily, while banana leaves, with their high moisture content and mineral composition, can help moderate combustion temperatures and reduce the risk of slagging and fouling (Kareem et al;, 2018).

Furthermore, another effective way to mitigate issues with ash melting and sintering is to add additives either before or during biomass combustion (Oladosu et al., 2024). The most used additives in combustion systems to reduce slagging and sintering problems include calcium-based additives, sulfur-based additives such as ammonium sulfate and lignosulfonate, and aluminium-based additives like bauxite, alumina (Al_2O_3) (Zhu et al., 2019), kaolin (Al2Si2O5(OH)4), kaolinite, and halloysite (Míguez et al., 2021). Among these additives, those based on aluminium silicates have been extensively researched in recent decades, yielding very positive results. However, at low temperatures, the mitigating effect of aluminium silicate-based additives may be less pronounced. This is unavoidable in certain localized fixed-bed reactors, such as grate furnaces, due to the unequal distribution of temperatures (Kareem et al., 2018).

Various additives have been explored by scholars in this field, each differing in their mechanisms and facing challenges related to temperature and cost. Recently, there has been a growing interest in Phosphorus-based additives. These compounds exhibit the capacity to create low-melting point eutectics with specific ash constituents, altering ash characteristics and mitigating fouling and corrosion Zhu et al., (2021). Thus, this study aimed to investigate the influence of mono ammonium phosphate-based additive on the ash yield of co-combustion of sugarcane bagasse and banana leaves in a muffle furnace. Determining the optimal process variables and predicting the ash yield for the SGB-BL-ammonium phosphate fuel mixture can be highly beneficial for industry stakeholders and policymakers, contributing to cost savings and improving the overall efficiency of energy production processes.

MATERIALS AND METHOD

Sample Collection and Preparation

Sugarcane Bagasse samples were collected from a local sugar processing factory in Lafiagi, Ilorin, Kwara State, Nigeria. The Banana leaves were procured from Malete, Kwara state, Nigeria. After the procurement of the biomass, they were left to dry in the sun for 2 weeks at 8 hours per day to remove moisture which hindered combustion. The Additive that was employed in this experiment is ammonium phosphate ($NH_4H_2PO_4$). It is an analytical grade additive that was procured from a reliable representative of the producer in Nigeria. They were procured from multi-chem Industries Limited located at Plot D2 Israel Adebajo Close, Off Ladipo Oluwole Avenue, Ikeja, Lagos Nigeria. Table 1 and Fig. 1 shows the constituents of the $NH_4H_2P0_4$ Additive and images of the raw sugarcane bagasse and banana leaves.

Table 1: Constituents of $NH_4H_2P0_4$ Additive

Impurity	Limit (%)
Chloride (Cl)	0.005
Nitrate (NO_3)	0.002
Sulphate (SO_4)	0.001
Arsenic (As)	0.0001
Lead (Pb)	0.001
Iron (Fe)	0.001

Design of Experiment

In this study, the experiments were designed and optimized using I-Optimal design under the Combined Methodology of Design Expert (version 13.0.5) within the ranges of the process mixture.

Fig. 1: (a) sugarcane bagasse, (b) Banana leaves

Table 2: Experimental components considered using the design expert software.

Name	Unit	Type	Level	
			Low	**High**
SGB	%	Component	65	75
BL	%	Component	20	35
$NH_4H_2PO_4$	%	Component	0	10
Particle Size	mm	Factor	0.3	0.6
Temperature	°C	Factor	700	950
Ash Yield	%	Response	--	--

Table 2 illustrates the components, factors, and responses under consideration. In total, 42 runs were generated based on the design of the experiment and a time of 120 minutes was maintained for all the experimental runs. Each of the runs was repeated in triplicate.

Determination of Ash Yield in the mixture of Biomass and Additive

Before the experimental setup for determining ash yield in the mixture of biomass and additives, a torrefaction process was conducted following the procedures outlined in Oladosu et al. (2022). Subsequently, the torrefied biomasses were milled and sieved into different particle sizes according to the experimental design (Table 3). The torrefied biomasses and additives were mixed in proportions according to the percentages generated using the I-Optimal design under the Combined Methodology of Design Expert (version 13.0.5). These mixtures were then introduced into a muffle furnace and subjected to ashing at various temperatures. Each crucible was left in the furnace for 120 minutes, and the resulting ash was weighed in grams (g) as measured by Equation 1 and in percentage (%) as measured by Equation 2. The ashes were subsequently labeled and stored for further analysis. This process was repeated for all experimental runs.

$$Weight_{ash} = Weight_{crucible + ash} - Weight_{crucible} \quad (1)$$

$$Ash(\%) = \frac{Weight(ash)}{5g} * 100 \quad (2)$$

Statistical Data Analysis

The Ash yield of the mixture of SGB, BL and additives were analyzed statistically with various tools such as 3D mix plots and Analysis of Variance (ANOVA) embedded in the Design Expert Software

(13.0.5.0). These analyses were carried out to determine the quality of the models generated using multiple co-efficient of determination R2, residual sum of square errors for optimal parameters coefficient fitness based on the linear mixture of the parameters.

Determination of HHV

The higher heating value of the biomass samples were determined using Oxygen Bomb Calorimeter. (Leco 672-100 Oxygen Bomb Calorimeter) The biomass sample was dried to remove moisture content and ground into a fine powder, then weighed to obtain a mass of 1gram. The calorimeter was filled with oxygen at a pressure of 30 atmospheres, and then the sample was placed in a crucible. The sample underwent complete combustion in the oxygen-rich environment. The initial and final temperatures of the calorimeter's water bath were recorded. The energy release Q was determined using equation (3).

$$Q = C \times \Delta \mathrm{T} \quad (3)$$

Where C is the heat capacity of the calorimeter., ΔT is the change in temperature (ºC)

$$HHV\ (MJ/kg) = \frac{Q}{sample\ mass} \quad (4)$$

XRD Analysis

The samples, with and without additives, at optimal conditions were selected for X-ray Diffraction Analysis (XRD). XRD is a non-destructive analytical method that measures the angles while magnifying the diffracted X-rays to ascertain the crystal structure of the materials. The transformation of the biomass from its raw state to its torrefied state, the diffraction pattern produced by a sample is specific to its crystal structure and can be used to identify the material and determine its crystallographic properties, such as its lattice properties due to the peaks from the crystals (Hafiz et al., 2023).

RESULT AND DISCUSSION

Experimental Results of the Ash Yield Samples.

Table 3 presents the experimental and predicted results of the ash samples, analyzed using Design Expert software. Table 3 indicates that Run 8 (75% SGB, 20% BL, and 5% NH4H2PO4 at 950°C) and Run 10 (65% SGB, 28% BL, and 7% NH4H2PO4 at 950°C) yielded the lowest ash content, at 6.46%. Additionally, Run 42 (80% SGB, 20% BL, and 0% NH4H2PO4 at 700°C) produced the highest ash yield of 23.68%. Further experiments were conducted to determine the higher heating values (HHV) using an oxygen bomb calorimeter for Run 8 and Run 10, respectively. It was observed that Run 8 yielded 22.40 MJ/kg, while Run 10 yielded 21.98 MJ/kg. Thus, Run 8 was considered to have the optimal process parameters for the lowest ash yield.

Experimental Results and Model Analysis

The experimental results of Table 3 were fitted to quadratic models to independently establish the relationship between the response (Ash yield) as a function of the SGB, BL and $NH_4H_2PO_4$ in Eq. 5.

$$\boldsymbol{Ashyield} = -81.964A + 13.6942B + -39.013C + 184.477AB + 326.294AC + 269.579AD + 213.95AE + 117.217BC + -4.16463BD + -0.961211BE + -92.7307CD + 8.6261CE + -429.099ABC + -544.206ABD + -442.116ABE + -412.517ACD + -486.937ACE + 178.085BCD + -1.00168BCE + 139.467AB(A-B) + 76.8775AC(A-C) + -138.197BC(B-C) + 753.833ABCD + 646.752ABCE + -384.378ABD(A-B) + -286.056ABE(A-B) + -784.612ACD(A-C) + -462.813ACE(A-C) + -192.069BCD(B-C) + 106.604BCE(B-C) \quad (5)$$

where A- Sugarcane Bagasse, B -Banana leaves, C - Ammonium Phosphate, D- Temperature and E - Particle size.

Table 3: Ash yield results from the runs generated by design expert.

Run	*A* *SGB* *(%)*	*B* *BL* *(%)*	*C* *MAP* *(%)*	*D* *Temperature* *(^{O}C)*	*E* *Particle Size* *(mm)*	*Ash Yield (%)* *Actual Value*	*Predicted value*	*Residual*
1	70	26	4	910	0.3	8.08	8.38	-0.3039
2	70	20	10	700	0.6	16.36	15.86	0.5046
3	68	27	5	700	0.3	11.74	12.25	-0.5071
4	65	25	10	713	0.3	20.5	20.58	-0.0809
5	73	27	0	866	0.6	10.9	12.03	-1.13
6	69	27	4	865	0.6	13.18	13.40	-0.2157
7	65	27	8	913	0.3	16.2	16.45	-0.2464
8	75	20	5	950	0.3	6.46	6.56	-0.0985
9	65	34	1	700	0.6	13.86	14.00	-0.1429
10	65	28	7	950	0.6	6.46	6.59	-0.1271
11	75	20	5	700	0.6	8.32	8.47	-0.1511
12	73	27	0	700	0.6	12.88	12.02	0.8562
13	65	35	0	738	0.3	15.64	15.63	0.0084
14	68	32	0	829	0.3	9.58	9.45	0.130.6
15	70	27	3	950	0.6	11.74	11.31	0.4337
16	73	27	0	906	0.3	10.86	9.78	1.08
17	75	25	0	950	0.6	7.48	7.30	0.1840
18	75	20	5	906	0.3	12.96	12.94	0.0201
19	69	27	4	805	0.3	13.62	14.08	-0.4577
20	69	26	5	700	0.6	12.88	12.73	0.1515
21	73	27	0	803	0.3	8.76	9.78	-1.02
22	66	34	0	950	0.6	11.02	10.94	0.0767
23	75	22	3	700	0.3	22.92	23.43	0.4911
24	70	22	8	804	0.3	22.76	22.85	0.0949
25	65	27	8	811	0.3	20.02	19.62	0.3997
26	69	27	4	805	0.3	15.22	14.08	1.14
27	66	33	1	950	0.3	11.76	12.06	-0.3032
28	70	27	3	950	0.6	11.16	11.31	-0.1463
29	65	26	9	863	0.6	16.12	15.78	0.3431
30	71	29	0	700	0.3	12.3	12.46	-0.1637
31	70	20	10	919	0.3	13.6	12.48	1.12
32	69	21	10	950	0.6	10.76	11.36	-0.6049
33	71	23	6	700	0.3	15.52	15.63	-0.1148
34	65	35	0	795	0.6	15.72	15.65	0.0650
35	70	20	10	810	0.3	16.22	17.29	-1.07
36	70	20	10	855	0.6	23.12	23.44	-.03224
37	75	20	5	803	0.3	13.74	13.75	-0.0081
38	69	27	4	805	0.3	14.34	14.08	0.2623
39	65	35	0	845	0.3	12.18	12.07	0.1133
40	65	26	9	700	0.6	22.6	22.75	-0.1463
41	75	20	5	868	0.6	12.86	12.94	-0.0898
42	80	20	0	700	0.6	23.68	23.68	-0.0023

Equation 3 above in terms of coded factors is used to make predictions about the response for given levels of each factor. By default, the high levels of the mixture components and process factors are coded as +1, the low levels of the mixture components are coded as 0, and the low levels of the process factors are coded as -1. The equation is useful for identifying the relative impact of the factors by comparing the factor coefficients. The fit statistic of the model is given in Table 4. The values for the coefficient of determination (R^2) and adjusted coefficient of determination (adjusted R^2) for the Ash yield model are 0.9825 and 0.9099 respectively which indicates that the coefficients were accurately determined for the model. The adequate signal measures the signal-to-noise ratio and in this case, a ratio greater than 4 is desirable. The value of the adequate precision is 15.868 which indicates an adequate signal.

Table 4: Fit statistics of the model

R^2	Adjusted R^2	Adeq Precision
0.9825	0.9099	15.8675

Table 5 shows that the Model has an F-value of 13.53, this implies the model is significant and according to the analyzed model, there is only a 0.08% chance that an F-value this large could occur due to noise. The maximum p-value of the analyzed model should be 0.05 and P-values less than 0.0500 indicate model terms are significant. Values greater than 0.1000 indicate the model terms are not significant.

Table 5: ANOVA analysis of the model

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remark
Model	563.79	29	19.44	13.53	0.0008	Significant
Linear Mixture	201.54	2	100.77	70.16	< 0.0001	Significant
AB	15.53	1	15.53	10.81	0.0133	Significant
AC	16.48	1	16.48	11.47	0.0116	Significant
AD	21.29	1	21.29	14.82	0.0063	Significant
AE	12.30	1	12.30	8.56	0.0221	Significant
ABC	14.07	1	14.07	9.80	0.0166	Significant
ABD	20.62	1	20.62	14.35	0.0068	Significant
ABE	12.51	1	12.51	8.71	0.0214	Significant
AB(A-B)	11.38	1	11.38	7.93	0.0259	Significant
ABD(A-B)	22.30	1	22.30	15.53	0.0056	Significant
ABE(A-B)	10.97	1	10.97	7.64	0.0279	Significant
ACD(A-C)	27.72	1	27.72	19.30	0.0032	Significant
ACE(A-C)	16.01	1	16.01	11.15	0.0124	Significant
BCD(B-C)	10.31	1	10.31	7.18	0.0316	Significant
Residual	10.05	7	1.44			
Lack of Fit	8.60	4	2.15	4.44	0.1254	
Pure Error	1.45	3	0.4842			
Corr Total	573.84	36				

The diagnostic plots of the actual and predicted values of the ash are shown in Fig. 2. The data points were reasonably distributed close to the straight line, and this shows a good correlation between the experimental and projected values of the response.

Influence of Process Variables on Ash Yield

Influence of Temperature on Ash Yield

The 3D surface plots in Figures 3 (a-b) were used to investigate the relationship between the fuel mixture (SGB and $NH_4H_2PO_4$), temperature, and ash yield at a constant particle size.

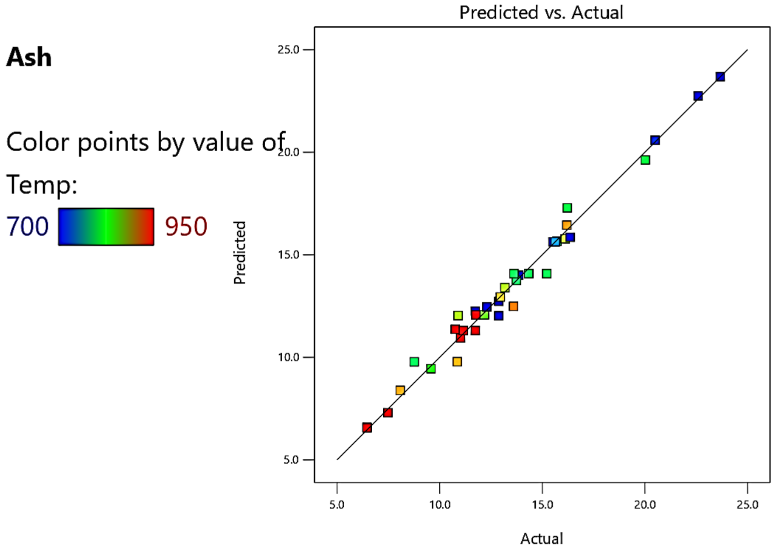
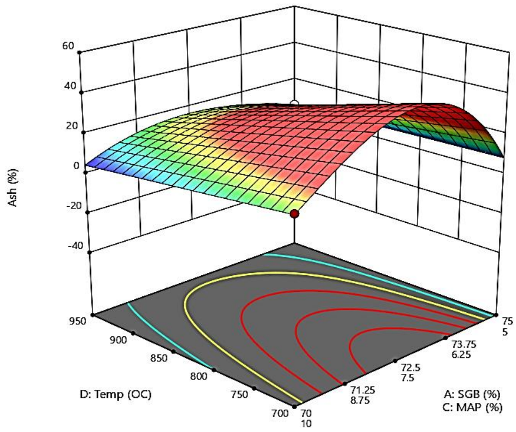


Fig 2: Cross plots of the predicted and actual values of the ash

(a)



(b)

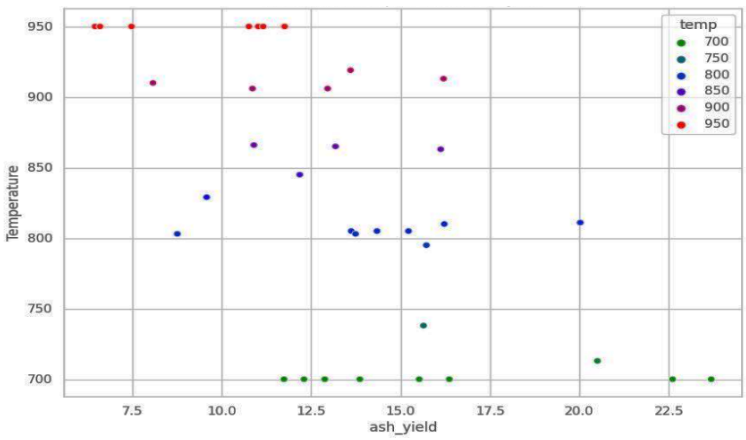


Fig 3: Ash yield of the fuel additive e mixture at different temperatures

It was observed that ash yield decreases with increasing temperature, reaching a minimum at 950°C. The lowest ash yield, 6.46%, was obtained at the highest temperature of 950°C. In contrast, the highest ash yield of 23.68% was observed at the lowest temperature of 700°C, in Run 42 (SGB: BL: $NH_4H_2PO_4$ at 80:20:0). Fig 3b further illustrates that the highest ash yield was observed at temperature

700°C. While the lowest yield was obtained at 950 ºC. Míguez et al., 2021 reported at higher temperatures, the use of additives enhances combustion reaction and promotes the vaporization of ash components, leading to a reduction in ash yield. These results highlight the importance of higher temperatures in reducing ash yield in the biomass fuel mixture.

Influence of Additive on Ash Yield

The influence of the SGB and BL mixtures on $NH_4H_2PO_4$ additive and Ash yield at constant particle size were critically examined using a 3D surface plot in Figure 4 (a-b). The ash yield was observed to vary along a specific range of additives. It was observed that the ash yield was high with additive between 0 to 3% after it reduced significantly between 4% and 7%, and then it was observed to increase significantly up to 10%. The optimal ash yield was observed at 5% additive as shown in Figure 4b. Based on the results, a moderate addition of additives reduces ash yield with an increase in temperature.

Table 6: Proximate and Ultimate Analysis of SGB and BL fuel mixture

(SGB) Property	Reported (Mantura et al., 2020)	(BL) Property	Reported (Noeli et al., 2016)	Experimental at optimal condition of (SGB: BL: $NH_4H_2PO_4$)
Moisture	5.4	Moisture	8.36	2.3
Volatile Matter	51.8	Volatile Matter	53.2	57.3
Fixed carbon	34.04	Fixed carbon	23.2	35.2
Ash	8.7	Ash	23.5	6.4
Carbon	58.2	Carbon	48.2	61.4
Hydrogen	2.0	Hydrogen	3.2	2.5
Nitrogen	0.3	Nitrogen	1.2	1.1
Oxygen	38.6	Oxygen	37.6	34.2
Sulphur	0.1	Sulphur	0.3	0.1
HHV (kJ/g)	19.8	HHV (MJ/kg)	17.3	22.4

Proximate and Ultimate Analysis of SGB and BL fuel mixture

The results of proximate and ultimate analysis of the SGB and BL (without additive) indicated that SGB had an ash yield of 8.7 % and HHV of 19.8 MJ/kg whereas BL had an ash yield of 23.5 % and an HHV of 17.3 MJ/kg (Table 6). In contrast, the optimal blend of SGB, BL and $NH_4H_2PO_4$, resulted in a significant reduction in ash yield to 6.4% and an increase in HHV to 22.4MJ/kg. The differences in the results could be attributed to the additive added to the fuel mixture, the species of the biomass and the climatic conditions where the study is conducted.

XRD analysis

X-ray diffraction (XRD) analysis was done on the Ash samples of Run 8 and Run 42 in the experiment to identify the mineral phase of the compounds formed and confirm the interaction of biomass and additive. The details of XRD ash samples of Run 8 and Run 42 are shown in Table 7. The identified peaks of Run 8 and Run 42 show different XRD patterns as shown in Fig 5 and Fig 6, this can probably be attributed to the fact that there are complicated interactions among the major ash forming contents from both samples.

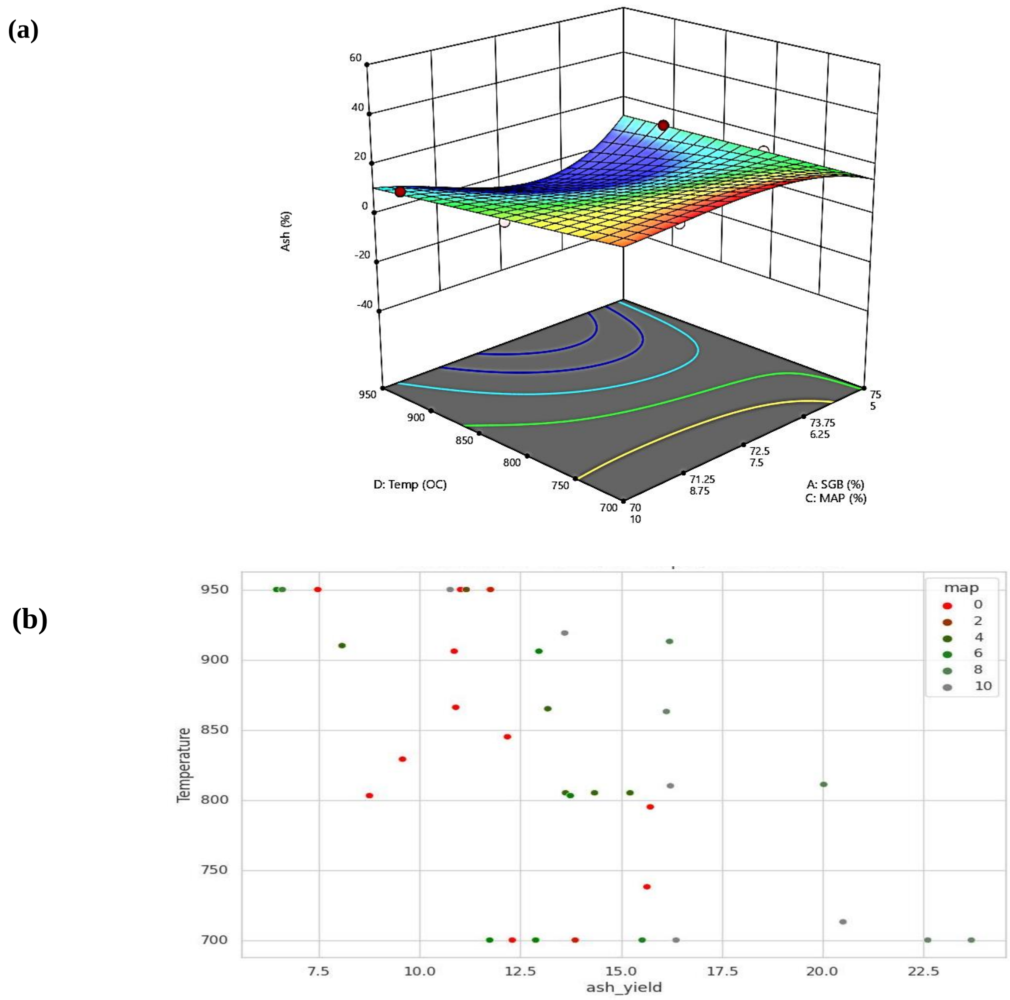


Fig 4.: Effect of $NH_4H_2PO_4$ additive on temperature and ash yield

Table 7: Constituents of XRD Ash samples

	Run 8	Run 42
SGB: BL: $NH_4H_2PO_4$ (%)	75: 20: 5	80: 20: 0
Particle size (mm)	0.3	0.6
Temperature (^OC)	950	700
Ash yield (%)	6.46	23.68

Table 8: Quantitative analysis plot of Run 8 vs. Run 42 ash.

Compound	Chemical formula	Value (wt %)	
		Run 8	**Run 42**
Sylvite	KCl	13.4	26.4
Quartz	SiO2	43.11	64.9
Muscovite	$KAl_2(Si_3Al)\ O_{10}(OH)_2$	29.12	8.11
Orthoclase	$KAlSi_3O_8$	15.17	2.7

On a close comparison on the XRD results of Run 8 and Run 42, SiO_2 is found to be higher in Run 42 (64.9%), this makes it better in mitigating slagging and fouling than Run 8 which has a SiO_2 value of 43.11% (Table 8). However, KCl was found to be very high in Run 42 (26.4%) which will mitigate the positive effects of SiO_2 in reducing slagging and fouling, this is contrasted to Run 8 which has a very small value for KCl (13.4%) thereby making it the better choice. The significant decrease in KCl in Run 8 clearly shows that the moderate presence of $NH_4H_2PO_4$ additive was impactful. However, it is expected that phosphates should be evident in Run 8 ash, but it is not reported by XRD, we can attribute its absence to the fact that the $NH_4H_2PO_4$ additive was added in a very small quantity of 5% thereby making it undetectable by XRD.

Chen et al., (2022) stated that SiO_2 co-combustion ash plays a major role in improving slagging and fouling behaviour as it can react with other compounds to form high melting point compounds and increase ash fusion temperature. According to Kunmi et al, (2023), KCl will give rise to the formation of other problematic species as the temperature increases. Wang et al, (2020) further stated that co-combustion with additives during the combustion process through the mechanism of chemical binding is a preferred way of mitigating ash-related issues, to capture and transform KCl into high-temperature melting compounds.

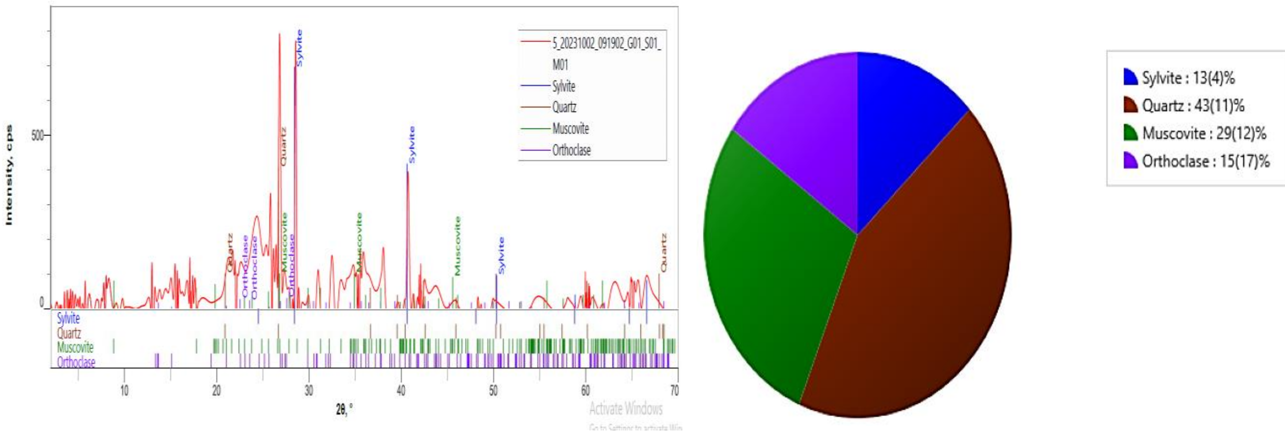


Fig 5. XRD spectra of ash resulting from ash yield of Run 8

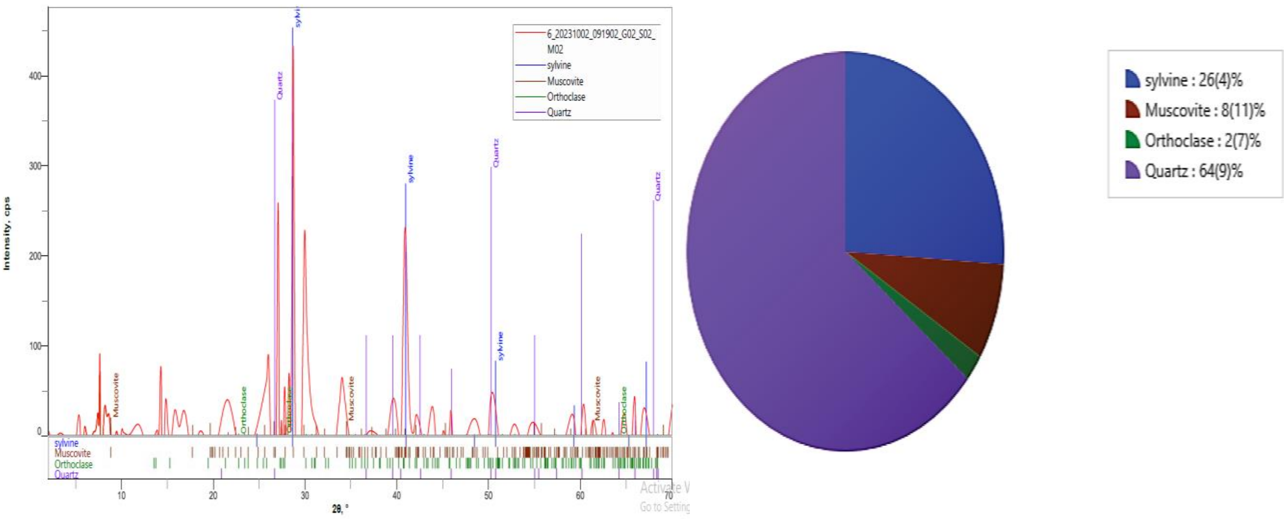


Fig 6. XRD spectra of ash resulting from ash yield of Run 42

CONCLUSIONS

The influence of ammonium phosphate on the co-combustion of torrefied sugarcane bagasse and banana leaves was investigated using the I-Optimal design in the Combined Methodology of Design Expert (version 13.0.5). The experiment was optimized based on process factors such as additive concentration, temperature, and particle size, with a constant duration of 120 minutes. The optimal composition was determined to be 75% SGB, 20% BL, and 5% $NH_4H_2PO_4$ at 950°C, resulting in the lowest ash yield of 6.46% and HHV of 22.4MJ.kg. The mathematical models developed for ash yield using I-Optimal Design demonstrate a strong fit, with an R-squared value of 0.9820. These refined models hold promise for application in thermal power plants, aimed at reducing ash yield during biomass combustion.

REFERENCES

Ajala, E. O., Ighalo, J. O., Ajala, M. A., Adeniyi, A. G., & Ayanshola, A. M. (2021). Sugarcane bagasse: a biomass sufficiently applied for improving global energy, environment, and economic sustainability. In *Bioresources and Bioprocessing* (Vol. 8, Issue 1). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1186/s40643-021-00440-z

Adeniyi, A.G., Abdulkareem, S.A., Ighalo, J. O. (2021). Thermochemical Co-conversion of Sugarcane Bagasse-LDPE Hybrid Waste into Biochar. *Arab. J. Sci. Eng*. 46, 6391–6397

Bianca G. de Oliveira Maia, Antonio P. N. de Oliveira, Therezinha M. N, Oliveira, Cintia Marangoni, Ozair Souza, and Noeli Sellin. (2017). Characterization and Production of Banana Crop and Rice Processing Waste Briquettes. https://doi.org/10.1002/ep.12798

Boström, D., Skoglund, N., Grimm, A., Boman, C., Öhman, M., Broström, M., & Backman, R. (2011). Ash Transformation Chemistry during Combustion of Biomass. *Energy and Fuels*, *26*(1), 85–93. https://doi.org/10.1021/EF201205B

Chen, P. Y., Chen, S. T., Hsu, C. S., & Chen, C. C. (2016). Modeling the global relationships among economic growth, energy consumption and CO2 emissions. *Renewable and Sustainable Energy Reviews*, *65*, 420–431. https://doi.org/10.1016/J.RSER.2016.06.074

Chen, W. H., Lin, B. J., Lin, Y. Y., Chu, Y. S., Ubando, A. T., Show, P. L., Ong, H. C., Chang, J. S., Ho, S. H., Culaba, A. B., Pétrissans, A., & Pétrissans, M. (2021). Progress in biomass torrefaction: Principles, applications and challenges. *Progress in Energy and Combustion Science*, *82*, 100887. https://doi.org/10.1016/J.PECS.2020.100887

Daniyanto, Sutidjan, Deendarlianto, & Budiman, A. (2015). Torrefaction of Indonesian sugar-cane bagasse to improve bio-syngas quality for gasification process. *Energy Procedia*, *68*, 157–166. https://doi.org/10.1016/j.egypro.2015.03.244

Eveline R. K., Fernandes, C. M., Ozair S. and Noeli S., (2013). Thermochemical characterization of banana leaves as a potential energy source. *Energy Conversion and Management* 75 (2013) 603–608. https://dx.doi.org/10.1016/j.enconman.2013.08.008

Field, C. B., Campbell, J. E., & Lobell, D. B. (2008). Biomass energy: the scale of the potential resource. *Trends in Ecology and Evolution*, *23*(2), 65–72. https://doi.org/10.1016/j.tree.2007.12.001

García, R., Gil, M. V., González-Vázquez, M. P., Rubiera, F., & Pevida, C. (2019). *Biomass Pelletization: Contribution to Renewable Power Generation Scenarios*. 269–294. https://doi.org/10.1007/978-981-13-3768-0_9

Granados, D. A., Ruiz, R. A., Vega, L. Y., & Chejne, F. (2017). Study of reactivity reduction in sugarcane bagasse as consequence of a torrefaction process. *Energy*, *139*, 818–827. https://doi.org/10.1016/j.energy.2017.08.013

Hafizh G., S., Moch. Z. P., Hanafi, P. P., Unggul P., A. Darmawan, H., (2023). A comprehensive evaluation of slagging and fouling indicators for solid fuel combustion. Thermal Science and Engineering Progress, 40, 1017690. https://doi.org/10.1016/j.tsep.2023.101769

Kareem B., Oladosu K.O., Alade A.O., and Durowoju M.O., 2018. Optimization of combustion characteristics of palm kernel-based biofuel for grate furnace. *Int J Energy Environ Eng* 9(1): 457–472

Kamoru O.O., Tesleem B. A., Abass O.A, and Mutiu F. E., (2021). Artificial Neural Network Prediction of CO Emission and Ash Yield from Co-Combustion of Empty Fruit Bunch, Palm Kernel Shell and Kaolin *Environmental Science and Pollution Research* 28 (31): 42596–42608. https://doi.org/10.1007/s11356-021-13783-z

Kunmi, J., A. Noorfidza Y. S., Sufian, M. Y., Hesam K. M., Abdalla H., A. Jagaba, S. S., Mohd U., B. Panditj & N. (2023). Regulation of ash slagging behavior of palm oil decanter cake by alum sludge addition. *Chemosphere*, 330,138452. https://doi.org/10.1016/j.chemosphere.2023.138452

Lawal, K. T. (2021). Law, Policy, and the Development of Renewable Energy for Electricity: A Case for a Renewable Energy Law in Nigeria. *International Journal of Legal Information*, *49*(1), 3–15. https://doi.org/10.1017/JLI.2021.7

Li, L., Ren, Q., Li, S., & Lu, Q. (2013). Effect of phosphorus on the behavior of potassium during the Co-combustion of wheat straw with municipal sewage sludge (2019). *Energy and Fuels*, *27*(10), 5923–5930. https://doi.org/10.1021/EF401196Y

Li, Y., Tan, Z., Zhu, Y., Zhang, W., Du, Z., Shao, J., Jiang, L., Yang, H., & Chen, H. (2022). Effects of P-based additives on agricultural biomass torrefaction and particulate matter emissions from fuel combustion. *Renewable Energy*, *190*, 66–77. https://doi.org/10.1016/j.renene.2022.03.101

Manatura, K., Lu, J. H., & Wu, K. T. (2018). Isothermal kinetics of torrefied Cryptomeria japonica in CO2 gasification. *Biomass Conversion and Biorefinery*, *8*(1), 125–133. https://doi.org/10.1007/s13399-016-0232-8

Manatura, K. (2020). Inert torrefaction of sugarcane bagasse to improve its fuel properties. *Case Studies in Thermal Engineering*, *19*. https://doi.org/10.1016/j.csite.2020.100623

Mansoor-Ul-, E., Suadi, H., & Pakistan, A.-. (2014). power generation methods, techniques, and economical strategy. *International Technical Sciences Journal*, *1*(1).

Míguez, J. L., Porteiro, J., Behrendt, F., Blanco, D., Patiño, D., & Dieguez-Alonso, A. (2021). Review of the use of additives to mitigate operational problems associated with the combustion of biomass with high content in ash-forming species. *Renewable and Sustainable*

Energy Reviews, *141*, 110502. https://doi.org/10.1016/J.RSER.2020.110502

Noeli Sellin, Diego Ricardo krohl, Cintia Marangoni, Ozair Souza. (2016). Oxidative fast pyroysis of banana leaves in fluidized bed reactor. https://dx.doi.org/10.1016/j.renene.2016.04.032

Nussbaumer, T. (2003). Combustion and Co-combustion of Biomass: Fundamentals, Technologies, and Primary Measures for Emission Reduction†. *Energy and Fuels*, *17*(6), 1510–1521. https://doi.org/10.1021/EF030031Q

Oladosu K. O., Olafimihan E.O., Oyetunji O.R., Adeoti M.O., and Adejare A.A., 2020. Influence of Kaolin Additive on Ash yield of Palm Kernel-Cashew Shells Combustion *Journal of Engineering and Engineering FUTAJEET* 231-240

Oladosu K., Olawore A., Alade A., and Kolawole M., 2022. Optimization of Hhv and Energy Yield from Torrefaction of Albizia Zygia Wood-Calcium Hydrogen Phosphate Catalyst Blends Using Optimal Combined Design. *Acta Periodica Technologica* (53): 109–122. https://doi.org/10.2298/APT2253109O

Oladosu K.O., Babalola S. A., Ajao R., K. & Erinosho M. F., (2024) Torrefaction of Bambara Groundnut Shell: experimental optimization and prediction of the energy conversion efficiency using statistical and machine learning approaches, *International Journal of Ambient Energy*, 45:1, 2277309,10.1080/01430750.2023.2277309

Qian Wang, Kuihua Han, Jiamin Wang, Jie Gao & Chunmei Lu (2017). Influence of phosphorous based additives on ash melting characteristics during combustion of biomass briquette fuel. Renewable Energy, 113, 428-437. http://dx.doi.org/10.1016/j.renene.2017.06.018

Wang, S., Zhao, S., Uzoejinwa, B. B., Zheng, A., Wang, Q., Huang, J., & Abomohra, A. E. F. (2020). A state-of-the-art review on dual purpose seaweeds utilization for wastewater treatment and crude bio-oil production. *Energy Conversion and Management*, *222*, 113253. https://doi.org/10.1016/J.ENCONMAN.2020.113253

Zhu, Y., Fan, J., Yang, P., Cheng, W., Zeng, K., Zhang, W., Yang, H., Shao, J., Wang, X., & Chen, H. (2019). P-Based Additive for Reducing Fine Particulate Matter Emissions during Agricultural Biomass Combustion. *Energy & Fuels*, *33*(11), 11274–11284.

Zhu, Y., Liu, Y., Wang, L., Yang, W., Yang, H., Jiang, L., Du, Z., Shao, J., & Chen, H. (2021). Effect of phosphorus-based additives on the sintering characteristics of cornstalk ash. *Journal of the Energy Institute*, *97*, 37–47. https://doi.org/10.1016/J.JOEI.2021.04.002