International Journal of Sustainable Energy and Environmental Research
2024 Vol. 13, No. 2, pp. 95-104
ISSN(e): 2306-6253
ISSN(p): 2312-5764
DOI: 10.18488/13.v13i2.3867

Influence of air staging variation on agglomeration behavior of biomass fuels in fluidized bed technology

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Article History
Received: 24 May 2024
Revised: 18 July 2024
Accepted: 2 August 2024
Published: 16 August 2024

Keywords
Ash
Biomass
Combustion
Eutectic
Fuel
Morphology and thermochemical.

ABSTRACT

The fluidized bed system is an effective approach widely accepted and commonly used for the thermochemical conversion of solid fuel such as biomass and agricultural residue. In most instances, there are some demerits usually associated with this approach such as development of eutectic mass, increased process of melting and bed agglomeration. This work was carried out to study the behavior of five readily available biomass fuels (Palm tree fronds, corn straw, plantain peels, sugarcane bagasse and domestic woods) in a bubbling fluidized bed (BFB) combustor. Characterization of the bed materials and ash samples were done using SEM-EDX, XRF and XRD. The effect of physical factors on the composition of obtained ash and particles from the bed was assessed. Also, the interaction between the fuel ash and bed particle was evaluated to reveal its influence on bed materials morphology. The results obtained revealed a combustion efficiency that varies between 96.2 to 99.6 % with the highest value obtained for sugarcane bagasse. The corn straw has the highest Potassium (K) content, while the domestic wood ash contained the highest Calcium (Ca) content. The XRF analysis revealed the conversion of the major potassium content of the corn straw to K2O. Meanwhile, bed agglomeration was absent when combustion was carried out with no staging-air as well as with staging air, despite high temperature above 800 oC used. Data obtained from this work revealed that agglomeration effect will be minimal issue when carrying out fluidized bed combustion of the selected biomass.

Contribution/Originality: An in-depth knowledge of the factors that influence the formation of agglomerates during combustion of biomass in a fluidized bed will assist in selecting the best approach for the combustion of selected biomass with zero or minimal agglomerate formation. This work provided this knowledge with respect to some selected biomass.

1. INTRODUCTION

Biomass is an excellent source of energy generation capable various forms of power. The global energy potential of biomass has been rated to follow closely behind that of fossil fuel. Some peculiarities of biomass energy are its renewable source, high productivity, carbon neutrality and flexibility in storage and transportation (Antar et al., 2021). Fluidised beds (FBs) are predominantly used for the production of energy from solid fuels, however there are technical issues associated with it such as agglomeration of the solid fuel during combustion (Miao, Jiang, & Hu, 2022). Ash formed during combustion is a leading factor causing agglomeration ahead of other factors in FBs (Kwong & Marek, 2021). The origin and source of the biomass utilized influences the characteristics of the ash obtained and biomass ash has been found to be notably composed of silicon, calcium, potassium and a minor proportion of aluminium (Maschowski et al., 2019). Studies has shown that ash related agglomeration is usually initiated by the interaction between ash particles and bed materials during biomass combustion processes (Namkung et al., 2019). Other factors that influence agglomeration in FBs include bed materials used, biomass type and prevailing temperature during combustion (Namkung et al., 2019).

The metals and oxides of metals which are components of the biomass affects the types of alkaline silicates which are combustion products and by such influence the formation of agglomeration (Niu & Tan, 2016). Identification of the specific alkali and alkaline earth metals responsible for biomass agglomeration is very important. Surface morphology studies of agglomerates produced during combustion can give vital information and this has revealed in the past the influence of different stages in combustion and temperature on agglomeration (Chi, Pans, Sun, & Liu, 2019). Notable success has been made with respect to the study of agglomeration in coal and coal mixed with biomass but much work is required to be done on agglomeration problems associated with combustion of biomass and gasification in fluidized beds. Also, mechanisms of agglomerations that has been established in the literature are required to be further studied to ascertain their applicability to the selected biomass used in this study. It has been found in the past that introduction of K_2CO_3 encourages agglomeration when combined with coal and soybean straw. Also, combining biomass rich in phosphorus with wheat straw in fluidized beds system reduces the possibility of bed agglomeration as a result of its ability to increase the melting temperature of the ash produced from the combustion (Wagner et al., 2019).

This study investigated important basic aspects responsible for biomass fuels agglomeration tendency when air-combusted in a bubbling fluidised bed combustor (BFBC). Characterization of the ash and bed materials samples were carried out and the results were analysed. The combustion was done on five different biomass which are; Palm tree fronds, corn straw, plantain peels, sugarcane bagasse and domestic woods. The samples characterized are the biomass, the bed materials prior to combustion and the bed materials after combustion. The combustion was done in a bubbling fluidized bed combustor. The characterization test done are scanning electron microscope (SEM) and energy dispersive X-ray (EDX), X-ray fluorescence analysis (XRF) and X-ray diffraction (XRD). The results obtained will give more clarity to the issue of agglomeration associated with biomass combustion and will open more channels for advanced studies.

2. METHOD

The biomass used in this study falls into two categories of woody and non-woody biomass. Palm tree fronds and domestic woods falls under the woody category while corn straw, plantain peels and sugarcane bagasse are non-woody. All the biomass while collected from Ibadan, Nigeria. The various biomasses were prepared into pellets of sizes between 12- and 30-mm. Preliminary tests were carried out on the fuel samples to determine their proximate, ultimate and heating values and these are presented in Table 1.

The rig of the BFB combustor has a reactor serving as the feeding system for biomass, a fan for steady air blowing, a cyclone, system for cooking and cleaning of gas with prompt analysis. The feeding section has a hopper with a geared motor controlled by an inverter. The prepared biomasses were imputed through the feeder hopper channel. Distribution plate used was a stainless steel whose thickness and pore sizes were 12 mm and 0.002mm respectively. The bed was loaded with silica sand of average diameter of 0.78 mm. Air was channeled through the base of the reactor straight to the plenum. The biomass was placed in the bed and combustion was aided by the supplied air. Hot air coming from the combustion was made to pass through a cyclone designed to remove its sand and ash contents. Once each run is completed, the ash together with the fine particle contents were taken for analysis. Immediately after three runs of each biomass, bed was opened to observe its materials for occurrence of agglomeration. Source of heating in the combustor is two heaters made of ceramic fibre rated 2100 W and installed on the main reactor. A blower fan supplied the air from the base through a flexible hose made of stainless steel with a 5 cm diameter. The temperature of the inlet air was steadily increased to as high as 450 ^oC using an installed flexible heating tape. Excess temperature in the reactor was removed using heat extractor water cooling probe channeled from the top of the reactor. Collection of gas samples to be analyzed was aided with the use of another water-cooling probe positioned at the exit. Collected gas was analyzed using gas analyzer.

Table 1. Proximate and ultimate analysis with calorific values of utilized biomass fuels.

Biomass fuels	Proximate analysis					Ultimate analysis				
	M (%)	VM (%)	FC (%)	Ash (%)	HHV (MJ/kg)	C (%)	H (%)	N (%)	O (%)	S (%)
Palm tree fronds	3.60	78.90	18.65	2.45	20.25	46.65	6.65	0.23	45.90	0.57
Domestic wood	3.96	84.25	14.95	0.80	19.50	47.10	6.85	0.18	45.68	0.19
Corn straw	4.90	77.15	17.07	5.78	17.18	43.40	6.87	1.57	47.75	0.41
Plantain peels	11.55	87.20	3.45	9.35	16.77	36.20	6.20	1.87	44.75	19.20
Sugarcane bagasse	0.65	84.64	11.21	3.15	9.81	49.20	4.69	0.18	43.00	0.02

Note: M: moisture, VM: volatile matter, FC: fixed carbon, HHV: higher heating value.

2.1. Procedure

The Garside silica sand of 0.78 mm particle size was input into the reactor via flange at the top and made to a height of about 25 cm. Combustions were carried out at temperatures between 750 and 850 ^oC. The rig was operated at atmospheric pressure and combustion of biomass was done using air. Air was supplied primarily to the reactor at the rate of 300 L/min while feeder air was at 50 L/min at STP. The reactor was preheated prior to the test also the air preheater was set at 450 ^oC to raise the temperature of air supplied to the reactor. Immediately the sand bed temperature was raised above 500 ^oC, the biomass was charged at a definite flow rate. The main preheater was switched off as soon as proper combustion began.

The variation in essential parameters (bed temperature, differential pressures, freeboard temperature and flue gas composition) were monitored and data collected every 10 s using a computer. At the end of each combustion, the bed was allowed to cool to ambient, sample of the bed material was observed for agglomerates and collected for analysis.

Without air staging (WAS) tests were done feeding the biomass continuously in BFBC giving results under steady state conditions. Test were carried out to examine the effect of excess air on the flue gas emission and efficiency of combustion using varying air ratios of 15, 30 and 45 %.

Air-staging effect was measured by supplying about 50 L/min of air flow to one of the air staging injection pipes while setting the overall air flow was at 350 L/min steady value. Secondary air was introduced at two different heights 70 cm (SA1) and 110 cm (SA2) to examine the influence of injection heights on gas composition. Table 2 shows all the test performed. Also, combustion efficiency was calculated for each biomass used to the determine the performance of the BFBC for each biomass using Equation 1 (Llorente & Cuadrado, 2007).

$$\eta = \frac{\%CO_2}{\%CO_2 + \%CO} \qquad (1)$$

2.2. Bed Material Sample and Ash Collection

Visual examination and collections of samples were carried out on completion of combustion for each test carried out on the selected biomass under various conditions. The sand was visually examined for any sign of appearance of agglomerates and it was weighed. About 200 g of the bed material was pulverized and sieved to pass 50 µm sieves and stored in plastic bags for various analysis.

Table 2. Experimental matrix for the tests performed without air staging and with air staging combustion.

Set no.	Biomass	Combustion condition	Feed rate (kg/h)	Excess air level	Temperature range (°C)	Cooling water flow rate (L/min)	Number of runs	Total run time (h)
1	Palm tree fronds	WAS	3-5	10 -50	750 - 850	1.2	4	8-12
	Corn straw	WAS	3-5	10 -50	750 – 850	1.2	4	8-12
	Plantain peels	WAS	3-5	10 -50	750 – 850	1.0	4	8-12
	Sugarcane bagasse	WAS	3-5	10 -50	750 – 850	1.0	4	8-12
	Domestic woods	WAS	3-5	10 -50	750 – 850	1.0	4	8-12
2	Palm tree fronds	AS1	3-5	10 -50	750 – 850	1.2	4	8-12
	Corn straw	AS1	3-5	10 -50	750 – 850	1.2	4	8-12
	Plantain peels	AS1	3-5	10 -50	750 – 850	1.0	4	8-12
	Sugarcane bagasse	AS1	3-5	10 -50	750 – 850	1.0	4	8-12
	Domestic woods	AS1	3-5	10 -50	750 – 850	1.0	4	8-12
3	Palm tree fronds	AS2	3-5	10 -50	750 – 850	1.2	4	8-12
	Corn straw	AS2	3-5	10 -50	750 – 850	1.2	4	8-12
	Plantain peels	AS2	3-5	10 -50	750 – 850	1.0	4	8-12
	Sugarcane bagasse	AS2	3-5	10 -50	750 – 850	1.0	4	8-12
	Domestic woods	AS2	3-5	10 -50	750 - 850	1.0	4	8-12

This was repeated for all the sample with the fresh Garside silica sand loaded into the reactor before combustion. Particle size distribution for used sand is presented in Table 3. Ash samples collected from cyclone was pulverised and stored in bags ready for analysis.

Table 3. Sand particle size distribution.

Particle size (µm)	Weight (gm)	Percentage (%)	Radius	Vp (kg/m³)	Ap (m²)	xi/dpi
850	1085.20	39.97	0.43	0.33	2.32	1276.71
600	1568.98	57.79	0.35	0.21	1.54	2614.96
300	56.76	2.09	0.24	0.05	0.72	189.20
210	3.28	0.12	0.12	0.01	0.18	15.62
150	0.56	0.02	0.08	0.00	0.08	3.73
0	0.34	0.01	0.04	0.00	0.02	0.00

2.3. Characterization of Samples

The bed materials that were ground to less than 50 µm was pelletized using hydraulic press to obtain pellets that were mm thick and 5 mm in diameter. The pellets were then mounted on the SEM to obtain its chemical composition. The SEM analysis was done by the backscattered electron (BSE) type detector, at 20 kV working under a mode of high vacuum. The quantification of materials under SEM-EDX was done using the interactive oxides mode method. The observed micrographs were taken at different magnifications of 50, 100, 150 and 300 times. EDX spot analysis was carried out using interactive oxides method which made it possible to determine elemental compositions of interested points on the agglomerate.

Xrd analysis was done on X-ray diffractometer D500 which was equipped with 9 sample holders. The sample to be tested was prepared into powdered and thereafter loaded. The equipment was operated with a parallel beam of low intensity revealing phases that has more than 1% presence. The result obtained was evaluated using TOPAS (Total Pattern Analysis Solutions) V5 software.

Powdered samples pressed into pellets were also analysed using XRF. The result obtained was analysed using Spectra Plus software version 2.0.

3. RESULTS AND DISCUSSION

The combustion of each of the biomass selected was done was one after the other in duplicate and each run lasted a period of about 9 – 12 hours. The temperature attained during each of the combustion ranged between 750 and 850 °C. Detailed monitoring was given to both temperatures and pressure to detect the onset of fluidization.

3.1. Combustion Efficiency Determination

The combustion efficiencies of the selected biomass combusted at various conditions which are without air staging (WAS), air staging at level one (SA1) and air staging at level two (SA2) are effectively compared. The combustion efficiencies were found to fall between 94 % and 99.7 %. All combusted biomass had their combustion efficiencies higher under the condition of air staging. The highest combustion efficiency 99.4 and 99.7 was respectively obtained with sugarcane bagasse under air staging SA1 and SA2. Domestic wood had 99.2 % combustion efficiency when 45% excess air was used. Generally, lower value of combustion efficiency was obtained when combustion was done without air staging with limited excess air. Marginal differences were obtained in the combustion efficiencies of all the biomass under air staging. The combustion efficiencies noticeably reduced as the level of excess air reduced and this was as a result of reduction in oxygen available for combustion. This however made the residence time of the fuel in the chamber to increase. The high gas temperatures under air staging conditions also had a positive effect on the combustion efficiencies as against without air staging. For all the selected biomass, there was a reduction in emission and increased combustion efficiencies when air was staged at the highest point SA2.

3.2. Visual Inspection

The bed samples obtained after the combustion of each biomass is presented in Figure 1. The bed samples collected during corn straw combustion revealed the presence bonded particles black in colour and relatively big Figure 1(d). There was colour transformation for each of the bed materials used for individual biomass combustion immediately after combustion. The initial colour was yellowish brown and the following changes occurred; brownish black for palm fronds and domestic woods, greyish black for corn straw, grey for sugarcane bagasse and dark brown for plantain peels. The observed colour change could be attributed to thermal breakdown of Fe_2CO_3 which is a constituent of the Garside sand used. Colour change also came based on temperature attained and the type of biomass used (Kwong, Harrison, Gebers, Dennis, & Marek, 2022).

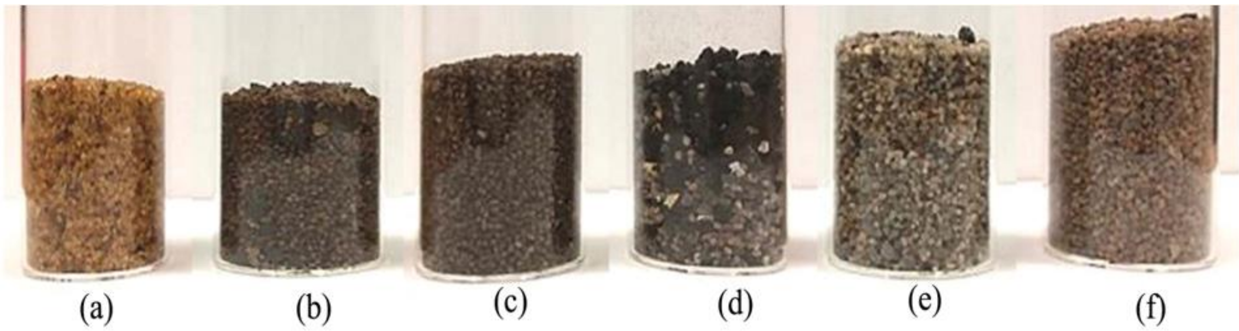

Figure 1. Bed samples from each biomass; (a) fresh sand (b) palm fronds (c) domestic wood (d) corn straw (e) sugarcane bagasse (f) plantain peels.

3.3. Air Combustion Agglomeration

Bed samples collected after corn straw combustion had some level of bounding which was agglomeration. The agglomerates which were round shaped and black in colour had an average size of 2 – 4 mm. The other biomasses were free of agglomerates after combustion. Factors that could have led to agglomerate formation could be poor fluidization, lower density and higher porosity in the biomass as compared to others.

3.4. Bed Samples Analysis

Analysis of bed samples is presented in Figure 2 (a) and (b). it could be observed that samples from plantain peels and corn straw combustion had the highest potassium (K) of about 13 % and 11 % respectively. Meanwhile, the palm tree fronds sample had the highest content of aluminium of about 10 %. Calcium is sufficiently present in all bed materials except domestic wood. It should be noted that the higher the elements retained in the bed, the lesser is the element content in the emission (Gogolev et al., 2021). Potassium was predominantly retained in the bed materials as observed in Figure 2 (a). Ash mostly acts as glue to enhance the bonding of materials in the bed thereby forming agglomerates (Öhman, Nordin, Skrifvars, Backman, & Hupa, 2000). High temperature during combustion could force the inorganic content of the char to the surface and at the surface the interact with the bed materials and stick to form agglomerates. Also, gases released during combustion could condense and form coatings that will encourage agglomeration.

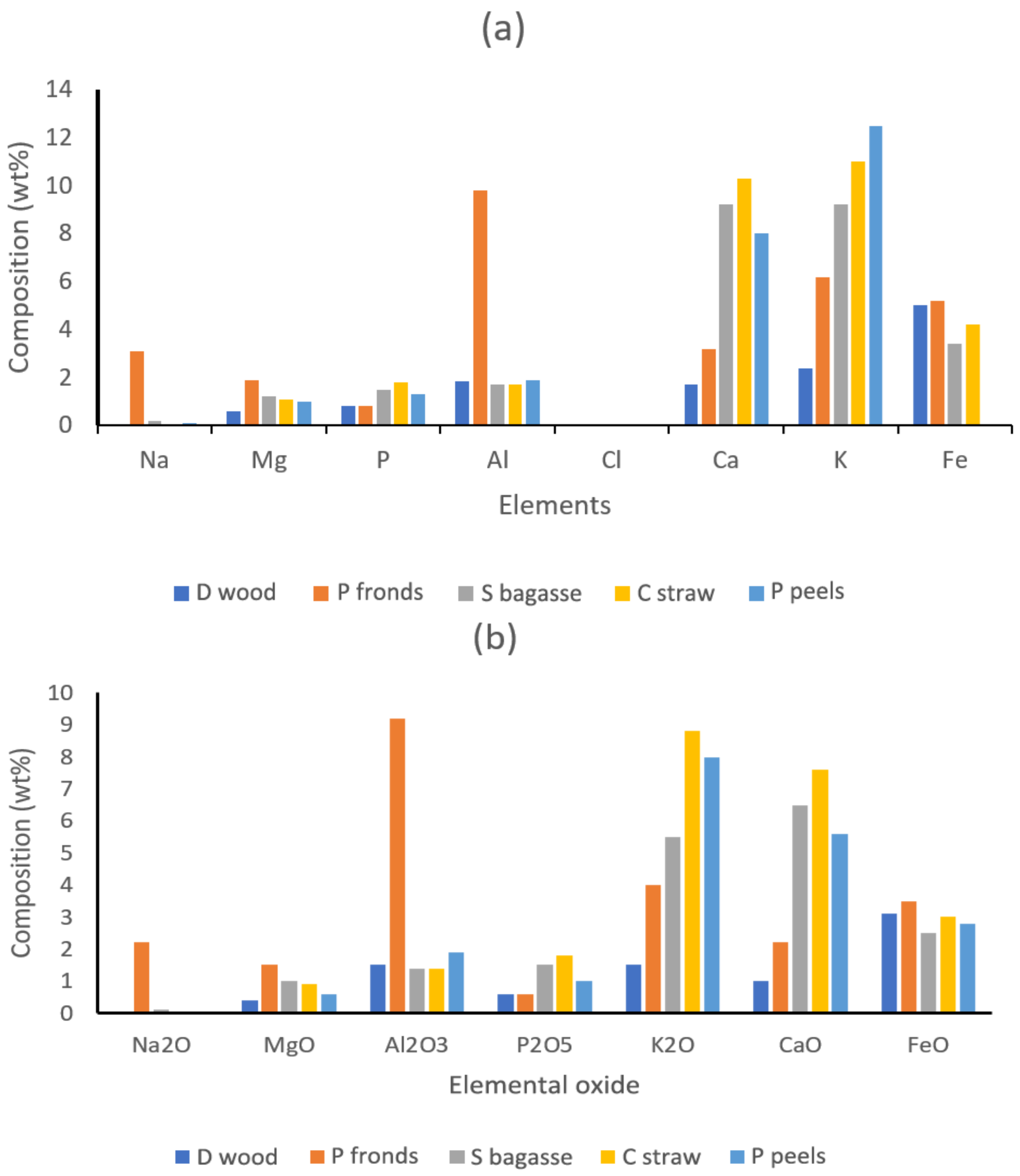

Figure 2. XRF analysis of bed samples obtained from different biomass fuels under air combustion; (a) elemental composition and (b) elemental oxides. Results are given as C and O free basis.

The corn straw behaved differently during combustion. Its ash began to melt at early temperature of 750 °C and this made only a minute portion of the ash available to evaporate at higher temperature. Thereafter, the potassium accumulation at the bed increases with time. So, only minor potassium got to the gas phase during corn straw combustion in the BFBC as observed in Figure 2 (a) and 2b for K content. The XRD results is shown in Figure 3, and it indicate that for corn straw, potassium was converted into KCl at about 55%. The bed materials for corn straw also reveal the presence of KCl. This suggest that agglomeration may be as a result of different volatilization of potassium content of different biomasses.

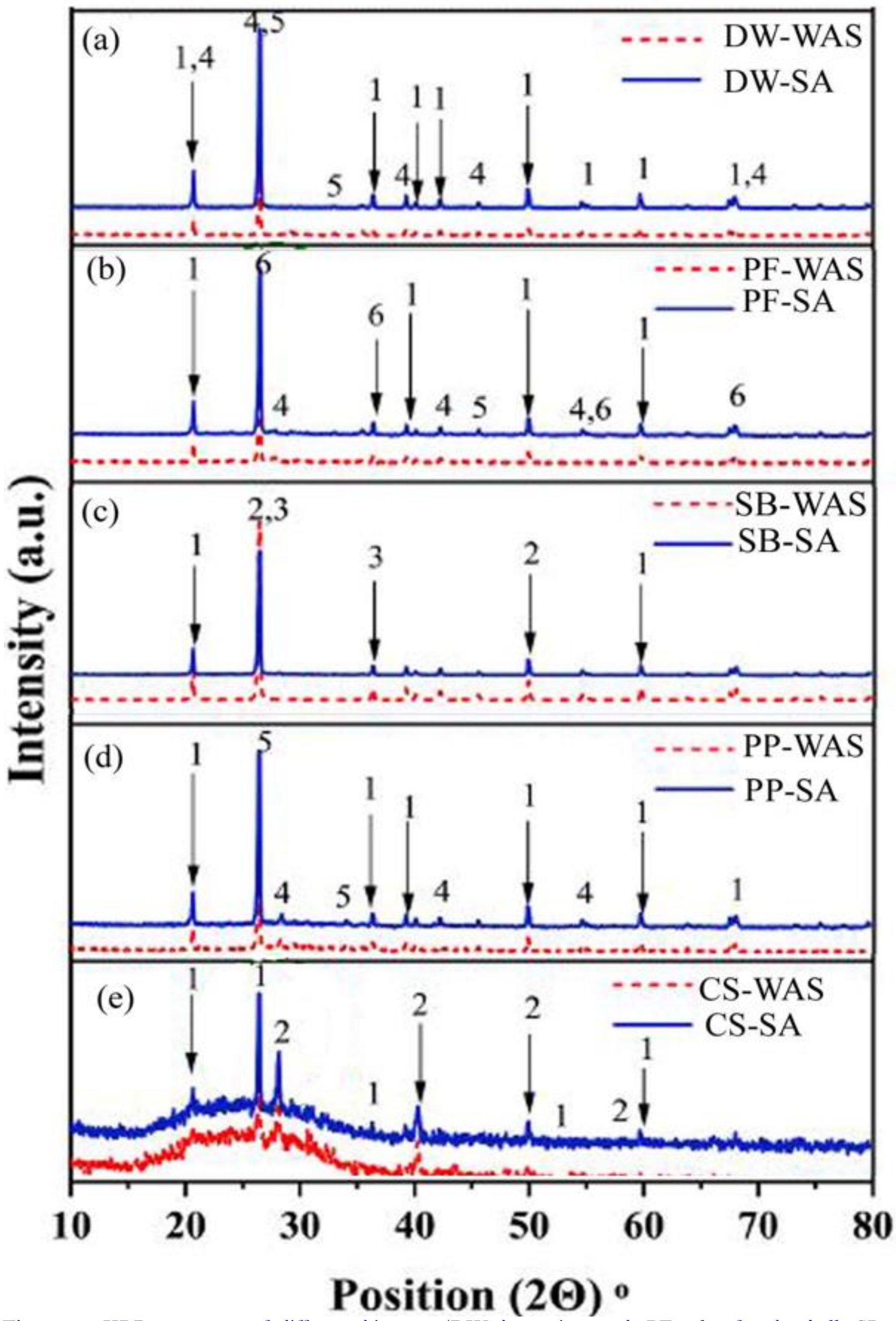

Figure 3. XRD spectrum of different biomass (DW-domestic wood; PF-palm fronds shell; SB-sugarcane bagasse; PP- plantain peels; CS-corn straw) under; (a) staging air (SA) and without air staging (WAS) conditions. (1. Quartz, 2. Sylvite, 3. Sodium phosphate hydrogen peroxide, 4. Coesite, 5. Hematite and 6. Albite).

3.5. Ash Sample Analysis

Biomass ash are different from coal ash and the composition are dependent on biomass type and conditions of collection. The main elements present in the ash are presented in Figure 4a. as observed, the ash of selected biomass has similar elemental composition (Leffler et al., 2023). The major oxides present in the studied biomasses are presented in Figure 4b. From the result, it can be seen that corn straw had the highest K_2O content. Major portion of the K in the corn straw was converted to K_2O (Awasthi & Bhaskar, 2019). This shows that K_2O rich ash assists the bed materials to glue together leading to agglomerates.

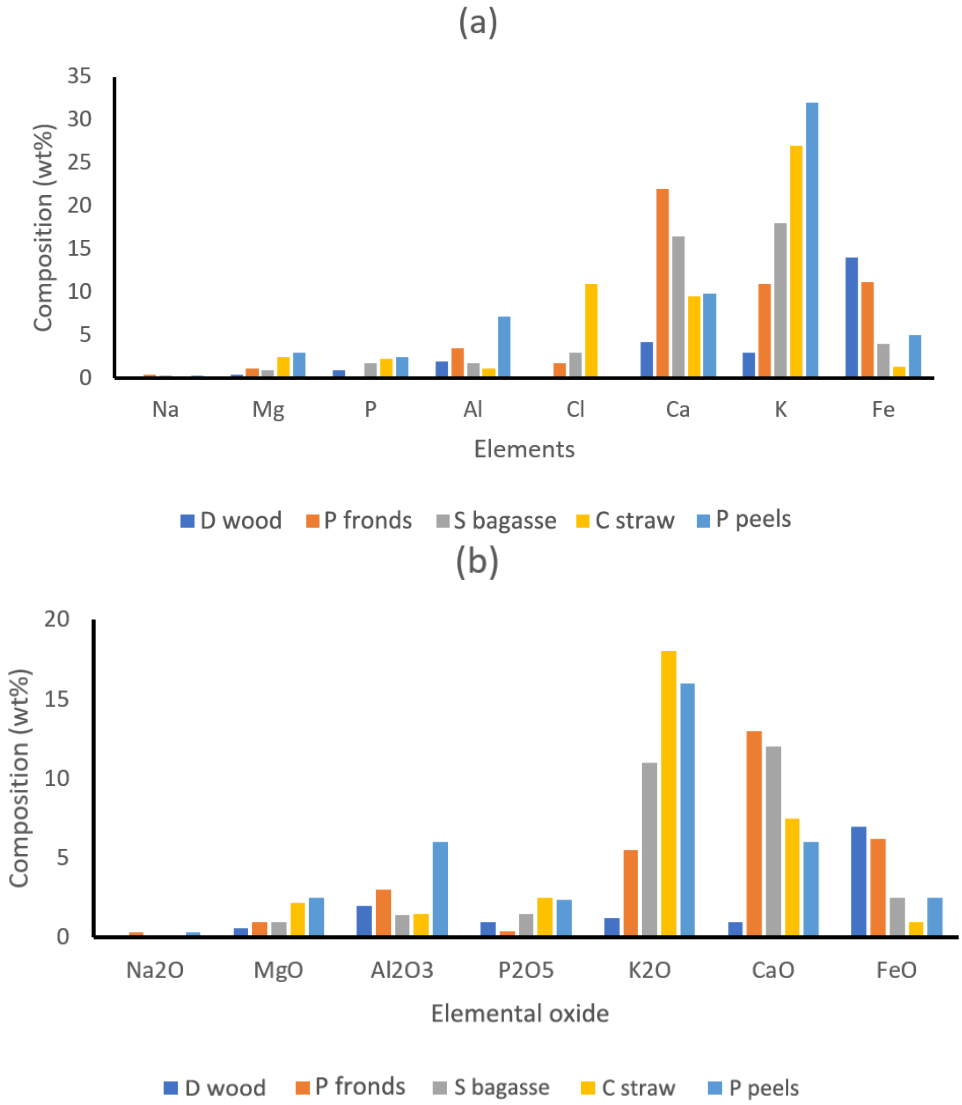

Figure 4. The XRF results for biomass ash under air combustion; (a) elemental composition and (b) elemental oxides. (Presented results are Si free basis).

3.6. Bed Samples Surface Morphology

Agglomerates collected from the bed came in different sizes. The images from the SEM studies of the various collected bed materials are presented in Figure 5. There were indications of damaged bed sand particles with domestic wood and sugarcane bagasse fuels. There are variations in the shape of the bed samples which could result from different fluid dynamic behaviours during combustion at various temperatures (Nisamaneenate, Atong, Seemen, & Sricharoenchaikul, 2020). In corn straw agglomerates the ash flakes were linked with bed particles and it shows some particles connected by necks. Also visible from the SEM images are bounded or coated particles having a glossy look implying the presence of molten viscous liquid during combustion in BFBC (Kuba, Skoglund, Öhman, & Hofbauer, 2021).

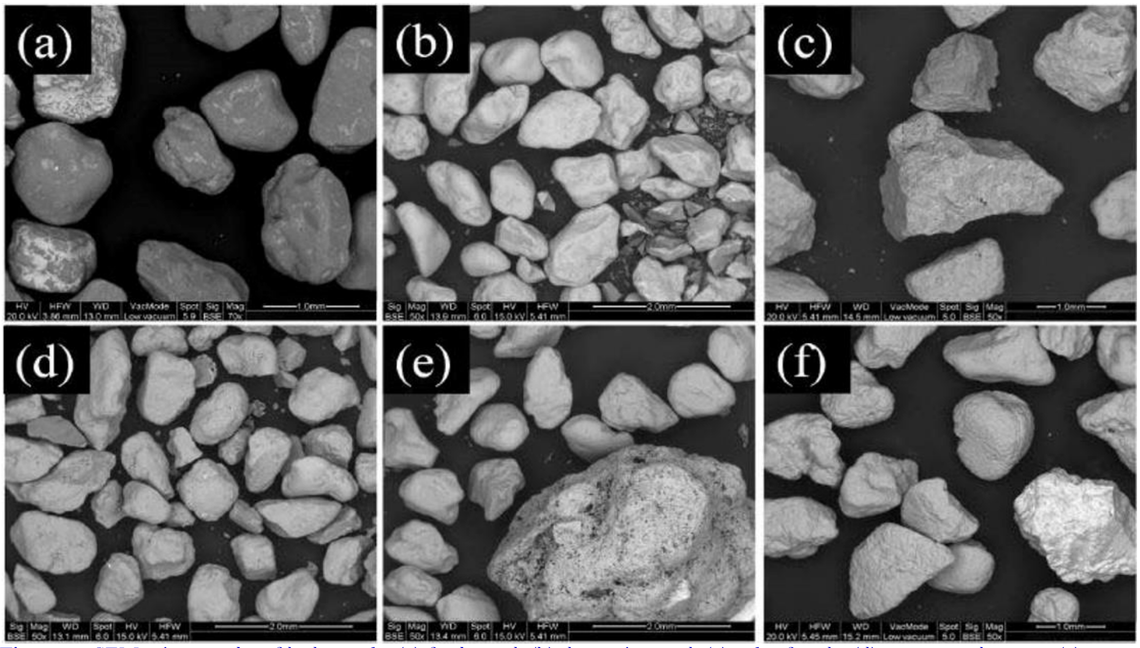

Figure 5. SEM micrographs of bed sample; (a) fresh sand, (b) domestic wood, (c) palm fronds, (d) sugarcane bagasse, (e) corn straw and (f) plantain peels.

4. CONCLUSION

The results of analysis of bed and ash samples obtained from the combustion of five selected biomass was discussed. Analysis was done using SEM, XRD and XRF. The results showed that agglomeration is significantly affected by temperature of combustion and the elemental composition of biomass ash. The efficiency of combustion of the selected biomass varies between 94% and 99.7%. Agglomeration was only detected with the combustion of corn straw which shows that combustion stoichiometry does not affect agglomeration. The SEM images indicated significant disparity between the structure of the agglomerate of corn straw and that of other biomass tested.

The potassium (K) content of plantain peels and corn straw were found to be about 13% and 11% and were actually the highest. The high content of potassium present in corn straw was notably responsible for the observed agglomeration during combustion of corn straw. The potassium content interacted with both organic and inorganic components to generate amorphous salts which were responsible for the agglomeration of bed contents. Majority of the compounds formed preferably stay at the base at temperatures below 900 °C which is the peak temperature used for the combustion. These materials melts and coat the bed particles, moulding them together to form agglomerates.

Funding: This study received no specific financial support.
Institutional Review Board Statement: Not applicable.
Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.

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