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COMBUSTION PERFORMANCE AND DURABILITY ANALYSIS OF BIOMASS FUEL PELLETS FROM OIL PALM RESIDUES

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ABSTRACT

This study investigated the durability and combustion performance of biomass fuel pellets produced from oil palm residues. The pellets were produced using different mixing ratios of residues and binder. The ratios are 90R:10B, 80R:20B, 70R:30B, 60R:40B and 50R:50B. The drop test method was used to test the durability of the pellets. The pellets were dropped four times each from a height of 1.85m. Crack particles resulted on all of them at various percentages. The pellet with 90R:10B mixing ratio was the most severe whereas 50R:50B was the least severe. The percentage durability results shows 89.3%, 91.3%, 92.7%, 94.7% and 96.7% respectively. Each of the pellets from the mixing ratio was combusted in a prototype boiler and pellets from 80R:20B was adjudged best based on their percentage durability, sustainability, steady flame and lower emissions. Combustion analysis shows that the chemical formulas for the pellets from palm kernel shell (PKS), palm fibre (PF) and empty fruit bunch (EFB) are $C_{3.86}H_{5.59}O_{2.90}N_{0.0643}S_{0.003125}$, $C_{3.325}H_{5.4}O_{3.055}N_{0.1436}S_{0.00375}$, *and* $C_{3.58}H_{5.27}O_{2.972}N_{0.032}S_{0.003125}$ *with stoichiometric A/F ratio of 5.28/1, 4.514/1 and 4.873/1 respectively. The wet and dry basis for the exhaust products from the combustion analysis also showed that sulphur dioxide* (SO_2) *for the pellets were very low with values ranging from 0.01% to 0.02%. This implies that the cost of maintenance of an industrial boiler would be less if the pellets are used as fuel.*

1. INTRODUCTION

Combustion is a process in which fuel is burnt with oxygen in air to release the stored chemical energy as heat in burners, boilers, internal combustion engines and turbines (Grass and Jenkins, 1994). Biomass combustion supplies about 11% of the world's total primary energy (Grass and Jenkins, 1994). There are several broad categories of combustion applications: heat for daily living use (stoves); community applications including district heating, industrial use for process heat and electricity production, combined heat and power (La Nauze, 1986). Each of these applications will use different biomass materials according to the local availability of such fuels (McIlveen-Wright and Williams, 2001).

Biomass is unique as a renewable energy source because it can be used for all three energy sectors such as electricity, heat and transport. The use of biomass for heating has been widely promoted (Jones, 2014). Of the different thermochemical conversion techniques, combustion is the most extensively used and developed technique for the utilization of biomass (Nussbaumer, 2003). Thus, to increase combustion development, the whole process needs to be optimized in terms of efficiency and cost. Because of this necessity, several researchers have focused on three main aspects: the fuel properties, boiler characteristics, and emissions (Al-Widyan and Al-Jalil, 2001; Senneca, 2007; Chaney et al., 2012; Collazo et al., 2012; Houshfar et al., 2012; Mehrabian et al., 2012; Wang et al., 2012; Anca-Couce et al., 2013).

Carbon dioxide is the leading greenhouse gas and the use of biomass is neutral with respect to global warming potential. There are however, a number of environmental costs of biomass combustion, which require innovation and significant investment for their mitigation (Tillman, 1987). These costs include both direct human health impacts as well as environmental damage to the earth's productive ecosystems (Tillman, 2000). As harvested from the field or forest, the biomass materials are not purely a mix of carbon, hydrogen and oxygen (CH&O), but also contain elements such as nitrogen (N), Phosphorus (P), potassium (K), and sulphur (S) as well as many trace elements that in the living plant are essential to maintaining metabolism, respiration and growth (Nordin, 1994). These additional chemical elements present challenges to combustion engineering technology in the form of fouling, deposition, slagging and corrosion of the internal burner structure and heat transfer surfaces. The emission of metals and other elements to the air and soil may also have environmental impacts. However, depending on the quality of the combustion process and the investment in emissions controls, the use of biomass fuels can be as clean as natural gas utilization or even dirtier than coal.

Thus, this study aims at investigating the durability and combustion performance of pellets produced from biomass oil palm residues such as palm kernel shell, palm fibre and empty fruit bunch in order to determine their suitability for combustion purposes in industrial boilers.

2. MATERIALS AND METHODS

2.1. Materials

The materials used for this study include pellets produced from palm kernel shell, palm fibre and empty fruit bunch. A prototype boiler was also used for the combustion test performance of the pellets.

2.2. Method

2.2.1 Durability test analysis

The durability of the pellets was measured by the drop test method reported in Al-Widyan and Al-Jalil, (2001), Khankari et al. (1989), Sah et al. (1980), and Shrivastava et al. (1989), where a single pellet was dropped from a 1.85m height on a metal plate for four times. This experiment was carried out and the durability test of the pellets was measured by the ratio of the final mass of the material retained after four drops to the initial mass of the pellets using Equation (1).

$$\% \text{ Durability} = \frac{\text{Final mass of pellet after four drops (kg)}}{\text{Inital mass of pellet (kg)}} \times 100 \quad (1)$$

2.2.2. Combustion performance test in a prototype boiler

The combustion performance analysis of the pellets was carried out in a locally fabricated prototype boiler. The prototype boiler is a fire tube system with a combustion chamber through which the biomass fuel pellets were tested for combustion performance. A very specific amount of oxygen (O_2) is needed for stoichiometric combustion and some additional (excess) air is required for ensuring complete combustion. However, too much excess air will result in heat and efficiency losses. The products of complete combustion of the fuel pellets are water vapour, carbon-dioxide and other by-products. The stoichiometric combustion equation of the various pellets in air is given by Equation (2).

$$C_aH_bO_cN_dS_e + x[O_2 + (79/21)N_2] \rightarrow pCO_2 + qH_2O + rSO_2 + tN_2 \quad (2)$$

3. RESULTS AND DISCUSSION

3.1. Durability Test Results

Table 1 shows the data obtained from the durability experiment and was substituted into Equation (1) to calculate the percentage durability of the pellets for each of the mixing ratio. The mixing ratio is the amount of raw residues to binder for pelletizing i.e. 90R:10B, 80R:20B, 70R:30B, 60R:40B, 50R:50B. The results are shown in Table 2.

Table 1: Durability test data

Mixing ratio	90R:10B	80R:20B	70R:30B	60R:40B	50R:50B
Final mass of pellet	0.134	0.137	0.139	0.142	0.145
Initial mass of pellet	0.15	0.15	0.15	0.15	0.15

Note: R is the residues, while B is the binder

Table 2: Percentage durability of pellets

Mixing ratio	90R:10B	80R:20B	70R:30B	60R:40B	50R:50B
% Durability	89.3	91.3	92.7	94.7	96.7

The effect of the binder was justified from observation when 90R:10B, 80R:20B, 70R:30B 60R:40B and 50R:50B pellets were dropped from a height of 1.85m. Crack particles from the 90R:10B pellet was the most severe whereas 50R:50B was the least severe. In other words, the 50R:50B pellets has the best percentage durability due to large percentage of binder in it than others.

3.2. Combustion Analysis

Under adequate inlet air condition, each of the pellets from the different mixing ratios was tested for combustion in a prototype boiler. The 50R:50B and the 60R:40B pellets was unable to maintain combustion effectively while their performance were not without a lot of smoke. This is due to high binding agent contained in them. Although the durability of 90R:10B and 80R:20B are lower than others, their combustion was steady with very little smoke. Therefore, considering the percentage durability and combustion tests of the various pellets which was observed in the combustion chamber of the boiler, 80R:20B percentage mixing ratio was considered the best because its durability is higher than the 90R:10B mixing ratio. From the results of the ultimate analysis of the pellets in Table 3 (Onochie et al., 2017), the equivalent chemical composition (molecular formula) by mass of fuel pellet is given by $C_aH_bO_cN_dS_e$

Table 3: Ultimate analysis of pellets

Fuel Pellets	% Carbon	% Nitrogen	% Sulphur	% Hydrogen	% Oxygen
Palm Kernel Shell, PKS	46.28	0.90	0.10	5.59	46.44
Palm Fibre, PF	39.90	2.01	0.12	5.40	48.88
Empty Fruit Bunch, EFB	42.91	0.45	0.10	5.27	47.55

By calculating the values of the variables, the chemical formula of the PKS, PF and EFB pellets are $C_{3.86}H_{5.59}O_{2.90}N_{0.0643}S_{0.003125}$, $C_{3.325}H_{5.4}O_{3.055}N_{0.1436}S_{0.00375}$ and $C_{3.58}H_{5.27}O_{2.972}N_{0.032}S_{0.003125}$ respectively. This is summarized in Table 4.

Table 4: Chemical formula of pellets

Fuel pellets	Chemical formula
Palm Kernel Shell, PKS	$C_{3.86}H_{5.59}O_{2.90}N_{0.0643}S_{0.003125}$
Palm Fibre, PF	$C_{3.325}H_{5.4}O_{3.055}N_{0.1436}S_{0.00375}$
Empty Fruit Bunch, EFB	$C_{3.58}H_{5.27}O_{2.972}N_{0.032}S_{0.003125}$

3.2.1. Combustion performance analysis of PKS fuel pellets

The stoichiometric equation for the combustion of PKS pellets $[C_{3.86}H_{5.59}O_{2.90}N_{0.0643}S_{0.003125}]$ using air as the oxidant is given by:

$$C_{3.86}H_{5.59}O_{2.90}N_{0.0643}S_{0.003125} + x_1\,[O_2 + (79/21)N_2] \rightarrow p_1CO_2 + q_1H_2O + r_1SO_2 + [t_1 + x_1\,(79/21)]N_2 \quad (3)$$

Thus, the chemical equation for the combustion of PKS in air becomes:

$$C_{3.86}H_{5.59}O_{2.90}N_{0.0643}S_{0.003125} + 3.810625[O_2 + (79/21)N_2] \rightarrow 3.86CO_2 + 2.795H_2O + 0.003125SO_2 + 14.36735833N_2$$

On a mass basis, the mass of 1kmol of PKS fuel pellet:

Molecular mass of PKS Fuel = $C_{3.86}H_{5.59}O_{2.90}N_{0.0643}S_{0.003125}$= 3.86(12) + 5.59(1) + 2.9(16) + 0.0643(14) + 0.003125(32) = 99.3102kg

In calculating the molecular mass of each constituent, the combustion equation by mass becomes:

$$99.3102kg\,C_{3.86}H_{5.59}O_{2.90}N_{0.0643}S_{0.003125} + 121.94kg\,O_2 + 402.29kgN_2 \rightarrow 169.84kgCO_2 + 50.31kgH_2O + 0.2kgSO_2 + 402.29kgN_2$$

The mass of air (oxygen and nitrogen) = 121.94kg + 402.29kg = 524.23kg, and the mass of PKS fuel is 99.3102kg. Therefore, the stoichiometric air/fuel ratio is given as:

$$\text{Stoichiometric Air-fuel ratio, } A/F = \frac{Mass\ of\ air}{Mass\ of\ fuel} \quad (4)$$

Stoichiometric Air-fuel ratio, $A/F = \frac{524.23}{99.3102}$ = 5.28/1

Hence, the stoichiometric air-fuel ratio, A/F is 5.28/1

For wet base analysis:

If the products of combustion are:

3.86kmol CO_2 + 2.795kmol H_2O + 0.003125kmol SO_2 + 3.810625kmol O_2 + 14.36735833kmol N_2

Therefore, the total amount of substance of wet products:
= 3.86 + 2.795 + 0.003125 + 3.810625 + 14.36735833 = 24.83610833kmol

Equation (5) was used to determine the percentage composition of the gases.

$$\% \text{ composition of component} = \frac{\text{Amount of substance of component}}{\textit{Total amount of substance of all component}} \quad (5)$$

Using Equation (5), the percentage composition of wet gases is shown in Figure 1. The carbon dioxide gas (CO_2) is 15.54%, water vapour (H_2O) is 11.25%, sulphur dioxide gas (SO_2) is 0.013%, oxygen (O_2) gas is 15.34% and nitrogen (N_2) gas is 57.85%.

From the percentage composition of wet gases in the PKS pellets as shown in Figure 1, the exhaust gases in focus is the amount of water vapour and sulphur oxide present during combustion of the fuel pellets. This is so in order to determine whether the fuel pellet is suitable for combustion in boiler. Bureau of energy efficiency reported that excess amount of sulphur (0.5% above) in fuel causes high rate of corrosion in boilers. Thus, the results showed that the sulphur oxide in the PKS pellets is very low and good enough for combustion in boilers. Therefore, at 0.013% exhaust sulphur oxide, the water vapour is 11.25%.

For dry base analysis:
The total amount of substance of dry products:
= 3.86 + 0.003125 + 3.810625 + 14.36735833 = 22.04kmol
Using Equation (6), the percentage composition of dry gases is shown in Figure 2. The carbon dioxide gas (CO_2) is 17.5%, sulphur dioxide gas (SO_2) is 0.014%, oxygen (O_2) gas is 17.29% and nitrogen (N_2) gas is 65.18%.

Figure 2 show the percentage composition of dry gases in the PKS pellets. The only exhaust gas in focus here is the amount of sulphur oxide present in the exhaust gases in the absence of water vapour. Thus, the results showed that on dry basis, the percentage composition of sulphur oxide in the PKS pellets during combustion would increase to 0.014% which is also very low and good enough for combustion in boilers.

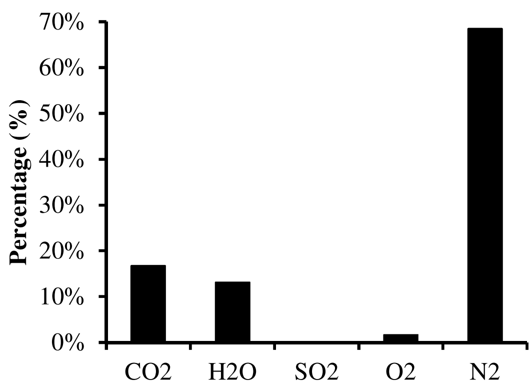

Figure 1: Percentage composition wet gases for PKS pellets

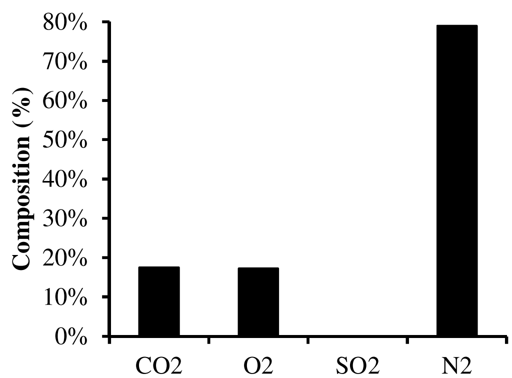

Figure 2: Percentage composition of dry gases for PKS pellets

3.2.2. Combustion performance analysis of PF fuel pellets

Using the combustion performance procedures in section 3.2.1, the data obtained from analysis of PF pellet $[C_{3.325}H_{5.4}O_{3.055}N_{0.1436}S_{0.00375}]$, is shown in Table 5. The stoichiometric equation is given by:

$$C_{3.325}H_{5.4}O_{3.055}N_{0.1436}S_{0.00375} + x_2\,[O_2 + (79/21)N_2] \rightarrow p_2CO_2 + q_2H_2O + r_2SO_2 + [t_2 + x_2\,(79/21)]N_2 \quad (6)$$

Table 5: Summary of analysis for PF fuel pellets

Parameters analysed	PF Fuel Pellets
$[x_2, p_2, q_2, r_2, t_2]$	$[3.15125, 3.325, 2.7, 0.00375, 0.0718]$
Mass of air required (O_2 and N_2) (kg)	434.74
Mass of reactants (kg)	531.19
Mass of products (kg)	531.16
Total amount of substance of wet products (kmol)	21.11
Total amount of substance of dry products (kmol)	18.41
Theoretical air required for combustion of 1kg PF fuel	96.31
Stoichiometric A/F ratio	4.514/1

For wet base analysis:

Using Equation (5), the percentage composition of wet gases is shown in Figure 3. The carbon dioxide gas (CO_2) is 15.75%, water vapour (H_2O) gas is 12.79%, sulphur dioxide gas (SO_2) is 0.018%, oxygen (O_2) gas is 14.93% and nitrogen (N_2) gas is 56.51%. The results showed that the sulphur content in the PF pellets is again very low and good enough for combustion in boilers. Figure 3 show the percentage composition of wet gases in the PF pellets. Also, the exhaust gases in focus here is the amount of water vapour and sulphur oxide present during combustion of the fuel pellets. Thus, the result showed that the sulphur oxide in the PF pellets at 0.018% with percentage water vapour of 12.79%. This is greater than that of the PKS exhaust sulphur oxide and water vapour.

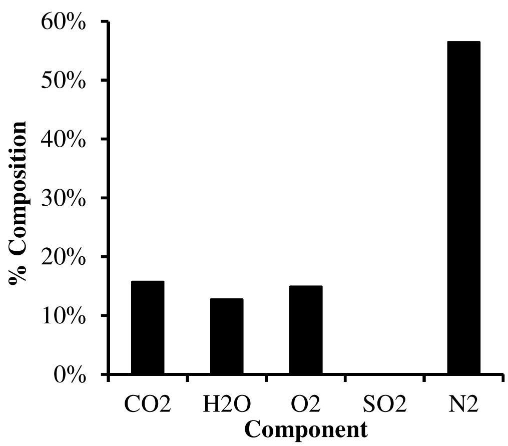

Figure 3: Percentage composition of wet gases for PF

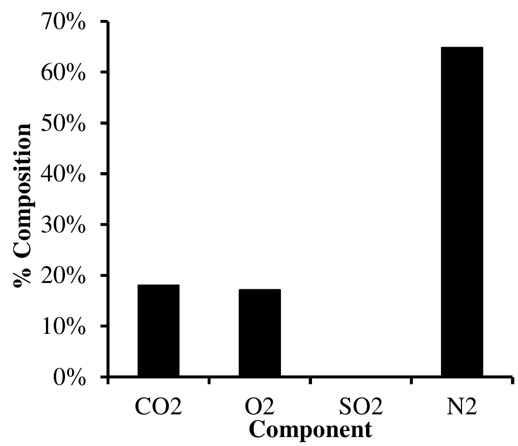

Figure 4: Percentage composition of dry gases for PF

For dry base analysis:

Again, from Equation (5), the percentage composition of dry gases for the PF pellets is shown in Figure 4. The carbon dioxide gas (CO_2) is 18.06%, sulphur dioxide gas (SO_2) is 0.02%, oxygen (O_2) gas is 17.12% and nitrogen (N_2) gas is 64.80%. Figure 4 show the percentage composition of dry gases in the PF pellets. Again, the only exhaust gas in focus here is the amount of sulphur oxide present in the exhaust gases in the absence of water vapour. The results showed that on dry basis, the percentage composition of sulphur oxide in the PF pellets during combustion is 0.02% without water vapour. This increases the percentage composition in other gases.

3.3.3. Combustion performance analysis of EFB fuel pellets

Also, using the combustion performance procedures in section 3.2.1, the data obtained from analysis of EFB pellet $[C_{3.58}H_{5.27}O_{2.973}N_{0.032}S_{0.003125}]$ is shown in Table 6. The stoichiometric equation is given by:

$$C_{3.58}H_{5.27}O_{2.973}N_{0.032}S_{0.003125} + x_3\,O_2 \rightarrow p_3CO_2 + q_3H_2O + r_3SO_2 + t_3NO_2 \quad (7)$$

Table 6: Summary of analysis for EFB fuel pellets

Parameters	Data
$[x_3,\ p_3, q_3, r_3, t_3]$	3.414625, 3.58, 2.635, 0.003125, 0.016
Mass of air required (O_2 and N_2) (kg)	469.35
Mass of reactants (kg)	565.68
Mass of products (kg)	565.23
Total amount of substance of wet products (kmol)	22.49
Total amount of substance of dry products (kmol)	19.86
Theoretical air required for combustion of 1kg PF fuel	477.34
Stoichiometric A/F ratio	4.873/1

For wet base analysis:

Using Equation (6), the percentage composition of wet gases is shown in Figure 5. The carbon dioxide gas (CO_2) is 15.92%, vapour (H_2O) gas is 11.71%, sulphur dioxide gas (SO_2) is 0.014%, oxygen (O_2) gas is 15.18% and nitrogen (N_2) gas is 57.18%. The results showed that the sulphur content in the EFB pellets is also very low and good enough for combustion in boilers.

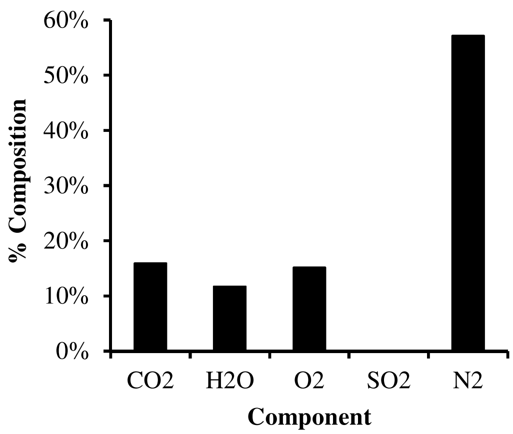

Figure 5: Percentage composition of wet gases of EFB

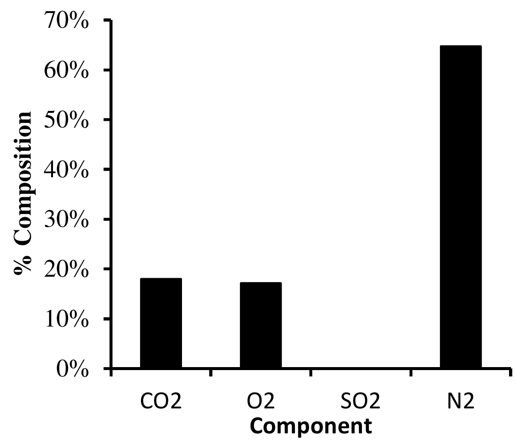

Figure 6: Percentage composition of dry gases of EFB

Figure 5 show the percentage composition of wet gases in the EFB pellets. Also, the exhaust gases in focus here is the amount of water vapour and sulphur oxide present during combustion of the fuel pellets. Thus, the result showed that the sulphur oxide in the EFB pellets also at 0.014% with percentage water vapour of 11.71%. This is also very low and good enough for combustion in boilers.

For dry basis analysis:

Also, from Equation (6), the percentage composition of dry gases for the EFB pellets is shown in Figure 6. The carbon dioxide gas (CO_2) is 18.03%, sulphur dioxide gas (SO_2) is 0.016%, oxygen (O_2)

gas is 17.19% and nitrogen (N_2) gas is 64.76%. Figure 6 show the percentage composition of dry gases in the EFB pellets. Again, the only exhaust gas in focus here is the amount of sulphur oxide present in the exhaust gases in the absence of water vapour. The results also showed that on dry basis, the percentage composition of sulphur oxide in the EFB pellets during combustion is 0.016%. This again increases the percentage composition in other gases.

4. CONCLUSION

Considering the percentage durability and combustion tests of the various pellets, 80R:20B was adjudged the best percentage mixing ratio due to its higher percentage durability than the 90R:10B mixing ratio even though both have good sustainability during combustion in the boiler. Combustion analysis shows that the chemical formulas for the pellets from palm kernel shell (PKS), palm fibre (PF) and empty fruit bunch (EFB) are $C_{3.86}H_{5.59}O_{2.90}N_{0.0643}S_{0.003125}$, $C_{3.325}H_{5.4}O_{3.055}N_{0.1436}S_{0.00375}$, and $C_{3.58}H_{5.27}O_{2.972}N_{0.032}S_{0.003125}$ with stoichiometric A/F ratio of 5.28/1, 4.514/1 and 4.873/1 respectively. The wet and dry basis for the exhaust products from the combustion analysis also showed that sulphur dioxide (SO_2) for the pellets were very low with values ranging from 0.01% to 0.02%. The low SO_2 shows that the various pellets would not be harmful to boilers because low SO_2 will not results in a high rate of corrosion..

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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