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GASIFICATION OF OIL PALM EMPTY FRUIT BUNCHES (OPEFB) BRIQUETTES FOR BIO-SYNGAS PRODUCTION

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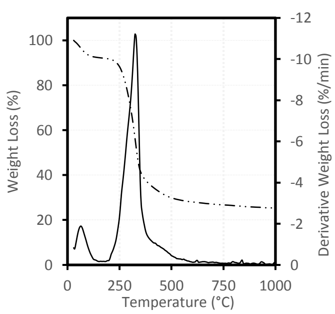
Graphical abstract



Abstract

Gasification of Oil Palm Empty Fruit Bunches (OPEFB) briquettes was investigated in an air blown 4.5 kW allothermal fluidized bed gasifier to examine the effects of bed temperature (600 – 800 °C) and equivalence ratio (λ = 0.25) on bio-syngas yield and composition. In addition, physicochemical and thermochemical characterization of the fuel properties of the OPEFB briquettes were also examined. The results demonstrate that pelletization improved the solid biomass fuel (SBF) properties of OPEFB including moisture content and higher heating value (HHV). The gasification of OPEFB briquettes produced bio-syngas comprising H_2, CO, CO_2, CH_4 as well as solid biochar with a HHV higher than the original OPEFB briquettes. The highest yield of H_2 was obtained at 600 °C while HHV of the bio-syngas was within the range 4 - 8 MJ/Nm^3 for air gasification in fluidized bed gasifiers. In addition, agglomeration of bed materials did not occur during OPEFB briquettes gasification despite its high bed agglomeration potential (BAP). In conclusion, the gasification of OPEFB briquettes into bio-syngas and biochar is a practical route for bioenergy production in Malaysia.

Keywords: Gasification, pelletization, oil palm, empty fruit bunches, bio-syngas.

Abstrak

Pengegasan Oil Palm Buah Tandan Kosong (OPEFB) briket disiasat di udara ditiup 4.5 kW allothermal gasifier katil fluidized. Kesan suhu katil (600-800 ° C) pada nisbah kesetaraan (λ = 0.25) pada hasil bio-syngas dan komposisi. Di samping itu, pencirian fizikokimia dan termokimia sifat-sifat bahan bakar briket OPEFB juga diperiksa. Keputusan menunjukkan bahawa pelletization meningkat bahan api keseluruhan pepejal biojisim (SBF) termasuk kandungan lembapan dan nilai pemanasan yang lebih tinggi (HHV). Pengegasan udara briket OPEFB dihasilkan bio-syngas terdiri H_2, CO, CO_2, CH_4 serta biochar kukuh dengan HHV lebih tinggi daripada briket OPEFB asal. Hasil tertinggi H2 telah diperolehi pada 600 C manakala HHV daripada bio-syngas adalah dalam had (4 - 8 MJ/Nm^3) untuk pengegasan udara di gasifiers katil fluidized. Di samping itu, katil penumpuan tidak dipatuhi semasa pengegasan OPEFB briket walaupun potensi penumpuan yang tinggi briket OPEFB. Kesimpulannya, keputusan menunjukkan bahawa pengeluaran bio-syngas dan biochar semasa pengegasan briket OPEFB adalah laluan praktikal untuk penaikan harga sisa ke dalam biotenaga di Malaysia.

Kata kunci: Pengegasan, pelletization, oil palm, buah tandan kosong, bio-syngas.

1.0 INTRODUCTION

The United Nations (UN) Conference on Climate Change has pledged to limit global warming to 2 °C by cutting greenhouse gas (GHG) emissions from 46 billion tons to zero within 50 years. The Paris Agreement plans to stimulate fossil fuels divestment by switching to nuclear power and renewables mainly solar, wind and biomass [1]. Biomass is one of the most practical sources of renewable fuels for the future. The deployment of biomass as a sustainable alternative to fossil fuels can potentially ensure the transition to clean energy [2, 3]. Biomass utilization, typically involves valorization of agricultural waste, forest residues, and energy crops, presents significant opportunities for clean energy and power generation [4]. In Malaysia, the large quantities of oil palm waste (OPW) generated annually present significant bioenergy potentials [5, 6]. Hence, several studies have examined the solid biomass potentials of OPW such as oil palm empty fruit bunches (OPEFB) [7, 8], palm kernel shells (PKS) [9, 10], palm fronds (OPF) [11, 12] through various characterization techniques [13, 14]. Due to its high fraction, thermochemical conversion of OPEFB through pyrolysis [15-18], hydrothermal conversion [19], torrefaction [20, 21], and gasification [13, 22, 23] is the focus of research groups.

However, the solid biomass properties of OPW including its bulky heterogeneous nature, high moisture content and low energy density presents problems for large scale commercial bioenergy projects. Consequently, research efforts have been invested in pretreatment of OPW through drying, pelletization, torrefaction, and hydrothermal treatment for integration into existing biomass conversion technologies. Among these, fluidized bed gasification is considered the most promising technology for the conversion of OPW into clean, renewable bio-syngas for future energy applications. However, high temperature gasification of pulverized OPEFB results in bed agglomeration, defluidization, tar formation and poor quality bio-syngas [13, 22-24]. However, these challenges can be potentially addressed by improving OPEFB fuel quality, gasifier operation and process design. These potential solutions can effectively exploit the dynamics of mass and heat transfer in fluidized bed gasification of OPEFB for efficient bio-syngas production.

Therefore, this study proposes modifying fuel properties of OPEFB through pelletization and low temperature gasification between 600 – 800 °C in an in-house designed 4.5 kW allothermal gasifier. This could potentially minimize bed agglomeration and increase the quality of bio-syngas. In addition, the paper presents a comprehensive biomass characterization of pelletized oil palm empty fruit bunch (OPEFB) using ultimate, proximate, calorific value analysis. Lastly, the solid biofuel potential of OPEFB pellets as a feedstock for bioenergy production will also be highlighted.

2.0 METHODOLOGY

The oil palm empty fruit bunch (OPEFB) briquettes were acquired from Felda Semenchu Oil Palm Mill in Kota Tinggi, Johor, Malaysia. Prior to characterization, the OPEFB briquettes were pulverized and sifted using an analysis sieve of mesh size 60 (Retsch™ D-42759, Haan Germany) to obtain homogeneous particles below 250 μm.

Next, the pulverized sample was characterized by ultimate, proximate and bomb calorific analyses. Metal oxide composition was examined by X-ray Fluorescence (XRF) spectroscopy, after ashing at 950° C, to examine the bed agglomeration potential (BAP) from the alkali index in Eq. 1 & 2 [25];

$$\frac{K_2O + Na_2O}{SiO_2} > 1 \tag{1}$$

$$\frac{K_2O + Na_2O}{HHV} > 0.34 \tag{2}$$

The thermal decomposition behaviour of OPEFB briquettes was examined using the Netzsch 209 F3 Tarsus Thermogravimetric (TG) analyser. For each run 10 mg of pulverized OPEFB briquette was heated at 15 °C/min in an alumina crucible from 30 – 1000 °C under nitrogen gas (flowrate 50 mL/min) atmosphere. The resulting thermograms were subsequently analysed with the proprietary Netzsch TGA software, Proteus (v.6.1) to determine the weight loss (%) – time/temperature curves, and temperature profile characteristics (TPC).

After characterization, the OPEFB briquettes fuel was gasified at atmospheric pressure in a 4.5 kW air blown, allothermal heated bubbling fluidized bed gasifier using air and silica sand as gasifying agent and medium, respectively. Gasification was carried out from 600 – 800 °C and equivalence ratio *ER*, λ = 0.25 to investigate the effect of the gasification parameters on bio-syngas yield and composition. The detailed gasifier design, specifications and materials selection is outlined in our previous studies [24, 26].

For each run, the gasifier was loaded with 1.10 kg of silica sand and heated to 500 °C by electrical heaters operating at a heating rate of 50 °C /min. At the required temperature, the air compressor (3 hp) and the fuel feeder were switched on to load the OPEFB briquettes and air (fluidizing gas (at λ = 0.25) into the gasifier at federate of 0.9 kg/hr. The introduction of air into the gasifier triggered fluidization of the bed materials and fuel leading in the production of bio-syngas.

The evolved bio-syngas mixture was collected in Tedlar® gas sampling bags and analysed by gas chromatography (GC) (Agilent 6890N Network GC system) equipped with thermal conductivity detector (TCD). The results were computed and presented in mol. %. The effect of bed agglomeration during gasification was assessed by examining the spent silica sand and waste char produced after gasification.

3.0 RESULTS AND DISCUSSION

3.1 Chemical Fuel Properties

Table 1 presents the bed agglomeration potential (BAP) of the OPEFB fuels determined from their alkali metal oxide compositions. The comparative analysis of the fuel properties of OPEFB briquettes and OPEFB fuel are presented in Table 2. The results demonstrate that pelletization improves its properties based on the significant difference in the elemental and the heating value of the fuels. However, the differences could also be due to the time of planting, harvesting, or soil characteristics of the oil palm fresh fruit bunches or pretreatment of the OPEFB fuels.

Table 1 Bed agglomeration potential of OPEFB briquettes

Biomass Fuel	Bed Agglomeration Index (> 0.34)	Bed Agglomeration Index (> 1)	Ref.
OPEFB Briquettes	5.36	27.08	This Study
OPEFB	2.93	1.65	[22]
OPEFB	3.25	5.10	[13]

Table 2 Chemical Fuel Properties of OPEFB briquettes

Fuel Characterization	Element/Compound	Symbol	OPEFB briquettes [This Study]	OPEFB [22]
Ultimate Analysis	Carbon	C	45.14	43.52
	Hydrogen	H	6.05	5.72
	Nitrogen	N	0.54	1.20
	Sulfur	S	0.20	0.66
	Oxygen	O	48.08	48.90
Proximate Analysis	Moisture	M	8.11	7.80
	Volatile Matter	VM	72.10	79.34
	Fixed Carbon	FC	14.91	8.36
	Ash	A	4.89	4.50
	Higher Heating Value	HHV	17.57	15.22
Metal Oxide	Iron Oxide	Fe_2O_3	0.36	3.00
	Manganese Oxide	MnO_2	0.01	0.00
	Sodium Oxide	Na_2O	81.08	0.55
	Magnesium oxide	MgO	0.00	4.80
	Aluminum oxide	Al_2O_3	0.00	0.97
	Silicon Oxide	SiO_2	3.48	27.00
	Potassium Oxide	K_2O	13.12	44.00
	Calcium Oxide	CaO	1.92	8.00
	Titanium Oxide	TiO_2	0.02	0.08

Furthermore, the results indicate that OPEFB briquettes possess high potential for bed agglomeration. This is largely due to the significantly high concentration of sodium oxide (Na_2O) and low potassium oxide (K_2O) composition as reported in Table 2. Bed agglomeration arises due to clinker formation resulting from the high temperature of alkali metal oxides and silica sand during gasification. The eutectic mixture of silicates formed modifies the particle size distribution of gasifier bed materials resulting in hot spots and ultimately defluidization during gasification.

Hence, it can be inferred that the high composition of alkali metal oxides in the OPEFB briquettes could potentially result in bed agglomeration, clinker formation and inefficient gasification. However this can be addressed by pre-treatment of OPEFB briquettes to lower alkali metal oxide content.

3.2 Thermal Fuel Properties

The thermal decomposition behaviour of OPEFB briquettes was examined from 30 – 1000 °C under inert atmosphere at 15 °C/min. The TG-DTG weight and derivative weight loss curves are presented in Figure 1. The TG curves revealed the downward sloping weight loss curves typically observed in thermally decomposition materials [5, 27].

The DTG curves revealed two endothermic peaks from 50-150 °C and 150 – 600 °C denoting the process of drying and devolatization, respectively. Drying is typically ascribed to loss of water and low molecular weight compounds. However, devolatilization is reportedly due to the decomposition of holocellulose and lignin [27]. Hence, thermal decomposition of OPEFB briquettes occurs in three (3) stages; drying, devolatilization and char decomposition (600 -1000 °C).

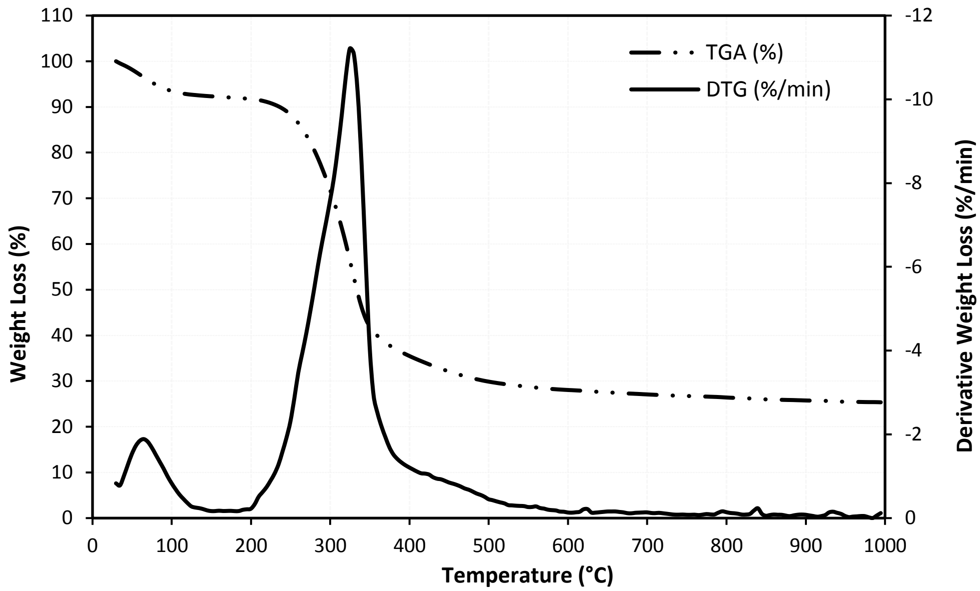


Figure 1 TG-DTG profiles of OPEFB Briquettes at 15 °C min from RT-1000 °C

The temperature profile characteristics (TPC); onset temperature T_{on}, peak decomposition temperature T_{max}, burn out temperature T_{end}, and residual mass R_m were deduced from the TG-DTG curves.

The T_{on} was observed at 275.40 °C; indicating devolatization commenced above 250 °C. The maximum decomposition of the fuel T_{max} was observed at 326.40 °C. Finally, the burn out temperature, T_{end} was observed at 363.60 °C with a residual mass R_m = 25.35 %. The results showed that the pyrolytic thermal decomposition of the fuel from 30 – 1000 °C resulted in 74.65 % decomposition.

3.3 Gasification Results

The air gasification of OPEFB briquettes was carried out in a bubbling fluidized bed gasifier at 600 – 800 °C, equivalence ratio, λ = 0.25 and atmospheric pressure. Table 3 presents the product gas composition of OPEFB briquettes H_2, CO, CO_2, CH_4, ethene and ethylene.

Table 3 Gas composition for OPEFB Briquettes Gasification

Gasification Temperature (°C)	Gas Composition (mol. %)					
	H_2	CO	CH_4	CO_2	C_2H_4	C_2H_4
600	4.35	3.20	1.73	13.70	1.49	0.73
700	3.11	6.27	1.06	10.88	1.00	0.38
800	4.21	2.94	1.89	14.26	1.31	0.81

As observed in Table 3, the composition of H_2, CH_4, C_2H_4 and C_2H_6 decreased at 700 °C but improved with increase in temperature to 800 °C. This can be attributed to the effect of temperature on the endothermic reactions of biomass gasification. In addition, the results confirm the importance of temperature during gasification. Similar results were reported for H_2 yield by *Lahijani & Zainal* [22].

However, the results for the other gases appears to differ from the trend observed for pulverized OPEFB biomass in literature. However, this is due to the effect of the large particle size of the OPEFB briquettes due to pelletization which results in low product gas composition. This is corroborated by the findings of *Lv et al.*[28], which showed that carbon conversion and product gas composition decreases with increase in particle size during biomass gasification. Hence, the mechanism for thermal decomposition is based on heat and mass transfer and not kinetics as typically observed for small particle sized biomass. In addition, the average higher heating value of bio-syngas was 5 MJ/Nm^3 which is within the range 4 - 8 MJ/Nm^3 typically reported for biomass gasification in fluidized bed gasifiers. Similar results have been reported in literature [13, 22, 28].

Furthermore, OPEFB briquettes gasification resulted in the production biochar (Figure 2b) with a higher heating value HHV of 24.50 MJ/kg. The biochar HHV is significantly higher than the original OPEFB briquettes HHV = 17.57 MJ/kg presented in Table 2.

Figure 2a Oil palm Empty Fruit Bunch (OPEFB) briquettes.

Figure 2b Biochar of OPEFB briquettes after gasification

Furthermore, the HHV of the OPEFB briquettes biochar falls with the range 19.72 - 26.24 MJ/kg reported for torrefied OPEFB briquettes [29]. This suggests that despite the low gas yield, gasification of OPEFB briquettes is an economically viable process due to the production of high calorific value biochar.

In conclusion, analysis of spent bed materials after gasification revealed bed agglomeration did not occur as reported for pulverized OPEFB despite the high bed agglomeration potential (Table 2). This may be due to the low gasification temperatures (600 – 800 °C) used in the study. However, analysis of the bed materials after gasification showed considerable bleaching of the silica sand from light brown to white coloration. This may be due to the adsorption of magnesium and iron oxides, responsible for the silica sand coloration, by the OPEFB briquettes biochar. However this requires further investigation to understand the process.

4.0 CONCLUSION

This paper was aimed at investigating the air gasification of Oil Palm Empty Fruit Bunches (OPEFB) briquettes for bio-syngas production using a bubbling fluidized bed gasifier. The characterization of the physicochemical and thermochemical properties of the OPEFB briquettes was also examined. The results demonstrated that pelletization can improve the solid biomass fuel (SBF) properties including moisture content and higher heating value. The gasification of OPEFB briquettes yielded gaseous products (bio-syngas) comprising H_2, CO, CO_2, CH_4 and low molecular weight hydrocarbons as well as solid (biochar) products. In addition, the agglomeration of bed materials was not observed during the OPEFB briquette gasification. In conclusion, the results suggest that the production of bio-syngas and biochar during the pelletized OPEFB gasification is a practical route for OPW valorization in Malaysia.

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