Thermochemical analysis of Palm Oil Wastes as fuel for Biomass Gasification

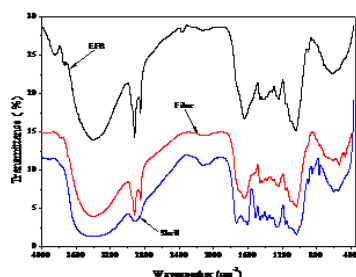Bemgba Bevan Nyakuma[a*], Anwar Johari[a], Arshad Ahmad[a]

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Graphical abstract

Abstract

The production of palm oil in Malaysia generates large quantities of solid waste annually. A small fraction is currently utilized for steam and electricity production in palm oil mills. However, a large fraction is openly combusted or incinerated resulting in increased greenhouse gas (GHG) emissions. Gasification is considered to be a promising technology for converting bio waste into clean energy. It involves the partial oxidation of carbonaceous materials into gaseous products at high temperatures. This study is aimed at evaluating the thermal and physical properties of EFB, Shell and Fibre palm oil waste as gasification fuel. This is vital for the design, optimization and operation of biomass gasifiers. Consequently, the heating value (HHV), specific heat (c), combustion rate (C_R), combustion heat (Q) of the wastes were determined. The results showed that the c, C_R, Q displayed an increasing trend in the order EFB, Shell and Fibre. Furthermore, c, C_R, Q were significantly influenced by the organic and mineral content of the fuels. The results for heating value were EFB 17.97 MJ/kg, Fibre 18.71 MJ/kg and Shell 19.07 MJ/kg.

Keywords: Biomass; palm waste; gasification; fuel properties; combustion; calorific value

Abstrak

Pengeluaran minyak sawit di Malaysia menjana kuantiti besar sisa pepejal setiap tahun. Walaupun sebahagian kecil digunakan untuk menghasilkan stim dan penghasilan tenaga elektrik di kilang minyak sawit, sebahagian besar dibakar secara terbuka dan ini mengakibatkan peningkatan penghasilan gas rumah hijau (GHG). Pengegasan adalah satu teknologi yang dapat menangani masalah sisa pepejal ini kepada penghasilan tenaga bersih. Proses ini melibatkan pengoksidaan separa bahan karbon kepada produk gas pada suhu tinggi. Kajian ini bertujuan untuk mengkaji sifat-sifat termal dan fizikal Tandan *(EFB)*, Tempurung *(Shell)* dan Sabut *(Fibre)* kelapa sawit sebagai bahanapi bagi proses pengegasan. Ini adalah penting bagi mereka bentuk, pengoptimuman dan operasi reactor biojisim. Oleh itu, nilai kalori (HHV), haba tentu (c), kadar pembakaran (C_R), haba pembakaran (Q) bahan buangan itu telah dianalisis. Dari keputusan, didapati bahawa peningkatan nilai-nilai C_p, C_R, Q adalah seperti berikut; Tandan *(EFB)* < Tempurung *(Shell)* < Sabut *(Fibre)*. Nilai kalori (HHV) Tandan *(EFB)* adalah 17.97 MJ/kg, Sabut *(Fibre)* adalah 18.71 MJ/kg dan Tempurung *(Shell)* adalah 19.07 MJ/kg.

Kata kunci: Biomas; sisa sawit; pengegasan; sifat bahan api; pembakaran; kalori

■1.0 INTRODUCTION

Palm oil production in Malaysia generates large quantities of waste annually. Estimates suggest up to 7 million tonnes of EFB, 4.5 million tonnes of palm fiber and 1.9 million tonnes of shell is generate yearly in the country [1]. A small fraction of this waste is currently utilized for steam generation, electricity production and agricultural applications [2, 3]. Conversely, a large fraction is simply combusted in open air, incinerators or used as landfill material [2, 4]. However, these conversion technologies are characterized by design and operational problems as well as low conversion efficiencies. This has resulted in increased carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions [4]. Therefore urgent solutions are required to effectively tackle the problems resulting from increased waste generated from palm oil production.

Gasification and pyrolysis are considered to be promising technologies for converting biomass waste into energy. Gasification is the thermochemical conversion of carbonaceous feedstock into gaseous products with a useable heating value [5,
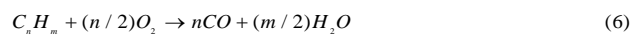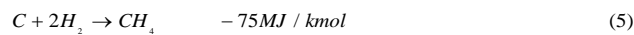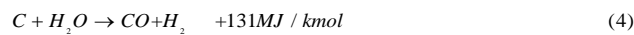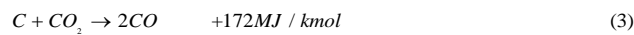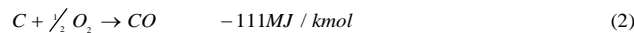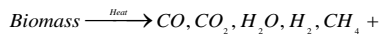
6]. It involves the partial oxidation of the feedstock at high temperatures (800 – 1800 °C) in the presence of a gasifying medium typically air, oxygen or steam [5]. The renewed interest in biomass gasification is largely due to increasingly high oil prices, declining global supplies and environmental concerns owing to overdependence on fossil based fuels [7].

However, the thermochemical utilization of biomass is considered to be an environmentally friendly route for the production of clean and sustainable fuels in the future [7-9]. The gasification of biomass is very efficient resulting in 97 % conversion of feedstock into syngas. Typically, biomass gasification occurs in four stages namely;

- Drying,
- Pyrolysis,
- Char gasification,
- Combustion.

The process of gasification takes place at high temperatures in specially designed equipment called gasifiers, typically classified according to the gasifying medium and gas-solid contacting mode [5, 8].

A summary of the major biomass gasification reactions are expressed in *equations 1-5*;

$$Biomass \xrightarrow{\quad Heat \quad} CO, CO_2, H_2O, H_2, CH_4 +$$

$$other (HCs) + tar + char + ash \qquad (1)$$

$$C + \tfrac{1}{2}O_2 \rightarrow CO \qquad -111 MJ/kmol \qquad (2)$$

$$C + CO_2 \rightarrow 2CO \qquad +172 MJ/kmol \qquad (3)$$

$$C + H_2O \rightarrow CO + H_2 \qquad +131 MJ/kmol \qquad (4)$$

$$C + 2H_2 \rightarrow CH_4 \qquad -75 MJ/kmol \qquad (5)$$

$$C_n H_m + (n/2)O_2 \rightarrow nCO + (m/2)H_2O \qquad (6)$$

Equations *2-5* represent combustion, Boudouard, water gas and methanation reactions respectively. Other reactions such as steam methane reforming (SMR) and water gas shift (WGS) also take place during gasification.

In practice, the thermal energy required to carry out biomass gasification is provided by exothermic combustion reactions. The exothermic reactions between the fuel and air/O_2 releases the heat required to drive the process of drying, pyrolysis and gasification. However, the product gas yield is dependent on the stoichiometry of the process and the partial oxidation of the volatile products as summarized in *eqn 6*.

Hence a detailed understanding of feedstock properties and operating parameters is vital for the design and operation of biomass gasifiers. The optimum operating conditions can be obtained either through trials or preliminary experiments [5].

This study is therefore aimed at evaluating the thermal and physical properties of palm oil waste as a fuel for gasification. The optimum operating conditions and values for heating value, calorific value, heat of combustion from gasification of the fuels will be analyzed.

■2.0 EXPERIMENTAL

The palm wastes used in this study include; Empty Fruit Bunches (EFB), palm shell and palm fibre. The samples were obtained from Felda Semenchu Sdn Bhd oil palm mill in Johor, Malaysia. The samples were dried and pulverised in a high speed crusher machine (Kimah Malaysia, Model RT 20) fitted with a 1 mm screen. The samples were analyzed using a Fourier Transform Infra-Red (FTIR) spectrophotometer (Model Perkin Elmer Spectrum One) and the FTIR spectra recorded from 4000 cm^{-1} to 370 cm^{-1}. The heating value (HHV) of the fuels was determined by bomb calorimetry (Model C2000 IKA calorimeter system) according to ASTM standard D-2015. Proximate analysis was carried out to determine moisture, ash, volatile matter and fixed carbon content of the fuels. Subsequently 1 g of each sample was weighed, placed in a 100 ml ceramic crucible and heated at 600°C for 60 minutes in a Carbolite furnace. This provides an alternative method for studying the thermal behavior of fuels feedstock in relation to thermal gravimetric analysis (TGA). The selected thermal reaction parameters were chosen due to the following reasons [5];

- To ensure an average heating rate of 10°C per min for the fuels under investigation. The heating rate of biomass particles plays a vital role in the composition and yield of pyrolysis and gasification products.
- The optimal hydrogen yield and removal of alkali salts from biomass gasification takes places at or above 600°C.
- The optimum temperature for primary pyrolysis and other gasification reactions such as the co-firing of gasified biomass and supercritical water gasification occur at 600 °C.

At the end of each reaction, the samples were cooled to room temperature in a desiccator and weighed to compute the total mass of fuel burnt. Consequently, the heat released during gasification, *Q*, the combustion rate, C_R, and specific heat capacity, *c*, for each fuel sample was computed using *eqns 7-9*. The calculated heating rate is presented in *eqn 10*.

$$Combustion\ rate,\ C_R = \frac{Total\ mass\ of\ fuel\ burnt}{Burning\ time} \qquad (7)$$

$$Heat\ released,\ Q = Calorific\ Value\ x\ Combustion\ Rate \qquad (8)$$

$$Specific\ heat\ capacity,\ c = \frac{Q}{m\Delta T} \qquad (9)$$

$$Heating\ rate,\ \beta = \frac{dT}{dt} \qquad (10)$$

Where *m*, mass of the fuel sample; *c*, is the specific heat capacity of the fuel; *ΔT* is the temperature change and *t*, time. In order to compute the experimental data for heat released during gasification, *Q*, the combustion rate, C_R, and specific heat capacity, *c*, the following assumptions are taken into consideration;

i. Gasification occurs *via* partial oxidation through the reaction of the biomass feedstock with limited air in the crucible, thereby functioning as a micro-fixed bed reactor.

ii. Gasifying medium is air and inherent moisture in the biomass feedstock.

iii. The gasification reactions; drying, devolatization and gasification are all assumed to take place in crucible.

iv. Direct heating is employed to heat the feedstock in the crucible during gasification.

■3.0 **RESULTS AND DISCUSSION**

3.1 Fourier Transform Infra-Red Spectroscopy (FTIR)

This is qualitative technique used to determine the functional group and elemental composition of materials. It is a vital technique for predicting the product composition and distribution during thermochemical conversion of biomass [10]. The FTIR analyses of the fuels were determined by Fourier Transform Infra-Red Spectroscopy (FTIR) spectroscopy as presented in Figure 1. This was used to determine the functional groups present in each fuel and hence predict the gaseous products of the thermochemical reactions.
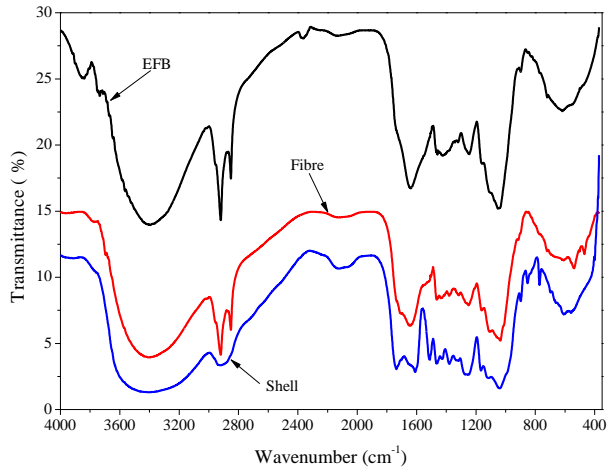

Figure 1 FTIR spectra of EFB, Fibre and Shell

The FTIR spectra of the fuels showed identical functional groups for the fuels as depicted in Figure 1. The broad O-H stretching vibration between 3200 and 3600 cm^{-1} indicate the presence of alcohols. The medium intensity band observed at 2368 cm^{-1} is due to nitrile C-N functional group indicating nitrogen is present in the fuels.

The strong intensity bands observed for the EFB and Fibre samples in the region 2800 and 3000 cm^{-1} are typical of C-H stretching vibrations found in CH_2 and CH_3, and the C-H deformation vibrations usually observed between 1350 and 1475 cm^{-1} for olefins. The presence of C=O stretching vibrations typical of ketones and aldehydes was observed between 1600 and 1750 cm^{-1}. Furthermore, ether groups may be responsible for the broad bands observed between 1000 and 1300 cm^{-1}.

3.2 Physical Properties

The thermochemical properties of the fuels are presented in Table 1. The results indicate the fuel samples have a high content of volatile matter (>80 %), low moisture content (<10 %) and low fixed carbon content (<10 %). The ash content of the fuels indicates that the shell sample will be least susceptible to the problem of slagging in a gasifier.

Table 1 Physical and thermal properties of EFB, Shell and Fibre

Fuel	Moisture M_{ad}	Volatile Matter V_{ad}	Ash, A_d	Fixed Carbon FC_{ad}	VM/FC	HHV (MJ/kg)
EFB	8.43	82.53	4.97	4.08	20.22	17.97
Shell	5.68	80.65	4.09	9.58	8.42	19.07
Fibre	7.17	81.83	4.56	6.44	12.71	18.71

Subscripts: "ad", air-dried basis; "d", dry basis

The HHV value of the fuels showed the trend Shell > Fibre > EFB which can be attributed to the increasing volatile matter, fixed carbon content and decreasing moisture content of the fuels. In general the low HHV values can be attributed to the low fixed carbon content observed during proximate analysis. The volatile matter to fixed carbon ration of the fuels is > 4.0 which is consistent with other biomass fuels observed in literature [5, 7].

3.3 Thermal Properties

The combustion rate, C_R, specific heat capacity, c, and the heat released, Q, during gasification in the furnace are presented in Table 2. From the heat released Q, the specific heat (J/kgK) can be calculated from *eqn 9*.

Table 2 Combustion characteristics of EFB, Shell and Fibre

Fuels	Combustion Rate, C_R (x 10^{-8} kg/s)	Heat Released, Q (J/g)	Specific Heat, c (J/kg K)
EFB	3.83	2472.74	2832.46
Shell	3.96	2718.29	3113.74
Fibre	4.19	2820.90	3231.28

The results indicate the heat released from gasification was between 2.4 and 2.8 kJ/g with heat capacities in the range from 2.8 to 3.2 kJ/kg K at the given reaction temperature. Consequently, the combustion rate, C_R, Q and c was observed to be in the order;

$$\xrightarrow{\substack{EFB,\ Shell,\ Fibre \\ increasing\ \ C_R,\ Q,\ c}}$$

This may be due to factors such as the particle size, reaction temperature, heating rate and the organic and inorganic composition of the fuels. The heating rate and reaction temperature in this study were set at 10 °C/min and 600 °C respectively. The structure and composition of biomass on the other hand, is a natural property of biomass.

Biomass generally consists of organic materials and inorganic minerals such as carbohydrates, fats, proteins, sodium, phosphorus, calcium, iron and ash. However the three main organic components are: hemicellulose, cellulose and lignin [5]. Table 3 presents an overview of the constituent composition and decomposition temperatures of palm waste.

Table 3 Chemical components of EFB, Shell and Fibre [5][11-13]

Fuels	Hemicellulose	Cellulose	Lignin
EFB	35.3	38.3	22.1
Shell	22.7	20.8	50.7
Fibre	31.8	34.5	25.7
Temperature (°C)	150–350	275–350	250–500

At the reaction temperature of 600 °C, it is assumed that all the organic components; hemicellulose, cellulose and lignin (HCL) of fuels are completely combusted. Therefore, at the selected reaction temperature and heating rate, the decomposition of the organic components of the fuel feedstock may be responsible for the values of C_R, and Q obtained during gasification. From the Table 4, it can be observed that the total organic constituent HCL for the fuels is 95.70, 94.20, and 92.00 for EFB, Shell and Fibre respectively.

Table 4 Comparison of biomass components with combustion of EFB, Shell and Fibre

Fuels	Organic Content	Inorganic Content	Combustion Rate, C_R (x 10^{-8} kg/s)	Heat Released, Q (J/g)
EFB	95.70	4.30	3.83	2472.74
Shell	94.20	5.80	3.96	2718.29
Fibre	92.00	8.00	4.19	2820.90

Adapted from Tables 2 & 3.

The observed trend in table 4, computed from [5][11-13], suggest that high HCL content in biomass fuels will result in lower combustion rates and heat released during thermal conversion. Furthermore, the C_R and Q values observed in Table 4 may be also due to the catalytic effect of the inorganic components present in the fuels. Similar results have been reported for unwashed and washed biomass samples which contain a small or zero percentage of inorganics like ash [14-16]. The inorganic components found in biomass samples include alkalis, chlorine, silicates etc.

■4.0 CONCLUSION

T The thermal and physical properties of EFB, Shell and Fibre palm oil waste were determined in this study. The results showed that the heating value (HHV), specific heat (c), combustion rate (C_R), combustion heat (Q) showed an increasing trend in the order; EFB, Shell and Fibre. The observed trend in the samples was significantly influenced by the organic and mineral content of the fuels. The heating values indicate that palm wastes can be effectively utilized as fuels for biomass gasification.

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