A Comparative Study On The Heat Release During The Combustion Of Coal And Oil Palm Biomass Charcoal Briquette Via Thermogravimetric Analysis (TGA)

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Abstract

The world is seriously searching for an alternative to fossil fuels due to their tremendous environmental effect. However, renewable energy sources such as solar, wind, hydropower, and biomass were anticipated to be alternative energies. In this study, the amount of heat generated from the combustion of coal and charcoal briquettes derived from oil palm biomass was investigated and compared. Charcoal briquettes were made from the biochar obtained after the pyrolysis of empty fruit bunches (EFB) and mesocarp fibre (MF). Coal and charcoal briquettes were subjected to combustion via thermogravimetric analysis (TGA) at a 10ºC min^{-1} heating rate to a maximum temperature of 850ºC. The ignition and burnout temperatures were 235ºC and 675ºC for EFB, 254ºC and 788ºC for MF, and 368ºC and 770ºC for coal. The maximum heat released 0.06 W was obtained from EFB charcoal briquette followed by 0.05 W and 0.04 W from coal and MF charcoal briquette, respectively. This finding indicated that charcoal briquettes derived from oil palm biomass (EFB) could be one of the potential solid fuels that can be used for coal replacement.

Keywords: biomass, heat release, combustion, coal, charcoal briquette, TGA

Introduction

Fossil fuels still controlled the world's energy market value of about 1.5 trillion dollars. For example, the World Energy Council (WEC) in 2007 estimated recoverable coal mineral deposits of about 850 billion tons in 2006 [1]. However, the quantity of CO_2 in the atmosphere will persist in increasing unless crucial modifications are made in the manner fossil fuels are utilized in the energy production [2]-[3]. Renewable energy sources such as small hydropower, solar, wind, geothermal and biomass have presently contributed 14% of total world energy consumption, of which 62% is biomass [4].

It is known that biofuels burning does not add to the greenhouse effect because of the CO_2 neutral conversion thanks to the renewability of biomass. The emphasis on bioenergy as a substitute for fossil energy has expanded colossally lately, considering the abnormal weather changes starting from fossil powers ignition. Along these lines, extensive investigations have been completed globally to improve biomass use for energy generation [5].

Internationally, Malaysia is known as the global second-biggest manufacturer and the most significant oil palm exporter of about 17.7 million tons or a 41.3% portion of the total world oil palm manufacture in 2008 [6]-[7]. However, this resulted in the production of a large quantity of biomass from oil palm industries. It has been declared that in the year 2012, there were profitable oil palm wastes (dry weight) of about 83 million tonnes in Malaysia. And, it will eventually ascend to 100 million tonnes in a few years to come, 2020 [8]. In 2009, the oil palm wastes rendered in Malaysia were 7.0 million tonnes of empty fruit bunch (EFB), 11.6 million tonnes of palm kernel shell (PKS) and mesocarp fibre (MF), 44.8 million tonnes of fronds and 13.9 million tonnes of trunks. However, the eminent expected utility of these wastes is assumed to be circumscribed [8]. These wastes will continue to contribute to the agricultural wastes disposal problem in Malaysia except necessary action being taken to bring out the best in them as fuel. Between the oil palm biomass, mesocarp fibre contains a high calorific value in comparison with palm shell and EFB [9].

Several studies have been conducted to investigate the thermal decomposition of biomass during pyrolysis via thermogravimetric analysis (TGA). TGA is used because it is the usual technique for the kinetic analysis of the devolatilization process [10]. Besides, TGA is typically used to study the solid-phase thermal degradation mechanisms and derive the kinetic parameters [11]. It was reported that the pyrolysis characteristics of rubber residuals such as rubber seed shell and high-density polyethylene can be studied using non-isothermal thermogravimetric analysis [12]. Furthermore, the catalytic co-pyrolysis behaviour, kinetics and product distribution of spirulina and oil shale can also be studied via thermogravimetric analysis and pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS) [13]. The kinetic parameters such as activation energy (E) and pre-exponential factor could be predicted by applying the model-free iso

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conversion methods of Kissinger-Akhira-Sunose (KAS) and Flynn-Wall-Ozawa (FWO) to the resulting thermogravimetric analyses [14].

Pyrolysis is one of the prominent thermochemical processes that convert biomass into high energy content biofuels [10],[15]. During thermal decomposition in pyrolysis, organic solids are transformed into combustible (tar), solids (biochar), and gases with a higher energy density than of the materials [16]. This process takes place in an inert environment, and the decomposition is based on a series of complex reactions that are controlled by main parameters like temperature, heating rate, pressure, residence time, moisture, size of particles and biomass composition in the material [10]. In this study, the amount of heat generated from the combustion of coal and charcoal briquettes derived from oil palm biomass (EFB and MF) was investigated and compared.

Experimental

Material

The oil palm waste was collected from Oil Palm mill located at Nibong Tebal, Pulau Pinang, Malaysia. The material received was relatively in a dry condition; it was, however, dried at 105ºC in an oven for 24 hours, and ground and sieved to 150 µm to 300 µm particle size. Sub-bituminous coal supplied by a company based in Sarawak, Malaysia.

Pyrolysis Setup

Pyrolysis experiment was performed at a temperature of 400ºC at a constant heating rate of 10ºC min^{-1} for 60 min reaction time. The volatile matter, fixed carbon and calorific value of the heated materials were measured and reported. The elaborated pyrolysis, elemental and proximate analysis procedures have been formerly depicted in previous studies [17]-[19]. Charcoal briquettes were made through the procedure previously reported in our article [20]. Figure 1 below illustrated the pyrolysis setup.

Briquetting is a process of compressing materials into a small portable size with a diameter ranging from 30 to 100 mm and of any length depending on the technology applied, which could either be screw or piston compression. The briquetting process is perhaps regarded as a way to improve the application of low-grade wastes materials. Briquetting is mainly used for compacting of biomass and none biomass sources such as plastic, many types of milled paper wastes and other combustible wastes [21].

Thermogravimetric analysis (TGA)

Thermogravimetric analysis (TGA) was performed on solid fuel. It was carried out at the School of Chemical Sciences, Universiti Sains Malaysia, using model Perkin Elmer STA 6000 thermogravimetric analyser. The analysis was carried out in the presence of nitrogen (N_2) gas at a flow rate of 80 ml/min and at of 10ºC min^{-1} heating rate. The samples were heated from ambient temperature to about 800ºC. The lignocellulosic compositions of the materials were measured according to the procedure prescribed by Li et al. [22]. With the known amount of total burnt briquette and burning time, the average combustion rate (CR) can be calculated by using following formula Equation (1). And, heat release computed with Equation 2 below [23].

$$\text{Combustion rate} = \frac{\text{total mass of burnt briquette}}{\text{burning time}} \ (\text{kg/s}) \qquad (1)$$

$$\text{Heat Release} = \text{Calorific value} \times \text{Combustion rate (W)} \qquad (2)$$

Results and Discussion

3.1 Physiochemical Properties of Oil Palm Wastes, Biochars and Coal

The results from the proximate, elemental and calorific value analysis of raw oil palm wastes, biochars, and coal are given in Table 1. The moisture, ash and fixed carbon contents were 3.30,

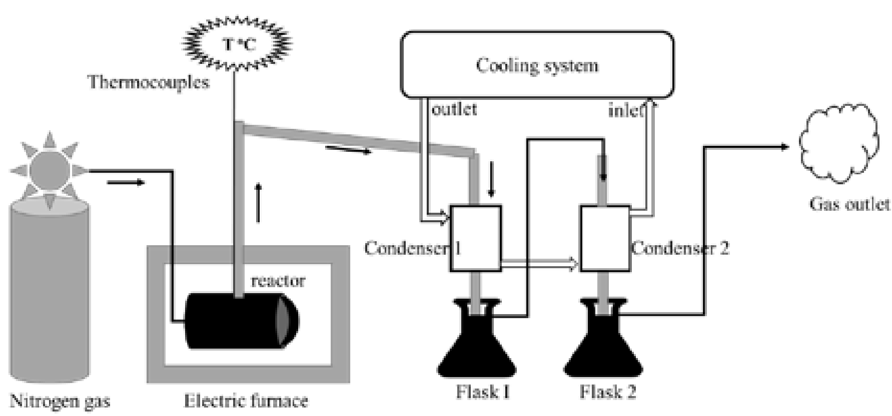

Figure 1 A schematic of the experimental system

6.21 and 9.09 wt% for EFB, 2.80, 5.02 and 15. 03 wt% for MF, and 2.01, 8.16 and 45.09 wt% for coal, respectively. The volatile matter content was between 41 to 81 wt%, whereby EFB has a high volatile matter than MF and coal. Relatively, similar results in (wt%) can be found in other work [24] for the same oil palm wastes. The biochar obtained from the pyrolysis of MF had shown a higher fixed carbon of 46.43 wt% than that of coal and EFB biochar. Jahirul et al. [25] reported that the ratios of volatile matter, fixed carbon, ash content, and moisture are also indicators of pyrolysis product yields. It was observed that biomass feedstock with high volatile matter generates high amounts of bio-oil and syngas, whereas fixed carbon enlarges the biochar generation. Moisture content in biomass influences the heat transfer system with primary outcomes on product distribution [25].

3.2 Thermogravimetric Analysis

The result of TGA and DTG conducted on EFB and MF are shown in Figure 2. The average weight of 10.33 mg EFB and 10.35 mg MF were heated between 30 – 850ºC at a heating rate of 10ºC min-1 separately. According to the curves, three zones were observed, the zones correspond to the starting and endpoints of the derivatives thermogravimetry (DTG) curve which indicates a thermal breakdown of the organic matters and volatiles [27]. The first zone started from 30 to 250ºC; it was due to the moisture evaporation for all the samples. The second zone ranged between 200-360ºC; it is within this zone the maximum weight loss happened due to oxidation and removal of the volatile matters for all the samples as shown in Table 2. The highest weight loss exhibited by EFB was because of the high volatiles content in EFB as reported in Table 1.

Table 1 Physiochemical properties of oil palm wastes, biochar and coal

Proximate analysis (wt%)[a]	Raw EFB	Biochar (EFB)	Raw MF	Biochar (MF)	Coal
Moisture content	3.30	4.65	2.80	4.00	2.01
Volatile matter	81.40	48.65	77.15	43.20	41.96
Ash content	6.21	7.40	5.02	6.37	8.16
Fixed Carbon[b]	9.09	39.30	15.03	46.43	45.09
Elements analysis (wt%)[a]					
Carbon	42.8	56.09	46.37	57.81	56.66
Hydrogen	6.20	3.89	5.52	4.93	7.91
Nitrogen	0.47	1.10	0.59	0.96	1.16
Sulphur	0.09	---	0.12	---	---
Oxygen[b]	50.44	38.92	47.47	36.30	34.27
Calorific value (MJ/kg)					
HHV	16.90	24.10	19.06	27.30	26.21

[a] Weight percentage dry basis (wt%). [b] By difference

The chemical composition stipulates the elements present. The results of the analysis in Table 1 revealed that the MF biochar comprises a high carbon content of 57.81 wt% followed by coal and EFB biochar with 56.66 wt% and 56.09 wt%, respectively. EFB biochar displayed a high oxygen content of 38.92 wt% than the contents in MF biochar and coal, respectively. The hydrogen and nitrogen contents were found to be respectively 3.89 and 1.10 wt% for EFB biochar, 4.93 and 0.96 wt% for MF biochar, and 7.91and 1.16 wt% for coal.

The calorific value is used to measure the energy content and thermal efficiency of materials. In this work, the higher heating values (HHV) of oil palm wastes were determined and calculated, respectively. The results acquired disclosed that the HHV of EFB, MF and coal were respectively found to be 16.90, 19.06 and 26.21 $MJkg^{-1}$ as shown in Table 1. Other fuels such as Olive husk, possess a high heating value of 21.80 $MJkg^{-1}$ [26]. The HHV of biochars was 24.10 $MJkg^{-1}$ and 27.30 $MJkg^{-1}$ for EFB and MF biochars, respectively.

It was reported that DTG curves for palm shell and MF attain separate peaks for hemicellulose at around 300ºC and cellulose above 300ºC [24]. It was observed in this study that the maximum temperatures reached for cellulose and hemicelluloses to decline between 300 to 360ºC and 270 to 300ºC for both EFB and MF, respectively, whereas the degradation of lignin was seen at 650ºC. It was reported that palm shells showed high resistant to temperature due to the high lignin content [28]. The char oxidation in the third zone between 340ºC - 800ºC was because of the removal of residual volatiles in the samples. According to TGA and DTG thermograms, the first, second and third zones can be described as dehydration, active and passive pyrolysis, respectively. The total weight loss between 100 to 450ºC is 78.6 and 75.71% for EFB and MF, respectively. It was reported that thermogravimetric analysis is used to investigate the thermal degradation behaviour and kinetic parameter of non-catalytic and catalytic pyrolysis of rice husk (RH) using rice hull ash (RHA) as a catalyst [29].

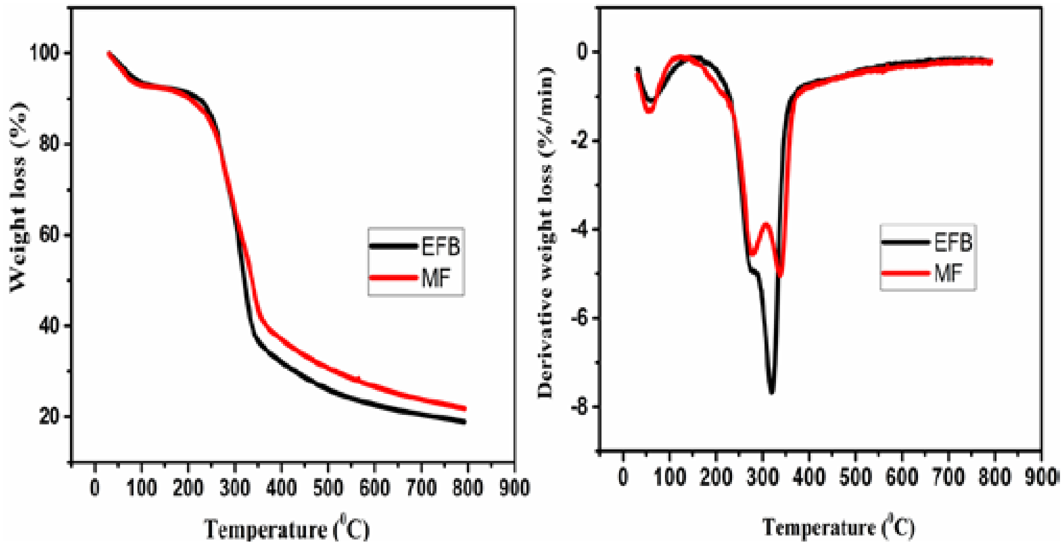

Figure 2 TGA and DTG curves oil palm wastes

Table 2 Temperature intervals and weight loss for different zones at 10°C min^{-1}

Oil palm wastes	Temperature intervals (°C)		Weight loss (wt%)	
	Second zone	Third zone	Second zone	Third zone
EFB	200-340	340-800	52.35	19.47
MF	220-360	360-800	47.53	18.90

The peak temperatures recorded in the second zone and burnout temperature for all the samples at 10°C min^{-1} heating rate are presented in Table 3. MF has shown the highest peak temperature of 338°C than EFB. However, EFB displayed the highest burnout temperature of 600°C. Burnout temperature is the highest temperature reached by a solid fuel to stopped burning. In other words, the maximum temperature reached by a solid fuel to form a straight line on the DTG curve (where no weight loss is experienced) is known as the burnout temperature.

Table 3 Peak and burnout temperatures of the samples

Oil palm wastes	Peak temperature (°C)	Burnout temperature (°C)
	Second zone	
EFB	320	600
MF	338	580

3.3 Combustion Characteristics of Charcoal Briquettes

The proximate analysis and HHV of the solid fuels are shown in Table 4. From the results, volatile matter, fixed carbon, ash, moisture content, and HHV were respectively found to be between 41 to 46 wt%, 40 to 48 wt%, 6 to 10 wt%, 2 to 4 wt%, and 24 to 27 MJkg^{-1}. The maximum volatile matter of 46.70 wt% was received from EBF briquettes, while the minimum value of 41.96 wt% was acquired from coal. Subsequently, MF briquettes had the highest fixed carbon and HHV of 48.16 wt% and 27.99 MJkg^{-1} due to the low volatile matter content in the briquettes. However, the low volatile matter and ash content could make MF briquettes challenging to ignite and could not be recognised as good combustible fuel compared to EFB which has a high content of volatile and ash. Comparably, all the charcoal briquettes produced had high HHV than coal and commercial briquettes (COMBr).

Table 4 Physical properties of solid fuels

Solid fuels	Proximate analysis (wt%)[a]				
	Moisture	Volatile	Ash	Fixed carbon[b]	HHV ($MJkg^{-1}$)
EFB Charcoal	3.04	46.70	10.20	40.06	26.93
MF Charcoal	3.11	42.12	6.61	48.16	27.99
Coal	2.01	41.96	08.16	45.09	26.21
COMBr	4.79	42.45	07.10	41.07	24.08

It was stated that for a solid fuel to ignite and burn easily, it must contain a moderate percentage of volatile matter. It was observed that high moisture and ash contents could lead to ignition and other combustion difficulties [27], [30]. The significant benefits that biomass has as a combustion fuel are the high volatility and high reactivity of the fuel and the resulting char [31].

Based on these reasons, and since all the charcoal briquettes obtained in this study had high HHV than coal and COMBr, the choice of the best briquettes is established on volatile, ash and moisture contents, respectively because of their role during combustion. The charcoal briquettes, coal, and COMBr were subjected to combustion at 10°C min^{-1}, and the results of combustion profiles acquired using DTG is shown in Figure 3.

Prior to analysis, the combustion temperature starting from 30 to around 900°C is partitioned into zones one, two and three as shown in Table 5. It is seen from the figure that all the solid fuels showed a comparable peak between the temperature of 30 and 200°C. This peak could be ascribed to dehydration of moisture during the combustion. However, inside the primary zone, coal showed most elevated weight reduction of 8.83 wt% and a peak temperature of 77°C, while MF briquette demonstrated the least weight reduction of 3.38 wt% and a peak temperature of 59°C as seen in Tables 6 and 7, respectively.

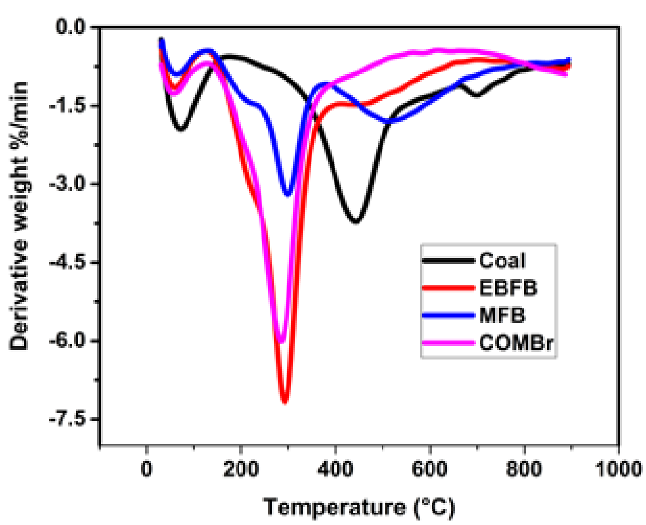

Figure 3 DTG curves for solid fuels combustion

Table 5 Temperature intervals for different zones

Solid fuels	Temperature intervals (°C)		
	First zone	Second zone	Third zone
EFB Charcoal	30 -140	140 - 360	360 - 644
MF Charcoal	30 - 140	140 - 356	356 - 780
Coal	30 - 200	200 - 557	557 - 780

Table 6 Weight loss of solid fuels at different zones, % by weight

Zones	Weight loss, wt%		
	EFB	MF	Coal
One	3.54	3.38	8.83
Two	30.73	12.00	29.60
Three	14.41	20.25	10.28

Zone two begun from 140 and lasted to around 560ºC. This zone showed the most significant weight reduction and most high peak temperature and ignition temperatures. As apparent from Table 7, EFB briquette and coal showed the most elevated weight reduction of 30.728% and 29.603%, individually.

The ignition temperature of the solid fuels in Table 7 was 235ºC for EFB, 254ºC for MF and 368ºC for coal. Along these lines, the peak temperature took after ignition temperature, and the value recorded was displayed in Table 7.

As seen from Figure 3, the solid fuels showed diverse conduct amid combustion particularly inside zones 2 and 3. In this manner, the amount of fuel consumed ought not to be equivalent because the time taken for each fuel to approach the burnout temperature is additionally not equivalent. As apparent from the figure and Table 8, EFB solid fuel indicated high reactivity and therefore brought about the high burning rate and heat discharge. The most extreme fuel consumed and heat discharge for EFB solid fuel were separately observed to be 5.248×10^{-6} kg and 0.06 W. MF solid fuel discharge less amount of heat since it is less reactive as shown in Figure 3 which prompted moderate amount of fuel consumed.

Table 7 Peak and burnout temperatures of solid fuels

Solid fuels	Peak temperature (ºC)			Ignition temperature(ºC)	Burnout temperature(ºC)
	Zone 1	Zone 2	Zone 3		
EFB Charcoal	57	280	472	235	675
MF Charcoal	59	287	513	254	788
Coal	77	440	671	368	770

Temperature extends between 356 and 780ºC is perceived as zone three. It can be seen from Figure 3 that the rapid combustion of MF briquette proceeded in this zone with a most extreme weight reduction of 20.247 wt% as listed in Table 6. The recorded burnout temperature was 675ºC, 788ºC and 770ºC for EFB, MF briquettes and coal separately in Table 7.

The combustion period for solid fuels was around 45 minutes. The amount of fuel consumed, and time taken to reach burnout temperature for each fuel was ascertained. The time taken was evaluated and found to be 40, 44 and 42 minutes for EFB, MF and coal individually. Likewise, the burning rate and heat discharge from the initial temperature to burnout temperature was additionally determined as displayed in Table 8.

Nonetheless, low heat discharged by MF briquette (0.04 W) amid burning could be identified with the low amount of fuel burnt (1.443×10^{-9}). Equivalently, the combustion of MF briquette and coal may require a higher temperature and longer burning time to finish the conversion. This might be because of the presence of a lot of inorganic material. It can, therefore, be presumed that MF fuel could be viewed as steady since it might deliver heat for an extended period.

Table 8 Combustion rate (CR) and heat release as at burnout temperature

Solid fuels	Fuel burnt (kg)	CR(kg/s)	Heat release (W)
EFB Charcoal	5.248×10^{-6}	2.187×10^{-9}	0.06
MF Charcoal	3.810×10^{-6}	1.443×10^{-9}	0.04
Coal	5.001×10^{-6}	1.985×10^{-9}	0.05

Conclusion

The ignition and burnout temperatures were 235ºC and 675ºCfor EFB, 254ºC and 788ºC for MF, and 368ºC and 770ºC for coal. The maximum and minimum heat release of 0.06 W and 0.04 W were obtained from the combustion of EFB and MF briquettes, respectively. Though Malaysian sub-bituminous coal has also released 0.05 W. It can be established that the 100 million tonnes of oil palm wastes expected to be produced in 2020 could be transformed into charcoal briquettes for domestic and industrial heat generation.

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