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Potential Application of Oil Palm Wastes Charcoal Briquettes for Coal Replacement

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Abstract

This study is aimed at investigating the potentials of oil palm wastes as an alternative to fossil fuels (coal) for domestic heat generation via briquettes (solid fuels) production. In this study oil palm wastes such as empty fruit bunches (EFB), mesocarp fiber (MF) and palm kernel shell (PKS) were pyrolyzed at temperatures of 400°C for 120 min and a heating rate of 10°C min⁻¹. The biochar and bio-oil obtained were blended in the ratio of 60:40 weight percentages and compressed at a constant pressure of 400 kg cm⁻² for charcoal briquettes production. The combustion profiles, heat release of the charcoal briquettes and Malaysian sub-bituminous coal were analyzed and compared through thermogravimetric analysis (TGA). Comparably, MF and PKS charcoal briquettes had higher HHV of 26.15 and 25.99 MJ kg⁻¹, individually than coal which has 24.21 MJ kg⁻¹, while EFB charcoal briquette showed the lowest value 23.93 MJ kg⁻¹. Therefore, it can be said that all the charcoal briquettes showed a positive sign to replace coal. The maximum and minimum heat released of 0.059 and 0.048 W were obtained from the combustion of EFB and MF charcoal briquettes. It was established that in each ton of raw (dry basis) of EFB, MF, and PKS, there is 0.177, 0.212 and 0.228 tons of charcoal briquettes which correspond to 1.866, 2.055 and 2.414 MW of heat. Therefore, the findings in this study could contribute toward achieving the targeted 500 MW of green energy initiated in 2005 by the Malaysian government. Furthermore, the production of charcoal briquettes could be one of the proper methods to minimize the agricultural disposal problem in Malaysia.

Keywords: oil palm wastes, charcoal briquettes, coal replacement, heat generation

1. Introduction

1.1. Energy demand

International Energy Agency (IEA) in its new policy scenario stated that the world energy demand is anticipated to persistently rise yearly to about 1.2% from 2008 to 2035, with 70% of the demand imminent from the developing countries. However, the majority (87%) of this energy demand will be obtained mainly from fossil fuels. The rise of the entire global energy demand is associated with the increase in the world population and global economic growth [1, 2]. Furthermore, the energy uses in the main cities of developing countries is related to stages of greenhouse-gas (GHG) emissions and are anticipated to increase [3]. Global warming has been one of the fundamental environmental problems for many decades. However, the quantity of CO₂ in the atmosphere will persistently increase, except key modifications are made in the manner fossil fuels are utilized in the energy production [4, 5]. Fossil fuels still control the world's energy market value of about 1.5 trillion United States Dollars (USD). For example, the World Energy Council (WEC) estimated in 2007 that recoverable coal mineral deposits would be about 850 billion tons in 2006 [6].

The burning of coal generates more CO₂ emissions than combustion of both oil and natural gas by 1.5 and 2 separately [7]. Malaysia is not an exception in the use of fossil fuels for power generation. As at 2010, the coal generation in Malaysia is derived majorly from six mines in Sarawak. There are about 1724 million tons of coal resources of which 274 million tons are identified, 347 million tons indicated and the balance of 1102 million tons as inferred [2]. Presently, community and political sensitivities to environmental problems and energy security have focused on the promotion of non-fossil fuel energy sources instead of fossil fuels. 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 [8].

1.2. Renewable energy sources

Renewable energy is an energy source which does not vanish. These types of energy sources have been in use since the beginning of human civilization. They are abundantly available because they exist naturally in our environment [9]. There are three sources of energy and these include; fossil fuels, renewable and nuclear power sources. However, among these energy sources, renewable energy is the only source that can be used to generate energy repeatedly. They can also be used easily to provide the domestic energy demand for local communities. **Table 1** presents the global renewable energy scenario as predicted by the year 2040. Sun is the largest source of all energies. Renewable energy sources (RES) have advantages for the alleviation of greenhouse gas emission, minimizing global warming by replacing conventional energy sources and reducing disposal of a lot of wastes. Renewable energy sources such as biomass, hydropower, geothermal, solar, the wind and marine energies provide about 14% of the total world energy demand. The percentage is predicted to improve extensively to about 30–80% by 2100 as shown in **Table 1** [10].

1.3. Biomass energy

Among the renewable energies, biomass is the largest and an essential one that has been employed in both developed and developing countries. Biomass is formed when carbon dioxide

Decades	2001	2010	2020	2030	2040
Total consumption (million tons oil equivalent)	10,038	10,549	11,425	12,352	13,310
Biomass	1080	1313	1791	2483	3271
Large hydro	22.70	266	309	341	358
Geothermal	43.20	86	186	333	493
Small hydro	9.50	19	49	106	189
Wind	4.70	44	266	542	688
Solar thermal	4.10	15	66	244	480
Photovoltaic	0.10	2.00	24	221	784
Solar thermal electricity	0.10	0.40	3.00	16	68
Marine (tidal/wave/ocean)	0.05	0.10	0.40	3.00	20
Total RES	1365.5	1745.5	2964.4	4289	6351
Contribution of RES in (%)	13.60	16.60	23.60	34.70	47.70

Table 1. Global renewable energy scenario by 2040.

and solar energy (sunlight) with water are mixed via photosynthesis. However, burning of biomass results in the release of carbon dioxide into the atmosphere accompanied by the conversion of stored chemical energy in the biomass into thermal energy [11]. Biomass supplies a clean, renewable energy source that could considerably improve our environment, economy and energy security by reducing the burning of fossil fuels, emission of greenhouse gasses (GHG) and environmental pollution [12].

Biomass can be used to generate heat and power for industry and domestic purposes. This particular value over wind power and solar energy via photovoltaic cells makes biomass a significant pillar in the energy contribution today and in the future. Biomass such as wood, energy crops, forest and agricultural residue, industrial and municipal wastes could be the prominent alternatives to coal [12, 13]. Moreover, according to statistics from the IEA, biomass contributed about 10% of primary global energy demand in the year 2005. Biomass can be converted into gas and liquid fuels (bio-oil, biodiesel, and bioethanol) through gasification and pyrolysis, transesterification and fermentation respectively [14].

Biomass is a lignocellulosic material obtained from living organic substances such as wood and agricultural wastes. However, non-lignocellulosic substances, like an animal and municipal solid wastes (MSW) are also regarded as biomass. The three major constituents of biomass [15, 16] are cellulose, hemicellulose, and lignin. It also contains water extractives and ash [16]. The constituents are highly associated and chemically bonded by noncovalent forces. They are cross-linked collectively, thus bearing composition and firmness of the plant [15]. The basic structures of biomass lignocelluloses components can be written as $(C_6H_{10}O_5)_m$, $(C_5H_8O_4)_m$ and $[C_9H_{10}O_3 \cdot (OCH_3)_{0.9-1.7}]_m$ for cellulose, hemicellulose, and lignin respectively, where m is a degree of polymerization [14].

1.4. Oil palm biomass in Malaysia

Palm oil has made significant and continued development in the worldwide market in the past few decades. Malaysia and Indonesia are the top producing countries of palm oil in the world, which together produced about 85% of the total world palm oil. Additional producing countries comprise Thailand, Columbia, Nigeria, Papua New Guinea and Ecuador [17]. Oil palm is the most important product that has changed the situation of the agricultural sector and economy in Malaysia. It is projected that in the period 2016–2020, the standard yearly production of palm oil in Malaysia will achieve 15.4 million tons. Lignocellulosic biomass which is produced from the oil palm industries incorporate oil palm trunks (OPT), oil palm fronds (OPF), empty fruit bunches (EFB) and palm pressed fibers (PPF), palm shells, and palm oil mill effluent (POME). The occurrence of these oil palm wastes has created a significant disposal crisis, but the primary objectives of waste management in Malaysia are to limit and reuse the waste and recuperate the energy. This principally applies to agro-industrial wastes, for example, palm oil residues as applied to municipal waste. One of the significant advantages of oil palm wastes is that the palm oil mill is independent in energy, utilizing PPF, EFB, and shell are used as fuel to generate steam in waste fuel boilers for handling, and power-generation with steam turbines [18].

The oil extraction rate is just around 10% of the palm oil production with the larger part 90% remaining as biomass. For instance, in 1 kg of palm oil about 4 kg of dry biomass is generated [19, 20]. The oil palm wastes generated from palm oil industry in Malaysia is among the most excellent biomass residues. After being lignocellulosic biomass, they also show non-edible characteristic which makes them attractive globally [21]. Specifically, Malaysia produced around 9.9 million tons of palm oil wastes as a fundamental of biomass sources including EFB, shell, and fiber, which continues to expand at 5% yearly [22]. However, the proportions of agricultural residues generated from oil palm include mesocarp fiber (13.5%), palm kernel shell (5.5%) and empty fruit bunch (22%). Palm shell and palm fiber were utilized as fuel to power the steam boilers, whereas empty fruit bunch is used for mulching in the plantation area [23].

In 2009, the oil palm wastes rendered in Malaysia were 7.0 million tons of EFB, 11.6 million tons of PKS and MF, 44.8 million tons of fronds and 13.9 million tons of trunks. However, the eminent expected utility of these wastes is assumed to circumscribe [24]. Between the oil palm biomass, mesocarp fiber contains a high calorific value in comparison with palm shell and EFB [23]. These oil palm residues comprise various chemical composition and high heating value of about 18–19 MJ kg⁻¹. They are better complement and ingredients for fuels in the form of pellets and briquettes [25]. It has been declared that in the year 2012 there were profitable oil palm wastes (dry weight) of about 83 million tons in Malaysia. Moreover, it will eventually ascend to 100 million tons in few years to come (2020) [24]. These wastes will continue to contribute to the agricultural wastes disposal problem in Malaysia except necessary action are taken.

1.5. Thermochemical conversion of biomass

The direct combustion of biomass is not the best way to use it as burning fuel. Some processes can be used to upgrade the standard of biomass for better and proper application. Some of

these processes include dewatering and drying, pulverization or grinding, and densification process such as pellets. Besides the above-mentioned conventional pre-treatment, there is also another important and efficient method for upgrading biomass as a fuel known as torrefaction [11]. Torrefaction can be described as a thermochemical process carried out in the temperature range of 200–300°C under an oxygen-free condition with a purpose to upgrade the quality standard of biomass [26].

Pyrolysis conversion process is one of the prominent thermochemical methods through which biomass are converted into three major by-products namely; solid char, bio-oil, and gases [27, 28]. A pyrolysis procedure is divided into slow pyrolysis and fast pyrolysis. Slow pyrolysis yields more biochar yet less bio-oil with around 35% as biochar, 30% as bio-oil and 35% as syngas. However, fast pyrolysis gives a yield of around 15% biochar, 70% bio-oil, and 13% syngas [20]. The pyrolysis parameters such as temperature, retention time, heating rate, particle size, inert gas and reactor type give different pyrolysis product yields. Temperature and holding time are among the most significant operating parameters. As the temperature and residence time rise, the biochar yield is reduced because of gasification of the solid biochar. With increased temperature up to 500°C, the greatest bio-oil yield can be accomplished. However, the yield drops with further increment in temperature. Interestingly, gas products are favored at high temperature and long holding time not surprisingly because of the quantity of volatiles released with increasing temperature [20]. For woody biomass, the liquid product is typically maximized at a temperature around 500–520°C for fast pyrolysis. However, lower temperatures favor the production of biochar [29].

1.6. Biomass briquetting for solid fuels

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 [30]. 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 non biomass sources such as plastic, many types of milled paper wastes and other combustible wastes [31]. Municipal solid waste (MSW), industrial waste and sludge are used to produce fuel briquettes in some countries [32]. It is well-known and believed that biomass residues could be utilized as a replacement to fuel for combustion at coal-fired power plants [33]. There are many processes for briquetting; they include pre-treatment and operational parameters (factors) that controlled the quality of fuel briquettes. Furthermore, physical properties such as a binder, moisture content, particle size and compressing forces (pressure) are among the factors that influence the quality of briquettes regarding durability and resistivity during transportation [34]. However, a briquette quality significantly depends on the drying process [35].

In this research, the potential application of empty fruit bunches, mesocarp fiber and palm kernel shell for coal replacement was investigated. These biomasses were pyrolyzed and the bio-oil and biochar obtained were used to form charcoal briquettes (solid fuels). The viscosity of bio-oil was improved by the addition of 10% starch and used as a binder.

2. Materials and methods

2.1. Biomass sample collection and preparation

The oil palm biomass used in this study include mesocarp fibers (MF), empty fruit bunch (EFB) and palm kernel shells (PKS) as shown in **Figures 1–3**. They were obtained freshly from a palm oil mill located in Nibong Tebal, Pulau Pinang, Malaysia. These biomass samples were the by-products from different procedures such as pressing and nut cracking in the milling process industries where crude palm oil is generated. The biomass samples were dried to a moisture content lower than 10 wt%, for 24 h at 105°C. EFB sample was cut into smaller sizes, and all the samples were stored into desiccators before experiments and analyses. The Sago starch was obtained from MYDIN shopping mall located at Bukit Jambul, Pulau Pinang, Malaysia. Sub-bituminous coal was supplied by a company based in Sarawak, Malaysia.

2.2. Physiochemical characterization

Proximate analysis was carried out by ASTM E871 for moisture content, ASTM E872 for volatile matter content, and ASTM E1755-01 for ash content, from which the difference was used to determine the amount of fixed carbon. Elemental analysis was conducted to analyze the percentages of carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O). It was performed using a Perkin Elmer 2400 analyzer, and 2–2.8 mg of sample was used to measure the percentage weight of each element present. The higher heating value (HHV) was determined using bomb calorimeter system IKA C 200, and oxygen station C248 with an empty water hose. For each test run, 0.5–0.8 g of the sample was measured and placed in the crucible joined to the thread from the ignition wire, which was then closed, and oxygen gas was pumped in. The lignocellulosic compositions of the materials were measured according to the procedure prescribed by Sukiran [22].

2.3. Pyrolysis experiment

The pyrolysis experiment was conducted three times separately using a stainless-steel reactor of 150 mm length and 70 mm internal diameter; about 180 g of raw biomass was weighed and placed inside the electric furnace. The reactor was heated at a temperature of 400°C for 120 min and at a heating rate of 10°C min⁻¹. During the pyrolysis, the reactor temperature was monitored using a K-type thermocouple, and nitrogen (N₂) was used as the reaction gas at a rate of 2 l/min as shown in **Figure 4**.



Figure 1. Oil palm EFB as received.



Figure 2. Oil palm fiber as received.



Figure 3. Oil palm kernel shell as received.

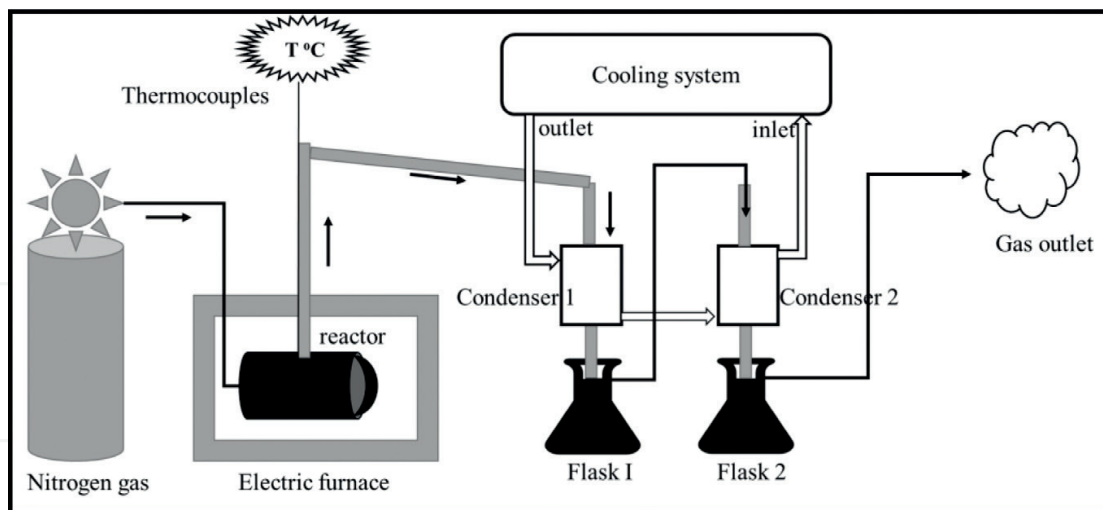


Figure 4. A schematic of the pyrolysis system.

2.4. Briquetting tools and methods

The cylindrical briquetting mold used was made from hardened steel with an inner diameter of 19.4 mm and a height of 50.2 mm. Other briquetting parts are press piston of 65.0 mm and stop piston of 10.0 mm. The manual hydraulic pressing machine (briquetting machine) used is purposely manufactured for experimental work. It has a maximum pressuring capacity of only 1000 kg cm⁻² (98.07 MPa). For each bio-briquettes made, about 10–20 g of the mixture was

placed into a mold and compressed at a constant pressure of 400 kg cm^{-2} for 2–5 min until no more change occurred on load reading. This procedure was replicated for all the briquettes produced. The mold and piston, and schematic briquetting machine setup are displayed in **Figures 5** and **6**, respectively.

The starch was ground to powder and mix with the bio-oil of about 50 ml and warmed. The mixture was stirred vigorously until a uniform solution was observed (bio-oil binder). The biochar and bio-oil (binder) were mixed in the ratio of 60:40 weight percentages. The mixture was allowed to dry for 10 min at room temperature before feeding into mold and press. The weight of briquette produced was recorded instantly and placed under ambient conditions for about 7 days to dry. The briquette procedure is summarized in **Figure 7**.

2.5. Thermogravimetric analysis (TGA)

Thermogravimetric analysis (TGA) was performed on the sample using a Perkin Elmer STA 6000 thermogravimetric analyzer. Thermal analysis was used to examine the thermal performance of the samples by observing the weight alteration that happened as the samples were heated, concerning hemicellulose, cellulose, and lignin, and identifying their thermal degradation behavior. The analysis was carried out in the presence of nitrogen (N_2) gas flow under a $10^\circ\text{C min}^{-1}$ heating rate, with a sample size of 250–355 μm and the samples were heated from ambient temperature to about 850°C .

After the charcoal briquettes had been manufactured and dried, they were ground and subjected to combustion together with coal via TGA from a temperature range of $30\text{--}850^\circ\text{C}$ at a constant heating rate of $10^\circ\text{C min}^{-1}$ under oxygen environment at a flow rate of 50 ml min^{-1} . In the combustion analysis, the combustion profiles such as peak temperature, ignition temperature, and burnout temperature at each combustion zone were determined. Also, the amount of weight loss, briquettes burnt, combustion rate and heat release during combustion were analyzed. The graph of DTG $\%/ \text{min}$ versus temperature was used to determine the combustion properties of the briquettes. The combustion rate and heat release were computed with the equations shown below [23].

$$\text{Combustion rate} = \text{total mass of burnt briquette} / \text{burning time} \quad (1)$$

$$\text{Heat release} = \text{calorific value} \times \text{combustion rate} \quad (2)$$



Figure 5. Briquette mold and piston.

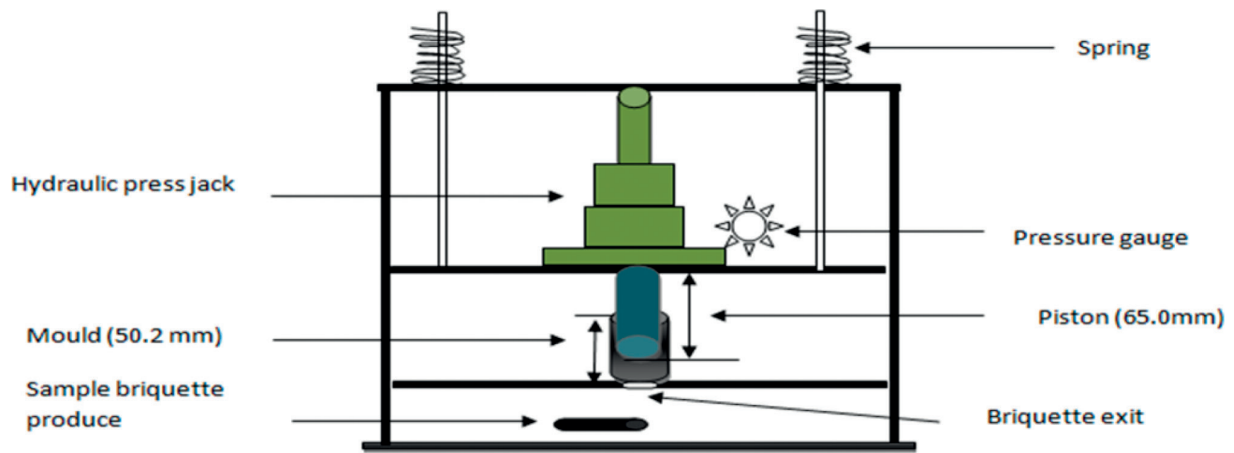


Figure 6. A schematic briquetting machine.

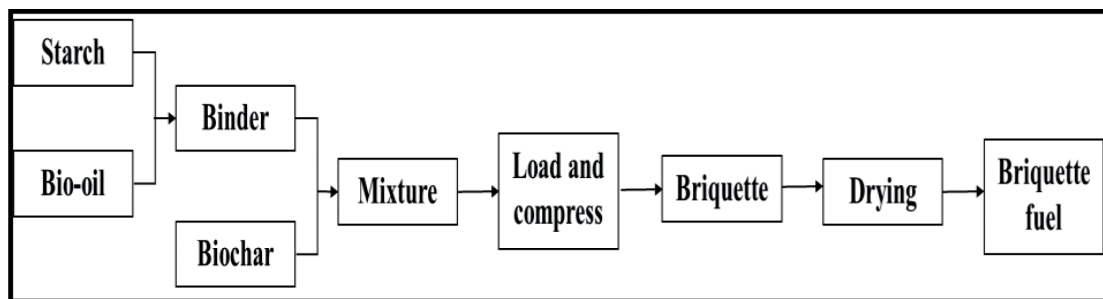


Figure 7. Briquetting processes.

3. Results and discussion

3.1. Lignocellulosic components of oil palm wastes

The composition of cellulose, hemicellulose, lignin, and extractive in the oil palm wastes was in the range of 20–39, 23–35, 20–49 and 3–10 wt%, respectively as shown in **Table 2**. Comparatively, empty fruit bunch has high cellulose and hemicellulose, and low lignin and extractives contents than others. Mesocarp fiber has a high content of extractive than PKS and EFB, which could be responsible for its higher heating value than others. The high lignin content in palm shell resulted in a high yield of biochar. The cellulose, hemicellulose, lignin, extractive and ash components of oil palm wastes were respectively found in other research to be 33.9, 26.1, 27.7, 6.9 and 3.5 (% dry wt.) for MF. While, 38.3, 35.3, 22.1, 2.7 and 1.6 (% dry wt.) for EFB, 20.8, 22.7, 50.7, 4.8 and 1.0 (% dry wt.) for PKS [20]. The percentage compositions of lignocellulosic play a vital role in the pyrolysis products yield. The lignocellulosic components of wood and Switchgrass were 35–50 and 30–50% cellulose, 20–30 and 10–40% hemicelluloses, and 25–30 and 5–20% lignin, respectively [36].

3.2. Proximate and elemental analysis

The results from the proximate analysis of oil palm biomass are given in **Table 2**. The moisture, ash and fixed carbon contents were 7.30, 7.51 and 10.09 wt% for EFB, 6.2, 7.02 and 15.83 wt%

Properties (wt%)	EFB	MF	PKS
Cellulose	39.80	32.60	20.70
Hemicellulose ^b	35.90	29.20	23.30
Lignin	20.40	27.90	49.50
Extractives	3.90	10.30	6.50
Moisture content	7.30	6.2	4.90
Volatile matter	82.40	77.15	75.40
Ash content	7.51	7.02	8.70
Fixed carbon ^b	10.09	15.83	15.90
Carbon	42.80	46.37	50.29
Hydrogen	6.20	5.52	6.35
Nitrogen	0.47	0.59	0.48
Sulfur	0.09	0.12	0.08
Oxygen ^b	50.44	47.47	42.82
HHV (MJ kg ⁻¹)	16.9	19.06	19.5
LHV (MJ kg ⁻¹)	15.5	17.9	18.1

^aWeight percentage dry basis (wt%).

^bBy difference.

Table 2. Physiochemical properties of oil palm wastes.

for MF, and 4.9, 8.7 and 15.9 wt% for PKS, respectively. The volatile matter content was between 75 and 82 wt%, whereby EFB has high volatile matter than MF and PKS. Relatively, similar results in (wt%) can be found in the other study [28]. Comparing with other biomass sources, EFB has similar volatile matter content with Sawdust (82.20 wt%) and lower than that of Rice husk (61.81 wt%). However, the cotton stalk has high fixed carbon and high ash content than all the oil palm wastes studied [37]. The percentage of volatile matter, fixed carbon, ash content, and moisture are reasonable parameters of pyrolysis product yields. Jahirul et al. reported that the percentages of volatile matter, fixed carbon, ash content, and moisture are suitable parameters of pyrolysis product yields. Biomass with high volatile matter generates large 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. Also, an increase in moisture content increases liquid product yield and reduces the yield of solid and gas product. Which could be associated with the huge amount of condensate water generates from the moisture in the liquid phase [36].

The chemical composition of oil palm wastes stipulates the elements present. The results of the analysis in **Table 2** above revealed that the PKS comprises a high carbon content of 50.29 wt% and low oxygen content of 42.82 wt% than the contents in MF and EFB, respectively. The hydrogen, sulfur, and nitrogen contents were found to be respectively 6.20, 0.09 and 0.47 wt% for EFB, 5.52, 0.12 and 0.59 wt% for MF, and 6.35, 0.08 and 0.48 wt% for PKS. Other oil palm

wastes such as oil palm frond and oil palm trunk have high and low content of oxygen (50.88 and 53.12 wt%) and carbon (42.76 and 40.64 wt%), respectively [38, 39], than EFB, MF, and PKS. For rice husk and Sawdust, they have a carbon content of 47.80 and 46.90 wt% [37] above that of EFB and MF.

3.3. Calorific heating value

The calorific value is used to measure the energy content and thermal efficiency of materials. In this work, the higher and lower heating values (HHV and LHV) of oil palm wastes was determined and calculated, respectively. The results acquired disclosed that the HHV of EFB, MF and PKS were respectively found as 16.9, 19.06 and 19.5 MJ kg⁻¹ as shown in **Table 2**. Other fuels such as Sub-bituminous Malaysian coal and Olive husk possess a high heating value of 24.6 MJ kg⁻¹ [23] and 21.80 MJ kg⁻¹ [37], respectively in relative to oil palm wastes studied in this work. The LHV was computed to be 15.5 MJ kg⁻¹ for EFB, 17.9 MJ kg⁻¹ for MF and 18.1 MJ kg⁻¹ for PKS, respectively.

3.4. Thermogravimetric analysis

Figure 8 displays the TGA and differential thermogravimetry (DTG) curves of the sample. The samples showed similar behavior during pyrolysis. The first small peak corresponds to the evaporation of moisture and the early weight loss at a temperature lower than 150°C for all the palm biomass samples. The degradation of hemicelluloses commences at temperatures of around 270°C for EFB, 290°C for MF, and 300°C for the PKS. It is reported by Sulaiman and Abdullah that DTG curves for PKS and MF attain separate peaks for hemicellulose at around 300°C and cellulose above 300°C [40]. In this study, the peak at about 310°C and the two peaks at 360°C correspond to the degradation of cellulose for EFB, MF, and PKS, respectively. Though the breakdown of cellulose and hemicelluloses is a constant progression, the weight loss of these constituents was sustained throughout nearly the whole heating period. However, the maximum decline speeds of the celluloses are between 300 and 360°C, and for the hemicelluloses,

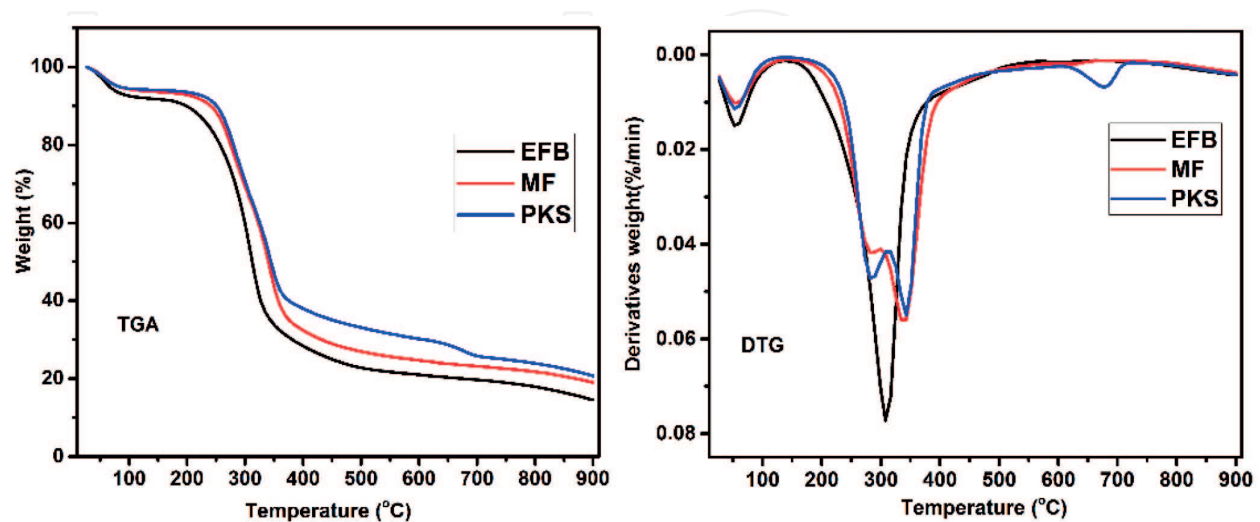


Figure 8. Thermal analysis (TGA and DTG curves).

they are between 270 and 300°C. The degradation of lignin is seen at 650°C, but PKS shows high resistance to temperature due to its high lignin content. The total weight losses between 100 and 450°C are 78.6, 75.71, and 98.5% for EFB, MF, and PKS, respectively.

3.5. Pyrolysis products yield

The biochar, bio-oil and gas yields obtained from the pyrolysis of oil palm wastes at a temperature of 400°C, a heating rate of 10°C min⁻¹ and for 120 min holding time are shown in **Figure 9** for EFB, MF, and PKS. Jahirul et al. reported that the decomposition of lignocellulosic components relies on temperature, heating rate, and other contaminants because of their different molecular structures. Hemicellulose ordinary decomposes easily, followed by cellulose, while lignin decomposes at last. However, during pyrolysis lignin and hemicellulose do not affect each other but both can influence the pyrolysis of cellulose. They also reported that the percentages of volatile matter, fixed carbon, ash content, and moisture are suitable parameters of pyrolysis product yields. [36].

3.5.1. Biochar yield

As evident in **Figure 9**, PKS and MF were distinguished as the samples that yielded a huge quantity of biochar compared with EFB. The quantities of biochar yield were 42.11% for EFB, 45.12% for MF and 46.57% for PKS, respectively. The influence of lignin (fixed carbon) and cellulose on biochar yields were observed accordingly. It was shown in **Table 2** that PKS and MF comprehend eminent quantity of lignin and fixed carbon, and less amount of cellulose than did EFB and therefore, they give rise to a large amount of biochar compared to EFB. It is known that biochar is from lignin content. Thus, biochar elemental composition is near to that of lignin [36].

The yield of biochar could be associated with either primary or secondary decomposition of raw samples during pyrolysis which consequently influenced the pyrolysis conversion processes. Moreover, the disintegration of cellulose, hemicelluloses, and lignin during the pyrolysis plays a vital function in the yield of biochar [28, 41]. The high yield of biochar at low temperatures demonstrates that the material has been only partially pyrolyzed [41]. It

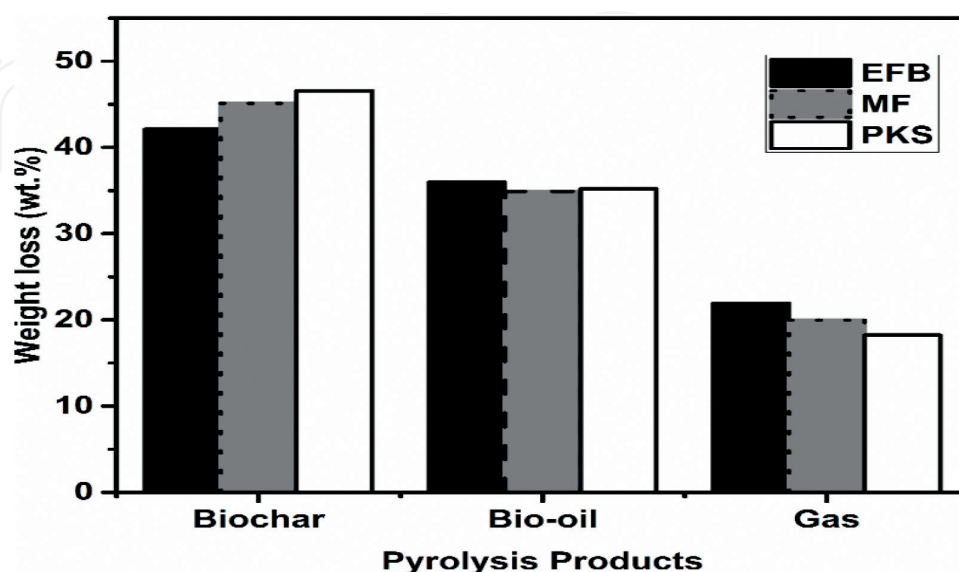


Figure 9. Pyrolysis products obtained from EFB, fiber and shell.

has been reported that during the pyrolysis process cellulose, hemicelluloses and lignin were respectively found to demonstrate the highest to the lowest disintegration rate. At temperature more than 400°C the cellulose content was almost pyrolyzed with a little quantity of solid remnant [42].

3.5.2. Bio-oil yield

The bio-oil yields as seen in **Figure 9** indicated that the quantity of bio-oil produced was between 34 and 35%. However, EFB and PKS produced the maximum and minimum quantities of 35.97 and 35.20% of the bio-oils, respectively. The fact that the EFB and MF generated a high amount of bio-oil than PKS could be attributed to the high amount of cellulose and hemicelluloses as shown in **Table 2**. It has been [36] noted that cellulose is principally responsible for bio-oil production during the pyrolysis of biomass (around 500°C). However, best quality of bio-oil can be generated from biomass with high lignin content. Biomass with high volatile matter generates large amounts of bio-oil and syngas. Moisture content in biomass has an influence in the heat transfer process with significant effects on product distribution [36]. The bio-oil binder viscosity has improved to 40 cP with addition of 10% starch from the initial value of 3 cP.

3.6. Combustion characteristics of charcoal briquettes and coal

The charcoal briquette samples produced, and its physical properties are displayed in **Figure 10** and **Table 3**, respectively. The physical and combustion properties of charcoal briquettes obtained in this work were compared with Malaysian sub-bituminous coal (Coal) for replacement purposes.

The proximate analysis and HHV of the charcoal briquettes are shown in **Table 3**. From the results, volatile matter, fixed carbon, ash, moisture content and HHV were respectively found to be between 41 to 49, 39 to 50, 6 to 11, 2 to 4 wt% and 23 to 26 MJ kg⁻¹. The maximum volatile matter of 49.74 wt% was received from EFB solid fuel, while the minimum value of 41.92 wt% was acquired from PKS solid fuel. Coal had shown the highest fixed carbon followed by MF, PKS and EFB solid fuels, respectively. The sequence of the calorific values was MF first, followed by PKS, coal and then EFB at last. The sequence could be according to the volatile matter



Figure 10. Charcoal briquettes samples.

Properties (wt%)	EFB	MF	PKS	Coal
Moisture content	4.23	3.87	2.91	2.65
Volatile matter	49.74	43.23	41.92	42.05
Ash content	11.20	6.61	8.15	7.44
Fixed carbon ^b	39.06	50.16	49.93	50.51
Carbon	58.11	62.93	65.07	64.66
Hydrogen	5.03	5.87	6.11	7.91
Nitrogen	0.97	0.98	0.93	1.16
Oxygen ^b	35.89	30.22	27.89	26.27
HHV (MJ kg ⁻¹)	23.93	26.15	25.99	24.21

^aWeight percentage dry basis (wt%).
^bBy difference.

Table 3. Physiochemical properties charcoal briquettes and coal (solid fuels).

content and other factors present in the solid fuels that determine the quality of fuel. However, the low volatile matter and high ash content could make fuel difficult to ignite and thus, could not be recognized as good combustible fuel. Comparably, MF and PKS charcoal briquettes had higher HHV of 26.15 and 25.99 MJ kg⁻¹, individually than coal which has 24.21 MJ kg⁻¹, except EFB charcoal briquette which showed the lowest value 23.93 MJ kg⁻¹. Therefore, it can be said that all the charcoal briquettes showed similar properties with coal. And, therefore regarded as the best choice to replace coal.

It was previously 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 [37, 43]. The significant benefits that biomass has as a combustion fuel are the high volatility and high reactivity of the fuel and the resulting char [44]. Based on these reasons, and since all the charcoal briquettes obtained in this study had similar properties or even better than coal, the choice of the best fuel is established on volatile, ash and moisture contents, respectively because of their role during combustion. All the solid fuels were subjected to combustion at 10°C min⁻¹ and the results of combustion profiles acquired using DTG is shown in **Figure 11**.

Before analysis, the combustion temperature starting from 30 to around 850°C is partitioned into zones as shown in **Table 4**. 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 the highest weight reduction of 8.825 wt% and a peak temperature of 77°C, while MF demonstrated the least weight reduction of 3.382 wt% and a peak temperature of 59°C as seen in **Tables 4** and **5** respectively.

The second zone began from 140 and lasted to around 560°C. This zone showed the greatest weight reduction and most astounding peak temperature, and ignition temperatures. As apparent from **Table 5**, EFB and coal showed the most elevated weight reduction of 30.728

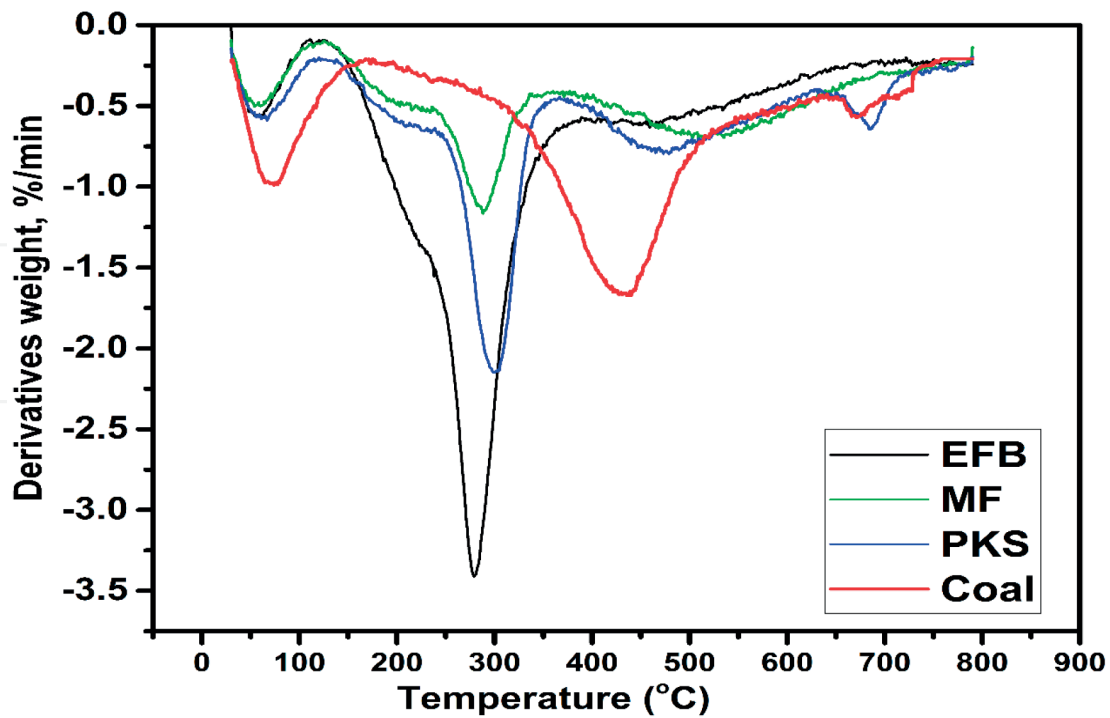


Figure 11. DTG curves for solid fuels combustion.

Solid fuels	Temperature intervals (°C)		
	First zone	Second zone	Third zone
EFB	30–140	140–360	360–644
MF	30–140	140–356	356–780
PKS	30–140	140–351	351–739
Coal	30–200	200–557	557–780

Table 4. Temperature intervals for different zones.

Zones	Weight loss, wt%			
	EFB	MF	PKS	Coal
I	3.539	3.382	4.461	8.825
II	30.728	12.00	18.868	29.603
III	14.408	20.247	21.62	10.278

Table 5. Weight loss of solid fuels at different zones, % by weight.

and 29.603%, individually. The ignition temperature of the solid fuels in Table 6 was 235°C for EFB, 254°C for MF, 265°C for PKS and 368°C for coal. Along these lines, peak temperature took after ignition temperature and the value recorded was displayed in Table 6.

Temperature extends between 356 and 780°C is perceived as zone three. It can be seen from **Figure 11** that the rapid combustion of MF and PKS proceeded in this zone with a most extreme weight reduction of 20.247 and 21.62 wt%, individually as listed in **Table 6**. The recorded burnout temperature was 675, 788, 786 and 770°C for EFB, MF, PKS, and coal separately. The peak around 700°C for PKS could be because of the breakdown of calcium carbonate.

3.7. Heat generated from the combustion of solid fuel

The combustion period for solid fuels was around 45 min. 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, 44 and 42 min for EFB, MF, PKS, and coal individually. Likewise, the burning rate and heat discharge from the initial temperature to burnout temperature was additionally determined as displayed in **Table 7**.

As seen from **Figure 11**, the solid fuels showed diverse conduct amid combustion particularly inside zones II and III. 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 7**, EFB fuel indicated high reactivity and therefore brought about high burning rate and heat discharge. The most extreme fuel consumed and heat discharge for EFB were separately observed to be 5.248×10^{-6} kg and 0.059 W. MF fuel discharge less amount of heat since it is less reactive as shown in **Figure 9** which prompted moderate amount of fuel consumed.

Nonetheless, low heat discharged by MF (0.048 W) amid burning could be identified with the low amount of fuel burnt (1.443×10^{-9}). Equivalently, combustion of MF, PKS, and coal may

Solid fuels	Peak temperature (°C)			Ignition temperature	Burnout temperature
	I	II	III		
EFB	57	280	472	235	675
MF	59	287	513	254	788
PKS	67	303	473	265	786
Coal	77	440	671	368	770

Table 6. Peak and burnout temperatures of solid fuels.

Solid fuels	Fuel burnt (kg)	CR (kg/s)	Heat release (W)
EFB	5.248×10^{-6}	2.187×10^{-9}	0.059
MF	3.810×10^{-6}	1.443×10^{-9}	0.048
PKS	4.830×10^{-6}	1.830×10^{-9}	0.051
Coal	5.001×10^{-6}	1.985×10^{-9}	0.052

Table 7. Combustion rate and heat release as at burnout temperature.

Solid fuels	Briquettes (ton)	Power (MW)
EFB	0.177	1.866
MF	0.212	2.055
PKS	0.228	2.414

Table 8. Power generated per 1 ton of raw oil palm biomass.

require 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.

It can be established from **Table 7** that in every 1 mg of EFB briquettes consumed; there is 0.0112 W of heat release. Therefore, based on these, the amount of heat that can be generated from 1 ton of EFB briquette is evaluated and shown in **Table 8**. It can be noticed that 1 ton of raw EFB can deliver 0.177 ton of briquettes which corresponds to 1.866 MW of heat. Furthermore, **Table 8** demonstrated that in every ton of raw MF, roughly 0.212 tons of briquettes could be obtained, which can give up to 2.055 MW of heat. For 1 ton of raw PKS, 0.228 tons of briquette can be delivered, and this connects to around 2.414 MW of heat.

4. Conclusion

During the combustion the primary zone, coal showed the highest weight reduction of 8.825 wt%. In the second zone, EFB showed the highest weight reduction of 30.728%. The rapid combustion of MF and PKS proceed in zone III with a most extreme weight reduction of 20.247 and 21.62 wt% individually. It was found that EFB is the easiest to ignite at 235°C due to high volatile matter content while MF attained the highest burnout temperature of 788°C. The maximum and minimum heat release of 0.059 and 0.048 W were obtained from the combustion of EFB and MF respectively. It was established that in each ton of raw (dry basis) of EFB, fiber, and PKS, there is 0.177, 0.212 and 0.228 tons of charcoal briquettes which corresponds to 1.866, 2.055 and 2.414 MW of heat respectively. Therefore, the findings in this study could contribute toward achieving the targeted 500 MW of green energy initiated in 2005 by the Malaysian government. It can also reduce dependence on fossil fuels for heat generation which in turn reduce the global warming, and minimize deforestation globally. Most importantly, the 100 million tons of oil palm wastes that will be generated in the year 2020 in Malaysia can easily be converted to useful products for heat generation. Also, application of various types of biomass for briquettes production can create job opportunities and enhance environmental sanitation in developing countries.

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Conflict of interest

The authors have declared no conflict of interest.

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