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Characterisation of Oil Palm Frond for Bio-oil Production

N.N. Omar[1]*, N. Abdullah[1], I.S. Mustafa[1] and F. Sulaiman[1]

[1]*School of Physics, Universiti Sains Malaysia, 11800 USM Pulau Pinang, Malaysia*

Oil palm frond is known to be the largest contributor to the oil palm residues, providing up to 50.3% of the total residues. Since it has a very limited utility, an initiative was taken by this study to investigate its suitability for bio-oil production. Hence, slow pyrolysis was conducted in an experimental setup equipped with a fixed bed reactor and a liquid collection system. From the experiments, the effect of reaction temperature on the bio-oil yield was examined. The characteristics of the obtained bio-oil were also investigated to study its potential as a substitute of phenol. It was found that at reaction temperature of 375°C, highest yield of bio-oil was obtained at 38.4 wt%. Meanwhile, the characteristics of oil palm frond and its bio-oil were found to be approximately similar to the characteristics of typical softwoods and their bio-oil. Most softwood biomass has been successfully used as a phenol substitute. Therefore, the potential of this bio-oil to be used as a phenol substitute was enhanced.

Keywords: characterisation, slow pyrolysis, oil palm frond, bio-oil, phenol substitute

I. INTRODUCTION

Since 1960, plantation area of oil palm tree in Malaysia has been growing rapidly. As shown in Figure 1, within 2 years after its initial plantation, approximately 1 million ha was planted with oil palm tree. In 2012, the total plantation area of oil palm tree was reported to be 5 million ha (Malaysia, 2013). In countries of West and Central Africa, Central America and South East Asia, massive plantation of oil palm tree has also been going actively, making the total area of oil palm tree plantation to be more than 13.5 million ha worldwide (Singh *et al.*, 2013).

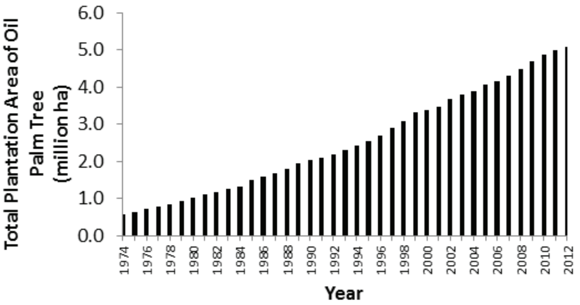

Figure 1. Plantation area of oil palm tree in 1974-2012 (Malaysia, 2013)

Together with the expanding growth of plantation, the destination of huge amount of residues from the oil palm tree raises a concern. Every year, oil palm industry produces more than one hundred million tonnes of residues worldwide. As shown in Table 1, 1 ha of oil palm

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*corresponding author: naja.nadiera@gmail.com tree plantation generates about 21.625 tonnes yr^{-1} residues, with fronds amounting up to half (50.3%) of the total residues (Kelly-Yong *et al.*, 2007).

Table 1. The quantity of oil palm residues generated per year (Kelly-Yong *et al.*, 2007)

Oil palm residues	Quantity generated per ha per year (tonnes)
Empty fruit bunch (EFB)	4.420
Palm kernel shell	1.100
Palm kernel trunk	2.515
Frond	10.880
Mesocarp fibre	2.710
Total	21.625

Therefore, pyrolysis process was used by researchers to optimally exploit these residues. Pyrolysis is a heating process of biomass at moderate temperature ranging from 300^{o}C to 500^{o}C over a period of time (Sulaiman *et al.*, 2013). It occurs in the absence of oxygen. The process decomposes biomass into three main products which are bio-oil, bio char and gaseous fractions. The percentage at which these products being produced is always different depending on the type of pyrolysis, type of biomass used as well as the process parameters such as pre-treatment condition (Sulaiman et al., 2013), reaction temperature and heating rate (Demirbas, 2010).

Pyrolysis can be classified into three main types which are slow, fast, and flash pyrolysis. Slow pyrolysis is the oldest type of pyrolysis and typically produces 30% of bio-oil, 35% of bio-char and 35% of gaseous fraction while fast pyrolysis produces around 50% of bio-oil, 20% of bio-char and 30% of gaseous fraction (Jahirul *et al.*, 2012). Although producing higher percentage yield of bio-oil, the characteristics of bio-oil obtained from fast pyrolysis are somewhat different than those obtained from slow pyrolysis. In slow pyrolysis, the total amount of phenols produced in the bio-oil is 65 wt% higher than those produced from fast pyrolysis of the same biomass. The amount of water present in the bio-oil produced from slow pyrolysis is also 60 wt% lower than those produced from fast pyrolysis (Duman *et al.*, 2011).

Meanwhile, in flash pyrolysis, the products yield is usually subdivided into 75% of bio-oil, 12% of bio-char and 13% of gaseous fraction. However, flash pyrolysis appears to have some technological limitations such as poor thermal stability and corrosiveness of bio-oil as well as high content of bio-char in the bio-oil which negatively affects its long-term viscosity through catalytic action. The alkali concentrated in the bio-char also tends to dissolve in the bio-oil and promotes the production of pyrolytic water (Jahirul *et al.*, 2012).

Various studies have been conducted to convert empty fruit bunch into bio-oil, either by fast pyrolysis (Abdullah and Gerhauser, 2008), slow pyrolysis (Khor *et al.*, 2009) or microwave assisted pyrolysis (Salema and Ani, 2012). The feasibility of palm kernel shell to produce bio-oil has been investigated as well (Kim *et al.*, 2010). However, limited studies were found related to the production of bio-oil originating from palm kernel trunk and palm frond. Slow pyrolysis has been conducted on the two residues to focus only on bio-char production (Khor *et al.*, 2010; Rahman *et al.*, 2014). On the other hand, an investigation has been made on the thermal behaviour of mesocarp fibre during pyrolysis process (Idris *et al.*, 2010).

Meanwhile, several studies have also been carried out to substitute the limited and expensive petroleum-based phenol; usually used in the production of Phenol Formaldehyde (PF) resin with a more natural and economical phenol-rich product (Athanassiadou *et al.*, 2002). Since bio-oil has a high content of phenolic compounds and moderate amount of water, several attempts have been made to incorporate the use of bio-oil into the production of PF resin. In regards to the effort, PF resin was synthesised using bio-oil obtained from fast and slow pyrolysis of pine softwood (Sukhbaatar *et al.*, 2009; Özbay and Ayrilmis, 2015). Bio-oil obtained from fast pyrolysis of white spruce softwood was also used for similar purpose (Chaouch *et al.*, 2014).

In this study, an investigation on slow pyrolysis process was conducted to convert oil palm frond into bio-oil. Pre-characterised oil palm frond was successfully pyrolysed in a fixed bed reactor with a nominal capacity of 150 g. The objectives of this study are to evaluate the effect of biomass used and its process parameters on the bio-oil yield as well as to study the characteristics of the obtained bio-oil so that its potential as phenol substitute can be further explored.

II. MATERIALS AND METHODS

A. Sample Preparation

The oil palm fronds used in this study were harvested in August 2014 in a plantation at Universiti Sains Malaysia (USM), Nibong Tebal district, Pulau Pinang, Malaysia (5^{o}08’48.2’N 100^{o}29’32.0’E). Oil palm fronds abandoned from harvesting process were collected and the leaves attached to them were properly removed using machete as shown in Figure 2(a). Immediately after the removal of the leaves, the oil palm fronds were dried in a Venticell oven at 105^{o}C until their moisture content reduced to less than 10.0 mf wt%, to avoid the growth of fungus or microorganism. The dried fronds were illustrated in Figure 2(b). Then, the length of the oil palm fronds was reduced to approximately 5 cm each using Hitachi band saw machine so that it can be milled by Riken grinder with a screen size of 1.5 mm to obtain samples with smaller size as in Figure 2(c). For that small size of sample, it was expected that other properties such as particle shape, regularity, surface area and volume ratio which may have an influence on the results of pyrolysis experiments will be negligible. These milled fronds were then stored in an airtight container at room temperature under dry condition to prevent any gains or losses in moisture from the atmosphere.

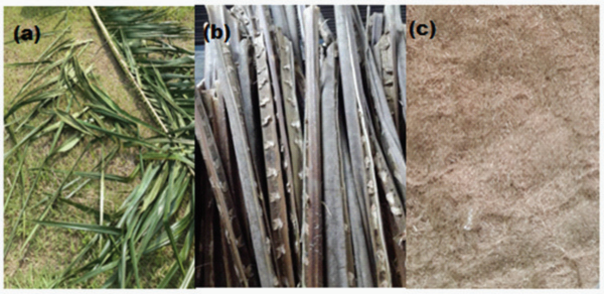

Figure 2. Oil palm fronds: (a) Removal of the leaves from the fronds, (b) Oven dried fronds, (c) Milled fronds

B. Sample Characterisation

Characterisation of the sample involved structural analysis, elemental analysis, proximate analysis, heating value analysis and thermogravimetric analysis. All of the characterisation procedures were performed three times to reduce the uncertainty of the measurements.

1. *Structural Analysis*

In structural analysis, the content of cellulose, hemicellulose and lignin in oil palm fronds were measured. These contents were measured in weight fraction % of dry material (mf wt%).

The analysis was performed by conducting four different tests. Ethanol-toluene solubility test was first conducted according to standard procedure D1107, to obtain extractive-free sample (ASTM, 2007). Using the air dried extractive-free sample, lignin test was carried out following standard procedure D1106 (ASTM, 2001a). Holocellulose test was undergone subsequently using the oven dried extractive-free sample to determine the holocellulose content of the fronds. The test was explained in detail in standard procedure D1104 (ASTM, 1978b). Lastly, cellulose test was performed to determine the cellulose content. The procedure was described in standard procedure D1103 (ASTM, 1978a). The difference between holocellulose and cellulose contents provided the hemicellulose value.

2. *Elemental Analysis*

In elemental analysis, the content of carbon (C), hydrogen (H), nitrogen (N), sulphur (S) and oxygen (O) were determined. Usually, in any biomass, these elements together with ash value sum up to a total of 100% as in Equation 1. The content of these elements were measured in weight fraction % of dry material (mf wt%).

$$Biomass\ (dry)\ :\ C+H+N+S+O+ash=100 \tag{1}$$

Elemental analysis was carried out using Perkin Elmer 2400 CHNS Analyser. During the analysis, combustion was allowed to take place; the sample was burnt in a pure oxygen atmosphere and combustion gases released were automatically measured. From there, carbon, hydrogen, nitrogen and sulphur contents were determined. The oxygen content was calculated by difference in reference to Equation 1.

3. *Proximate Analysis*

In proximate analysis, properties such as moisture content, volatile matter, ash residual and fixed carbon content were investigated. These contents were measured in weight fraction % of dry material (mf wt%).

a. Moisture Content Moisture content in biomass is routinely indicated as the percentage of dry weight present in the biomass. Its determination was conducted as received sample according to the standard procedure E871 and was calculated using Equation 2 (ASTM, 1998).

$$Moisture\ content,\ MC(\%) = \frac{W_i - W_f}{W_i} x100 \tag{2}$$

Where, W_i is the initial weight of the sample, while W_f is the final weight of the sample after drying procedure.

b. Volatile Matter Volatile matter refers to the fraction of biomass that will be readily volatilised when heated to a high temperature, in a standard condition. This volatile matter usually consists of combustible gases and incombustible gases.

In the study, volatile matter was determined following standard procedure E872 (ASTM, 2006). From the standard procedure, weight loss and volatile matter were calculated using Equation 3 and Equation 4 respectively.

$$Weight\ loss,\ WL(\%) = \frac{W_i - W_f}{W_i} x100 \tag{3}$$

$$Volatile\ matter,\ VM(\%) = WL(\%) - MC(\%) \tag{4}$$

c. Ash Content Ash content is defined as the residue or the incombustible material left off the biomass after a complete combustion was introduced. To determine the value of ash content, standard procedure D1102 and Equation 5 were used (ASTM, 2001b).

$$Ash(\%) = \frac{W_i - W_f}{W_i} x100 \tag{5}$$

d. Fixed Carbon Fixed carbon is the remaining weight of the biomass after its volatile matter and ash contents are removed. Throughout the study, fixed carbon was calculated according to Equation 6.

$$Fixed\,carbon,\ FC(\%) = 100 - VM(\%) - Ash(\%) \tag{6}$$

4. *Higher Heating Value (HHV) Analysis*

HHV analysis was performed using a Nenken 1013-B bomb calorimeter. In this analysis, combustion of sample was allowed to take place under certain defined conditions. The analysis was precisely conducted according to the standard procedure D2015 (ASTM, 2000).

5. *Thermogravimetry (TG) and Derivative Thermogravimetry (DTG) Analysis*

TG/DTG analysis examined the thermal behaviour of biomass using Thermal Gravimetric Analyzer TGA/DSC-1 Mettler Toledo. During the analysis, nitrogen gas with 50 ml min^{-1} flow rate was employed to introduce an inert atmosphere. The heating temperature was varied from room temperature to 650^{o}C with 10^{o}C min^{-1} as the heating rate.

C. Pyrolysis Experiments

A series of experiments was conducted to determine the percentage yield of bio-oil from pyrolysis of oil palm fronds. Figure 3 shows the schematic diagram of pyrolysis experimental setup constructed in the study. It involved two main parts; fixed bed reactor and liquid collection system. The fixed bed reactor was equipped with a pyrolyser manufactured by Fobina Engineering & Supply Sdn Bhd, Pulau Pinang, Malaysia. This pyrolyser is a stainless steel container with 15 cm in length and 6.5 cm in diameter. A K-type thermocouple with diameter of 1.6 mm and length of 283 mm was installed to the pyrolyser to monitor the reaction temperature. This thermocouple was then connected to TC-08 Pico Data Logger which was supplied with Pico Log data acquisition software for data recording. On the other hand, the liquid collection system comprised condensers and oil pots that helped to condense the vapours released from the reaction and collect the condensed liquid (bio-oil) respectively. The condensers were cooled to 5^{o}C using a mixture of distilled water and ethylene glycol at 1:1 volume ratio while the oil pots were cooled to 0^{o}C using ice.

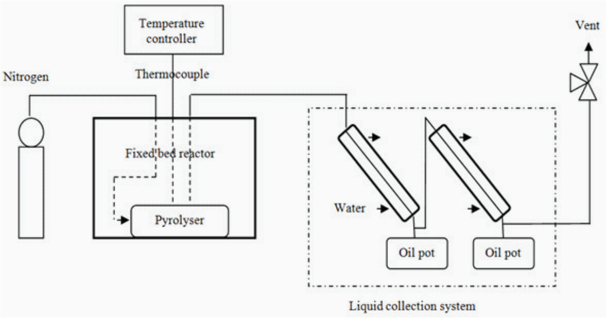

Figure 3. Schematic diagram of pyrolysis experimental setup

Before any run, all equipment such as pyrolyser, connecting tubes, condensers and oil pots were weighed. Then, 150 g of oil palm frond was introduced into the pyrolyser so that it can be heated externally by Thermolyne F62700 muffle furnace. This furnace was manually set to the required temperature and heating rate. The heating rate was standardised at 100^{o}C min^{-1} since highest yield of bio-oil was obtained at that heating rate (unpublished data). In every run, the percentage deviation of temperature between furnace and the thermocouple was from 3% to 5%. From the start, nitrogen gas with 99.9% purity was purged into the system at 100 ml min^{-1} to sweep the vapours released during the reaction away from the hot zone so that secondary cracking can be prevented.

The reaction was maintained at the required temperature for 1 hour. After 1 hour of elapsed time, the muffle furnace was allowed to stabilize to room temperature before any measurement was taken. The char yield from the run was calculated from the weight difference of pyrolyser while bio-oil yield was determined from the weight difference of connecting tubes, condensers and oil pots. The percentage of gas yield was calculated from the percentage difference of bio-oil and bio-char yields.

D. Analysis of Bio-oil

Bio-oil obtained from the pyrolysis experiment was subjected to several analyses to determine its elemental composition, ash content, char content, HHV and pH value.

The elemental composition of bio-oil such as carbon, hydrogen, nitrogen and sulphur were determined using Perkin Elmer 2400 CHNS Analyser while oxygen content was calculated from the percentage difference of the other components and ash value. This ash value was determined according to standard procedure D1102 (ASTM, 2001b). Besides, filtration method was initiated to define the char content of bio-oil. The bio-oil was diluted using methanol at 1:10 weight ratio. Then, it was filtered using Advantec Grade No. 1 qualitative filter paper. The residue left off the filter paper was oven dried at 105^{o}C to conclude the char content. HHV was determined using Nenken 1013-B bomb calorimeter while pH value was determined using Accumet AB15 pH meter. All of the measurements were conducted in triplicate at room temperature (unless stated) to calculate the uncertainty of measurements.

III. RESULTS AND DISCUSSION

A. Sample Characteristics

Table 2 presents the data obtained from different type of analyses conducted throughout the study. From structural analysis, it was shown that fronds had comparable amount of cellulose and hemicellulose with other softwood but lower amount of lignin. It has been reported that during pyrolysis, cellulose was usually decomposed into bio-oil. Therefore, assuming that the other characteristics were identical to typical softwood, it was expected that fronds may produce approximately similar yield of bio-oil as the other softwood (Jahirul *et al.*, 2012).

Apart from that, an abundance of carbon and oxygen were found in oil palm frond and other typical softwood. High content of carbon and oxygen were seen to be quite promising in producing high yield of organic-rich bio-oil, which was made of mainly hydrocarbon and free oxygen. Oil palm frond was also seen as an environmentally friendly material with a trace content of nitrogen and sulphur. It has been previously reported that nitrogen and sulphur in biomass were the main environmental impact of biomass decomposition. During the decomposition, nitrogen was converted into ammonia gas and hydrogen cyanide gas, while sulphur was transformed into hydrogen sulphide gas (García *et al.*, 2012).

Besides, pyrolysis process required biomass with moisture content around 10 mf wt% (Yang *et al.*, 2005). Higher moisture content in biomass had negative impact on the physical properties of bio-oil since bio-oil with less stability and low viscosity might be produced. From the table, oil palm frond had high amount of moisture. Therefore, before being pyrolysed, the oil palm frond was dried sufficiently.

From proximate analysis also, it was shown that oil palm frond had significantly higher ash content than any other typical softwood. Hence, fronds may produce higher yield of bio-char at every reaction temperature as compared to those produced from pyrolysis of softwood (Demirbas, 2010).

In addition, although the HHV of oil palm frond was calculated to be 18.1 MJ kg^{-1}, slightly lower than the heating value of softwood, it was reported that biomass with heating value greater than 15 MJ kg^{-1} was still suitable to produce a commercially beneficial bio-oil (Saidur *et al.*, 2011).

In general, it can be summarised that the composition of oil palm frond displayed a great resemblance to the composition of any other type of softwood, except for the value of ash. As previously explained, this difference may contribute to higher yield of bio-char when pyrolysis of oil palm frond was conducted.

Table 2. The characteristics of oil palm frond

	Oil palm frond			Typical softwood	
Type of Analysis	Measured value	Literature value	Reference	Literature value	Reference
Structural (mf wt%)					
Cellulose	47.3 ± 1.1	49.8	(Atnaw et al., 2012)	45-50	(Saidur et al., 2011)
Hemi-cellulose	27.3 ± 1.9	23.5		25-35	
Lignin	20.1 ± 2.4	20.5		25-35	
Elemental (mf wt%)					
C	42.9 ± 1.2	42.4	(Atnaw et al., 2013)	47.0-54.0	(Telmo et al., 2010)
H	6.9 ± 1.4	5.8		5.6-7.0	
N	0.5 ± 0.1	3.6		0.1-0.5	
S	0.03 ± 0.02	-		0.01-0.05	
O	46.3 ± 2.4	48.2		40.0-44.0	
Proximate (mf wt%)					
Moisture	37.47 ± 0.25	-	(Atnaw et al., 2013)	-	(Telmo et al., 2010)
Volatiles	82.4 ± 1.4	85.1		76.0-86.0	
Ash	3.44 ± 0.02	3.4		0.3	
Fixed carbon	14.2 ± 1.6	11.5		15.0-25.0	
Heating Value					
HHV (MJ kg^{-1})	18.1 ± 0.3	17.3	(Guangul et al., 2012)	19.5	(Saidur et al., 2011)

In addition, Figure 4 shows TG/DTG curve of oil palm frond with temperature ranging from 100^oC to 650^oC. At 100^oC, the TG curve marked the value of 92.7 mf wt%, signifying that at room temperature, 7.3 mf wt% of moisture existed in the biomass. The curve then illustrated that from 100^oC to 220^oC, no significant change in weight loss occurred indicating that a very small amount of extractives is present in the biomass. It was stated that degradation of extractives occurred within that range of temperature (Abdullah *et al.*, 2007). However, from 220^{o}C to 335^{o}C, noticeable change in weight loss was observed, probably due to the decomposition of lignocellulosic components (cellulose, hemicellulose, and lignin) in the biomass. The DTG distribution verified that the decomposition of lignocellulosic components occurred within 220^{o}C to 335^{o}C since the two significant change at 280^{o}C and 320^{o}C indicated maximum hemicellulose and cellulose degradation respectively.

Meanwhile, lignin has a more heterogeneous behaviour and decomposed over a wide range of temperature until it reached maximum decomposition at 335^{o}C. From 335^{o}C onwards, moderate weight loss observed was attributed to the presence of lignin with higher difficulty to degrade thermally. At 650^{o}C, around 22 mf wt% of biomass remained as residue.

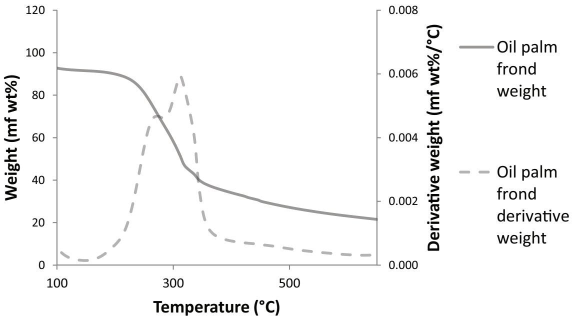

Figure 4. TG/DTG curve of oil palm frond

A study on a common type of softwood biomass (white pine) for energy production has been reported previously. The thermal degradation behaviour of the biomass was investigated using TG analyser (Netzsch Thermische Analyse TASC 414/2) at temperature ranging from 25^{o}C to 900^{o}C. The TG curve of the biomass showed significant weight loss between 180^{o}C to 500^{o}C. Moreover, DTG peaks of the biomass were obtained at 315^{o}C and 380^{o}C, which indicated maximum decomposition of hemicellulose and cellulose respectively (Chiodo *et al.*, 2016). This implies that softwood biomass needed higher temperature to allow maximum degradation to occur than those required by oil palm frond.

B. Pyrolysis Yield

From the TG/DTG analysis result, it was shown that at 335^{o}C, maximum degradation of lignocellulosic components of oil palm frond has been achieved; as indicated by the noticeable change in weight loss. Therefore, the pyrolysis temperature was selected to be above the decomposition temperature so that maximum degradation of the biomass sample can be established.

In Figure 5, the effect of pyrolysis temperature on the products distribution was illustrated. When the temperature was increased from 350^{o}C to 375^{o}C, the bio-oil yield increased from 36.8 wt% to 38.4 wt% of the overall product. However, upon reaching 375^{o}C onwards, the bio-oil yield decreased continuously reaching the lowest yield of bio-oil which was 35.9 wt%. This implies that at higher temperatures, secondary cracking of pyrolysis vapours occurred. The yield of pyrolysis gas was promoted at the cost of bio-oil when this secondary cracking took place. On the other hand, bio-char yield decreased gradually with increasing temperature, probably due to the secondary decomposition as well (Ertaş and Alma, 2010).

The bio-oil yield in this study seemed to be quite low, considering other slow pyrolysis studies involving softwood sample. In a study by Boucher et al. (2000), vacuum pyrolysis of softwood bark composed of 70 wt% fir, 28 wt% white spruce and 2 wt% larch was carried out. From the study, maximum yield of bio-oil was calculated to be 44.0 wt%, at pyrolysis temperature of 500^{o}C (Boucher *et al.*, 2000). Another study reported that the pyrolysis of Douglas-fir and pine bark at 500^{o}C in a fixed bed reactor generated 48.2 wt% and 45.2 wt% of bio-oil respectively (Pan *et al.*, 2013). Similarly, pyrolysis of Picea abies softwood residues was conducted in a fixed bed reactor. At 550^{o}C, 50 wt% of bio-oil yield was produced (Torri *et al.*, 2016). The low percentage yield of bio-oil obtained from pyrolysis of oil palm frond was mostly possible due to the high content of ash in oil palm frond, which eventually increased the total percentage yield of bio-char.

C. Analysis of Bio-oil

In all experiments, the bio-oil obtained was homogenous and dark brown in colour. The characteristics of bio-oil (obtained at 375^{o}C) were tabulated and compared with other softwood-derived bio-oil as in Table 3.

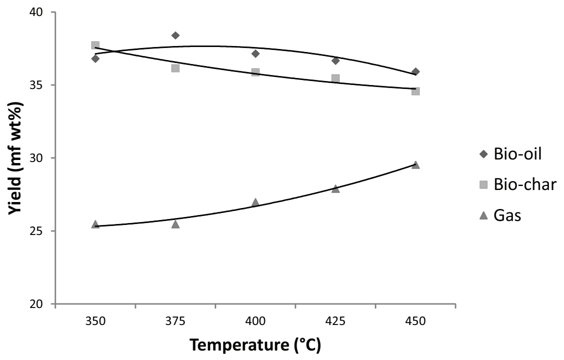

Figure 5. The effect of pyrolysis temperature on the products distribution

From the elemental analysis, an increase in carbon content and a decrease in oxygen content as compared to the raw oil palm frond were observed. This was favourable since low oxygen content of bio-oil initiated a possibility for petroleum fuel replacement (Abdullah *et al.*, 2007). The amount of ash found in the bio-oil was 0.6 mf wt% while the char content was determined to be 0.3 mf wt%. In addition, the energy content was calculated to be 18.2 MJ kg^{-1}; approximately similar to the energy content of raw sample of oil palm frond. The pH value of bio-oil was found to be within the acidic range. This finding is in agreement with other published data that mentioned bio-oil generally contained substantial amount of organic acid, mostly acetic acid and formic acid, hence giving the bio-oil its low pH (Duman et al., 2011).

In general, the characteristics of bio-oil produced from oil palm frond were found to be very similar to those produced from pine wood, pine bark, fir wood and other typical softwood, except for the value of ash content. The ash content of bio-oil produced from oil palm frond was calculated to be higher than the other softwood. This is indeed expected since the ash value of raw oil palm frond was higher than those of other type of woods.

Table 3. The comparison of bio-oil characteristics obtained from oil palm frond and other softwood biomass from other published results

Characteristics	Oil palm frond	Pine wood (Ingram et al., 2007)	Pine bark (Ingram et al., 2007)	Fir (Boucher et al., 2000)	Typical value from other softwood (Mohan et al., 2006)
Element (mf wt%)					
C	66.2 ± 1.1	52.64	53.99	58.12	54-58
H	9.4 ± 1.2	7.53	6.97	6.55	5.5-7.0
N	0.05 ± 0.02	0.09	0.37	0.52	0-0.2
S	0.00 ± 0.00	0.02	0.04	–	–
O	23.8 ± 2.3	39.52	38.21	34.81	35-40
Ash content (mf wt%)	0.6 ± 0.0	0.20	0.43	< 0.05	0.2
Char content (mf wt%)	0.3 ± 0.1	0.19	2.10	–	0.2-1.0
HHV (MJ kg^{-1})	18.2 ± 0.6	21.9	18.3	22.2	16-19
pH	3.0 ± 0.0	3.1	3.2	–	2.5

The characteristics of bio-oil produced from oil palm frond have shown a great resemblance with bio-oils produced from softwood in terms of physical and elemental characteristics. For future works, this bio-oil can be further investigated as a phenol substitute since several successful attempts have been made to incorporate the use of bio-oil obtained from softwood into the production of PF resin (Sukhbaatar *et al.*, 2009; Chaouch *et al.*, 2014; Özbay and Ayrilmis, 2015).

IV. CONCLUSION

A series of pre-characterised oil palm frond has been successfully pyrolysed using a fixed bed reactor. The highest yield of bio-oil was produced at reaction temperature of 375^{o}C. At that temperature, the characteristics of bio-oil produced were found to be very similar to the typical characteristics of bio-oil produced from other softwood that has been successfully used as a phenol substitute. Hence, the potential of bio-oil produced from oil palm frond to be adopted as a phenol substitute was enhanced as well.

V. ACKNOWLEDGEMENTS

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