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Bio-oil from the pyrolysis of palm and Jatropha wastes in a fluidized bed

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ABSTRACT

The pyrolysis of Jatropha seedshell cake (JSC), palm kernel shell (PKS) and empty palm fruit bunches (EFB), as waste from the palm and Jatropha oil industries, was investigated in a fluidized bed (0.102 m id., 0.97 m-high). The effects of bed temperature and gas flow rate on the product yields and properties of pyrolytic liquid have been determined. The pyrolytic liquid product and fractionated oil yields of JSC were maximized at 48 wt.% and 32 wt.% with increase of bed temperature. Gas velocities of 8–9 U_{mf} led to maximized pyrolytic liquid yield by balancing yield-increasing by much vigorous bubbling and bed mixing in fluidized bed reactor and yield-decreasing by reduction of heat transfer coefficient with increase of gas velocity. The pyrolytic oils from the wastes are characterized by more oxygen, lower HHVs, more nitrogen and less sulfur than petroleum fuel oils. The oils from JSC and PKS contained more fatty acid and glycerides than other oils from lignocellulose biomass such as the EFB, which contained more phenolic derivatives. The finding indicates that they were similar to palm fatty acid distillate from palm oil and could be used as alternative feedstocks for biodiesel production using hydrotreating process.

1. Introduction

Much attention has focused on identifying suitable biomass species capable of high energy outputs to replace conventional fossil fuels. However, low conversion efficiency, availability and logistical constraints are major challenges to the large scale development of biomass-based facilities for the production of fuels and chemicals [1]. One of the most viable renewable energy sources is biomass from agricultural residues [2], because it is cheap, abundant and does not require significant effort to collect. The residue from agricultural product such as fruit for oil production has an additional benefit in terms of transportation because it can be utilized on the spot after oil processing.

Palm and Jatropha oils are produced in mills by streaming and pressing the fruits. Significant amounts of solid wastes, including shells, fiber and kernels, are generated, some of which is currently used as low energy efficiency fuel for boilers [3]. Efficient management of the wastes like thermochemical conversion to valuable product is required to improve process efficiency and economics in overall oil production.

Pyrolysis is one of the most promising technologies of biomass utilization, which converts the biomass to bio-oil, char and gasses depending on the pyrolysis conditions [4]. The pyrolysis is a thermal degradation of materials in the absence of oxygen. The pyrolysis can be a promising residue management option because bio-oils derived from biomass pyrolysis could act as feedstocks for producing hydrocarbons that may be readily integrated into the existing petroleum refineries or future bio-refineries.

The effects of pyrolysis parameters on oil yields from Jatropha and palm wastes in fixed and fluidized bed reactors have been widely studied [2,3,5–7]. These studies showed that different types of waste have their own optimal operating conditions for relatively high bio-oil yields. However, the bio-oils in these studies were not considered practically for use as fuel and pyrolysis product yields and compositions depend greatly on the biomass species and composition [3].

In this study, Jatropha and palm wastes were pyrolyzed in a fluidized bed pyrolyzer. Pyrolysis behavior and yields have been determined and the pyrolytic bio-oils were characterized and compared with petroleum fuel oils and feedstocks for bio-diesel production. Possible applications of the oils are discussed with respect to their practicalities in refineries.

2. Materials and methods

2.1. Raw material

Samples of Jatropha (*Jatropha curcas* L.) seedshell cake (JSC), palm kernel shell (PKS) and empty palm fruit bunch (EFB) were acquired from an oil extraction plant in Indonesia. Properties of JSC and palm

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Table 1
Characteristics of Jatropha seedshell cake, palm kernel shell and empty palm fruit bunch.

Biomass feedstock	JSC	PKS	EFB
Proximate analysis (wt.%)			
Moisture	2.65	5.92	7.38
Volatiles	79.80	71.31	76.41
Fixed carbon	14.13	17.81	11.57
Ash	3.42	4.99	4.64
HHV (MJ/kg)	20.80	18.51	18.74
Elemental analysis (wt.%)			
C	50.52	44.6	51.78
H	6.15	6.50	7.04
O	39.41	40.20	40.31
N	2.32	2.92	0.72
S	–	<0.1	0.16
Component analysis (wt.%)			
Cellulose	36.64	30.59	59.7[a]
Hemicellulose	4.82	30.64	22.1[a]
Lignin	39.61	20.41	18.2[a]
Others	18.94	18.36	

[a] Data from Abdullah and Gerhauser (2008) [8].

shell, including proximate and elemental analyses, higher heating values (HHV) and chemical compositions are listed in Table 1. Proximate analysis was carried out by an analyzer of model Thermostep (ELTRA) according to the ASTM 5142 standard test method. The proximate analysis showed volatiles (mainly organic), of 79.80 wt.% in JSC, 71.31 wt.% in PKS and 76.41 wt.% in EFB. Elemental composition by ultimate analysis was obtained by an elemental analyzer of model EA 1108 (Fisons instruments) according to the ASTM D3176 standard procedures. The elemental analysis showed that JSC and palm wastes mainly consisted of carbon and oxygen. The HHVs (Parr-1261, Parr Instrument) of JSC and palm wastes were *ca.* 18–21 MJ/kg, similar to that of typical biomass. Chemical composition for macrocomponents was determined according to the TAPPI (Technical Association of the Pulp and Paper Industry) method. For these determinations, first removal of soluble extractives was performed according to TAPPI T264 om-97. Then, lignin and cellulose were determined according to TAPPI T222 om-83 and TAPPI T203 os-74, respectively, and holocellulose according to Browning method [9]. Hemicellulose concentration was calculated as the difference between holocellulose and cellulose. Chemical composition analysis showed JSC to have higher lignin and lower hemicellulose contents than palm wastes.

To compare the properties of the pyrolytic oils with petroleum fuel oils, high sulfur diesel (HS diesel) and heavy fuel oil (HFO) samples with low and high sulfur content were acquired from SK Energy's Ulsan complex, Korea. Crude palm oil (CPO) and palm fatty acid distillate (PFAD) samples were also obtained from an oil mill in Pertamina, Indonesia.

2.2. Experiments

JSC and palm waste samples were ground and sieved to 0.125–1.40 mm using an electric mixer and standard sieves. The resulting particles were dried at 80 °C for 24 h until constant weight. Bed materials for the fluidized bed pyrolyzer were selected considering fluidity, stability and abrasion resistance: silicon carbide ($d_p = 190\ \mu m$, $\rho_s = 3210\ kg/m^3$) was used for JSC and PKS and non-catalytic zirconia beads ($d_p = 187.5\ \mu m$, $\rho_s = 3800\ kg/m^3$) for EFB.

The pyrolysis system (Fig. 1) consisted of a mass flow controller (MFC), main column, screw feeder, cyclone, condensers, and accumulative flowmeter. The flow rate of nitrogen (99.9%) for fluidization was controlled by the MFC and the volume of product gas was measured by the accumulative flowmeter. Before entering the stainless steel fluidized bed reactor (0.102 m id. and 0.97 m high), the fluidizing N_2 gas was preheated in the air plenum to 450–600 °C. A distributor with 7 bubble caps, each with 4 orifices (holes of 1 mm), was fitted at the bottom of the reactor to allow even gas distribution. To prevent condensation of the pyrolysis vapor, the reactor's top and the pipe connecting the reactor to the 1st condenser were maintained at 400 °C. Refrigerant was circulated in the shell of the condensers by a chiller system. The gas was sampled by a gas sampler to analyze its composition.

Pyrolysis tests were conducted at 380–530 °C with N_2 flow rates of 15–41 L/min at 25 °C (superficial gas velocities of 0.031-0.084 m/s), corresponding to *ca.* 4–11 U_{mf} at 500 °C and bubbling fluidization

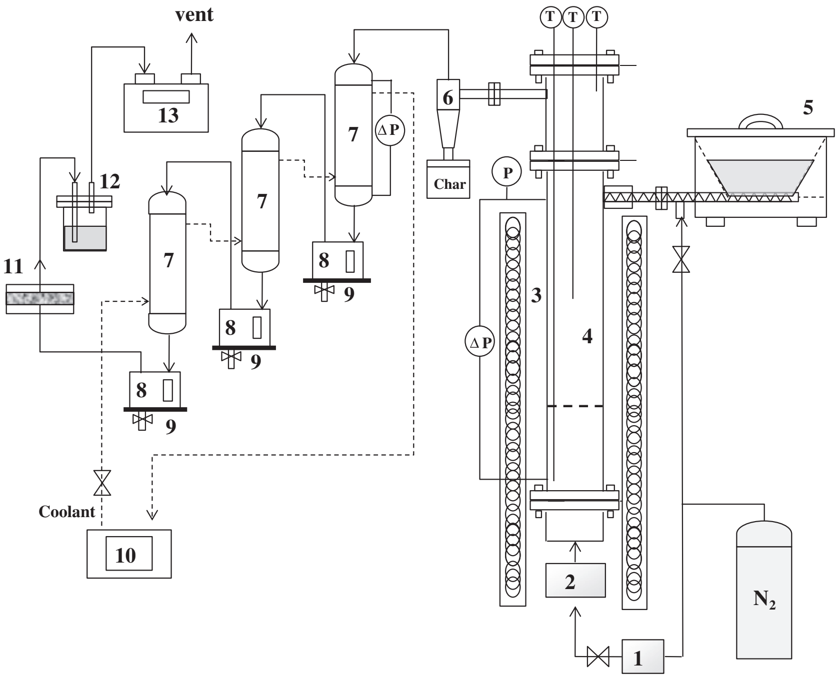

Fig. 1. The experimental apparatus. 1 mass flow meter; 2 preheater; 3 furnace (electric heater); 4 fluidized bed reactor(pyrolyzer); 5 screw feeder; 6 cyclone; 7 condenser; 8 sampling pot; 9 heating plate; 10 chiller; 11 oil filter; 12 water trap; 13 accumulated gas flowmeter; P pressure gage; ΔP differential pressure gage; T thermowell.

regime. Static bed heights of 0.2 m were maintained in each test, giving residence times of the pyrolysis vapor out of the bed of *ca.* 3.3–4.9 s considering expansion of the fluidized bed, which depended on temperature and gas velocity. Biomass particles (average size = 0.7 mm) were fed at 0.94 kg/h. Pyrolysis liquid product was collected in the oil sampling pots. Aerosol from the condenser was trapped in an oil filter. After pyrolysis, the filter was washed with methanol. The amount of trapped pyrolysis oil was determined after evaporating the solvent.

2.3. Product analysis

The collected liquid was distilled at 100 °C to separate aqueous and oil phases using a set of 3 batch fractionators which simulate simple oil refining. To assess the oils' applicability as fuel, the oil phase products were characterized by the standard procedures used to assess conventional petroleum fuel. The following properties were determined: (a) specific gravity (ASTM D-4052), (b) calorific values (ASTM D-2222), (c) total acid number or TAN (ASTM D-664), (d) distillation curve (ASTM D-2887), (e) proximate analysis by thermogravity analyzer (Thermostep, ELTRA), (f) elemental analysis by elemental analyzer (EA1110, CE instruments), and (g) water content by Karl fisher titration (ASTM D-1744). The oil phase was characterized by GC/MS analysis (GC/MS 5972, Agilent) to determine its qualitative and quantitative composition.

3. Results and discussion

3.1. Pyrolysis behavior and product yields

The effect of pyrolysis temperature on the JSC product yield is shown in Fig. 2(a) at a fluidizing gas velocity of 0.15–0.18 m/s (7.6–9.6 U_{mf}) in a 0.2 m high static bed height. Pyrolytic liquid and fractionated oil yields were maximized at 48 wt.% and 32 wt.% at 470–480 °C. Gas yield increased and char yield decreased with increasing temperature. At below 400 °C, incomplete pyrolysis led to low liquid yield and high char yield. As temperature increased, primary thermal decomposition and the subsequent secondary reactions of char with volatiles increased to yield more volatiles [10]. At above 500 °C, heavy molecular hydrocarbons were decomposed by secondary thermal decomposition and cracking reactions that converted pyrolytic liquid to gas [11] as shown in the figure.

The effect of pyrolysis temperature on molecular ratio of the pyrolytic oil and its higher heating value (HHV) is shown in Fig. 2(b) and (c). The O/C molar ratio decreased and the H/C molar ratio increased with increasing temperature. At low temperature, the primary decomposition of hemicelluloses and cellulose in lignocellulosic biomass produces oxygen containing gasses and decreases the O/C ratio in the liquid product. At higher temperatures, secondary reactions of volatiles dominate and CO and methane become the main components of the product gas [12]. The increase of methane possibly makes H/C ratio low in liquid product at above 480 °C. These variations of O/C and H/C molar ratios resulted in HHV being maximized at 480 °C because of its dependence on the oxygen and hydrogen contents of the liquid.

Many researchers have studied biomass pyrolysis in both fluidized bed reactor and fixed bed reactors with much attention paid to the effect of temperature. However, biomass pyrolysis is also influenced by many other parameters including particle size, heating rate, feed rate and biomass species [13]. In many parameters, particle size, heating rate and feed size are related with the fluidization properties. Pyrolysis also should be analyzed with respect to the factors affecting the fluidization properties, even though temperature plays a major role in the biomass pyrolysis.

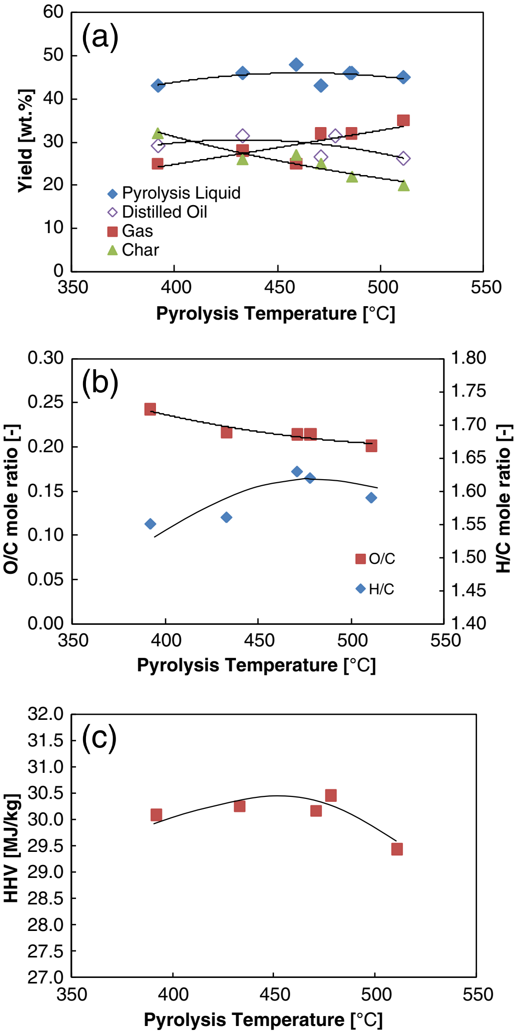

Fig. 2. Effects of bed temperature on pyrolysis product yield (a), molecular ratio (b) and higher heating value of distilled pyrolytic oil (c).

Effects of fluidization properties on pyrolysis behavior were assessed at 478 °C in Fig. 3(a)–(c). The effect of gas velocity (u_g) on bubble fraction was analyzed in Fig. 3(a). Bubble fraction (δ_b) was calculated within the experimental range based on the Kunii–Levenspiel model [14] (Eq. (1)).

$$\delta_b = \frac{u_g}{u_b} \tag{1}$$

where the bubbles' rising velocity(u_b) is calculated by Eq. (2).

$$u_b = \left(u_g - u_{mf}\right) + u_{br} \tag{2}$$

where u_{mf} is the minimum fluidization velocity. The u_{mf} is 0.0196 m/s at 500 °C, which was determined by the measurement of pressure drop across bed as the gas flow was increased.

A single bubble's rising velocity (u_{br}) is calculated by Eq. (3).

$$u_{br} = 0.711\left(gd_b\right)^{1/2} \tag{3}$$

Average bubble diameter (d_b) is obtained by Eq. (4) [15].

$$d_b = 0.138 h_b^{\;0.8}\left(u_g - u_{mf}\right)^{0.42} \exp\left(-2.5\times10^{-5}\left(u_g - u_{mf}\right)^2 - 10^{-3}\left(u_g - u_{mf}\right)\right)$$

where h_b is bed height and is 0.2 m in this study.

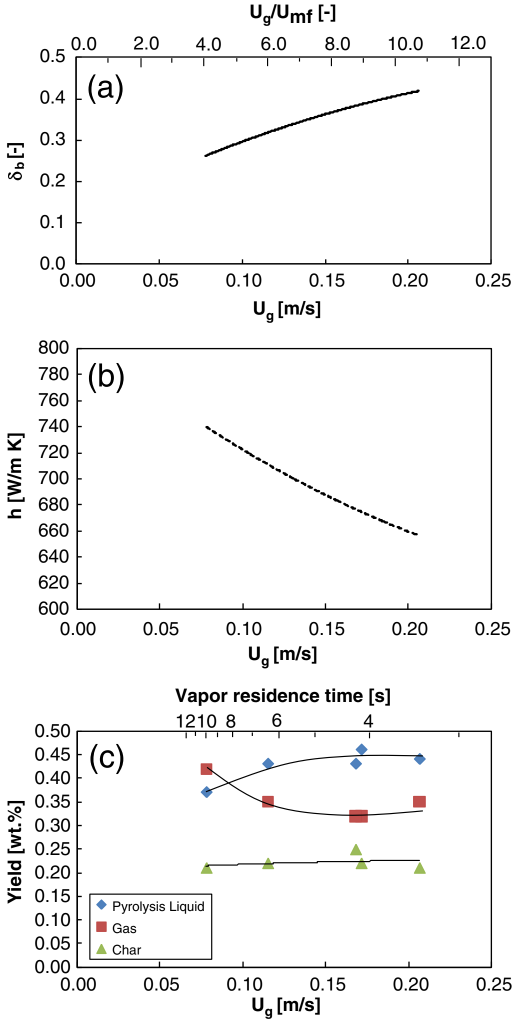

Fig. 3. Effect of gas velocity on bubble fraction (a), heat transfer coefficient in the bed (b) and product yield (c).

Bubble fraction increased with increase of gas velocity (u_g) and fluidizing number (u_g/u_{mf}). Bubble behavior becomes more vigorous with increase of bubble fractions induced at higher gas velocity. This resulted in vigorous solid movement and better mixing in the fluidized bed. Increasing gas velocity made more bubbles that aided contact between the hot bed material and the injected feedstock. However, heat transfer between immersed object and bed particles is governed by particle packet movement [16,17]. The heat transfer coefficient (h, Eq. (5)) is slowly decreased at increased gas velocities through the decreased contacting time of the packets and the objects due to the increased bubble fraction as in Fig. 3(b) [17].

$$h = h_r + h_g + 1.13\left[k_e \rho_s \left(1-\varepsilon_{mf}\right) C_{ps} n_w \left(1-\delta_b\right)\right]^{1/2} \tag{5}$$

where, k_e is the effective thermal conductivity of the bed and 0.213 W/m K in the study, which is calculated based on nitrogen conductivity (0.026 W/m K) and particle conductivity (18 W/m K) [14,17]. C_{ps} is the particle specific heat (837 J/kg K), and ε_{mf} is the measured voidage (0.492) at u_{mf} condition. n_w is bubble frequency and is 2.0 in the study, which is obtained from Kunii and Levenspiel's study [14].

The trade-off between bubble behavior and heat transfer resulted in gas velocities of 8–9 u_{mf} being optimal for liquid yield as shown in Fig. 3(c). This gas velocity range resulted in short vapor residence times of typical fast pyrolysis. Although the *ca.* 2 s, optimal vapor residence times to prevent the secondary cracking of volatiles in fast pyrolysis [18], were not achieved, the system approached maximum liquid yield with showing little variation at higher gas velocity as in Fig. 3(c). This is because ejected particles from the bed with the high particles entrainment rates at increased u_g led to further cracking through the contact of hot particles and volatiles. Based on the results, a u_g of 0.17 m/s at 478 °C was chosen for the comparison of the pyrolysis of different wastes.

3.2. Characterization of the pyrolysis product of different wastes

Fig. 4 shows product distribution in pyrolysis of palm and Jatropha wastes at 478 °C. Pyrolysis liquid yields showed 48–54 wt.% and JSC and PKS showed no significant differences of the liquid yields. EFB showed a higher fractionated oil yield than the other wastes. The liquid yield is seem to be reasonable, compared with other fast pyrolysis studies [2,3,5–7], although yields varied with reactor type or geometry and the fluidizing conditions, such as gas velocity and static or expanded bed height in the bed. The lowest amount of char was obtained from PKS. Char formation is related with the lignin [19] and cellulose [20,21] contents. The lignin, which is polyaromatic compound, can be partly converted into the char in the pyrolysis. The char may form directly from cellulose by dehydration and secondary char can be formed from the repolymerization of primary product. Although the primary char formation from cellulose pyrolysis is not the dominant reaction in the fluidized bed pyrolysis with high heating rate, the secondary char formation can contribute to the increase of char yield in this study because hot particle entrainment causes the secondary reaction of volatile by as described in Fig. 3(c). Such a relationship between lignin and cellulose contents and char yield was observed here. The pyrolysis liquid's aqueous proportions did not vary greatly between wastes. This is reasonable, given that it originated from dehydration reactions of organic compounds at similar temperature and free water in biomass after the same pretreatment of the raw materials.

EFB showed the lowest gas yield. In composition of gas, carbon oxides (mainly CO_2) were dominant at *ca.* 94–97 wt.%. CO_2 is produced by the primary pyrolysis of cellulose and hemicellulose [22]; CH_4 and CO are mainly produced by the secondary cracking of volatiles [13]. Methane was produced at 2.7–5.4 wt.% and hydrogen at 0.1–0.3 wt.% because the experimental conditions were chosen to maximize primary cracking. The composition of gas products did not vary greatly between the biomass types, and these results agreed well with previous works on fast pyrolysis [12,13].

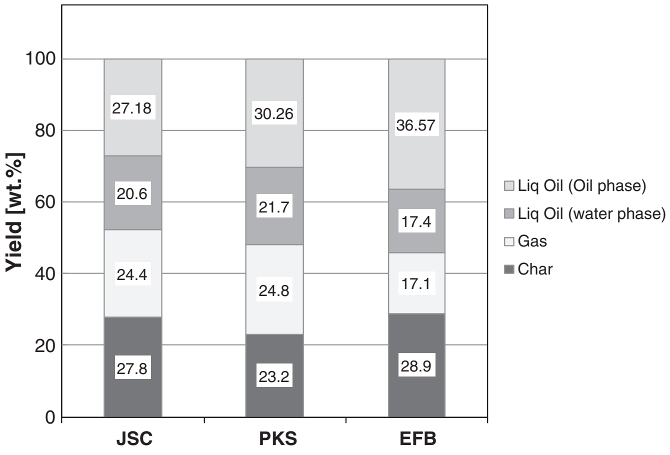

Fig. 4. Product distributions from the pyrolysis of Jatropha and palm wastes.

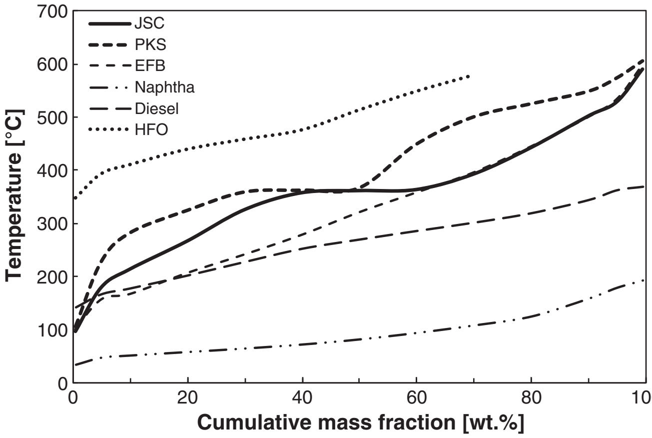

Fig. 5. Boiling point distributions of pyrolytic oils and petroleum fuel oils.

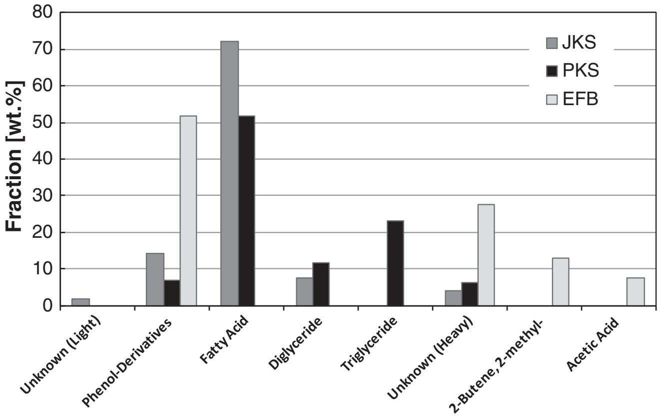

Fig. 6. Compound distributions of pyrolytic oils from Jatropha and palm wastes.

Fig. 5 shows boiling point distributions of pyrolytic oils and their comparison with petroleum fuel oils to provide basic information that the obtained oils correspond to which petroleum fuel application. Oils from palm and Jatropha wastes showed wide distributions from 100 to 600 °C due to water removal. EFB showed a uniform distribution with almost constant slope; JSC and PKS showed plateaus at *ca*. 360 °C, implying that several compounds were highly concentrated in the pyrolytic oil. In comparison with petroleum fuel oil, the pyrolytic oils are in the range of diesel and heavy fuel oil. Major portion of the JSC and PKS oils is expected to be shifted possibly into the diesel range if they were deoxygenated for blending with petroleum fuel oil.

Table 2 lists the properties of the fractionated pyrolytic oils and petroleum fuel oils. High-sulfur diesel and high and low sulfur fuel oils (Bunker-C oils) as petroleum fuel oils were chosen for comparison. The pyrolytic oils showed specific gravities higher than those of the petroleum oils because they had wide distributions of compounds similar to crude petroleum oil and possibly had small amount of char from nature of thermal decomposition. The pyrolytic oils had higher oxygen contents than the petroleum oils and showed lower HHVs and higher TANs consequently. Another feature is relatively lower sulfur and higher nitrogen contents. Their low sulfur contents are positive for fuel application, though their high nitrogen contents are not favorable due to causing NOx emission in fuel use and catalyst poisoning of deoxygenation step for further processing [23]. This implies that the pyrolytic oils should be denitrogenated before deoxygenation to improve their applicability as fuels.

Fig. 6 shows comparison of pyrolytic oils' compound distributions. JSC and PKS had high concentrations of fatty acid and low concentrations of phenol derivatives. EFB oil showed high contents of phenol derivatives and heavies, with fatty acid not detected. High fatty acid yield in JSC and PKS is consistent with the results obtained by Sricharoenchaikul and Atong's study [2]. These results may be originated from waste characteristics. All the wastes are of lingocellulose nature like woody biomass. JSC and PKS are remnants from oil extraction and likely contain oil residue in the shell cakes. From the results, EFB, like woody biomass, can be used to make aromatic products or gasoline, as suggested by previous studies [18,24]. The high fatty acid and moderate glyceride contents of JSC and PKS suggest that they could be used as feedstocks for biodiesel like palm oils.

Table 2
Properties of distilled pyrolytic oils and petroleum fuel oils (dry basis, wt.%).

Properties	JSC	PKS	EFB	HS diesel	HFO (0.3S B–C)	HFO (4.0S B–C)
Specific gravity	1.13	1.23	1.18	0.87	0.94	0.98
Elemental composition [wt.%]						
C	65.8	71.5	58.65	85.90	87.30	82.79
H	8.92	10.3	7.02	12.98	12.19	12.98
O	18.8	15.9	30.14	0.10	0.17	0.48
N	5.62	2.82	2.74	0.57	0.06	0.20
S	0.19	0.12	<0.1	0.46	0.28	3.55
H/C molar ratio	1.63	1.729	1.436	1.813	1.675	1.881
O/C molar ratio	0.21	0.17	0.39	<0.005	<0.005	<0.005
TAN [mg KOH/g]	153.7	113	110	0.25	0.451	N/A[a]
HHV [MJ/kg]	30.2	30.9	24.9	39.1	44.7	43.4

[a] N/A = not available.

The boiling point distributions of pyrolytic oils from JSC and PKS were compared with those of representative biodiesel feedstocks crude palm oil (CPO) and palm fatty acid distillate (PFAD) in Fig. 7. CPO showed a high boiling point range because of its high triglyceride content. The major part of PFAD is in 350–370 °C boiling range where JSC and PKS showed plateau regions, indicating high portions. JSC and PKS showed distribution curves more similar to PFAD than those of CPO or petroleum fuel oil.

Table 3 compares the properties of the fractionated pyrolytic oils, CPO and PFAD. The pyrolytic oils showed higher specific gravities than the palm oils because they contained unstable and heavy long chain compounds and small amount of char from nature of fast thermal decomposition. Their oxygen contents and O/C ratios were slightly higher than the palm oils. The high oxygen contents resulted in low HHVs. However, the properties gap between pyrolytic oils and palm oils were smaller than that with petroleum oils. The pyrolytic oils' TANs were much higher than that of CPO and slightly lower than

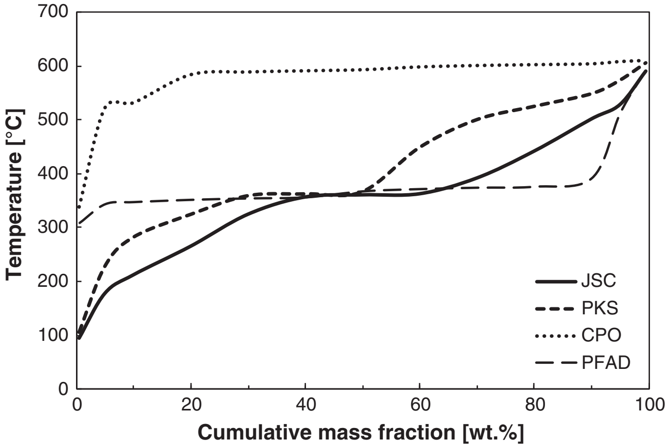

Fig. 7. Boiling point distributions of pyrolytic oils and palm oils.

Table 3
Properties of fractionated pyrolytic oils and palm oils (dry basis, wt.%).

Properties	JSC	PKS	CPO	PFAD
Specific gravity	1.13	1.23	0.91	0.90
Elemental composition [wt.%]				
C	65.8	71.5	76.8	76.2
H	8.92	10.3	12	12.1
O	18.8	15.9	11.5	11.5
N	5.62	2.82	<0.1	<0.1
S	0.19	0.12	<0.01	<0.01
H/C molar ratio	1.63	1.729	1.875	1.906
O/C molar ratio	0.21	0.17	0.11	0.11
TAN [mg KOH/g]	153.7	113	6.8	187.9
HHV [MJ/kg]	30.2	30.9	39.6	39.4
Water content [wt.%]	1.5	1.2	<0.005	<0.005

that of PFAD, indicating that the pyrolytic oils and PFAD had higher amounts of carboxylic acid groups than CPO. The pyrolytic oils from JSC and PKS showed higher nitrogen contents than CPO and PFAD, likely due to organically bonded nitrogen in the raw materials.

For detail analysis, the oils' compound distributions are compared in Fig. 8. The pyrolytic oils showed similar distributions to PFAD, with both mainly comprising fatty acid. The majority of CPO was triglyceride. Therefore, the pyrolytic oils and PFAD showed higher TANs than CPO because fatty acid is a cause of high acid number as shown in Table 3. JSC pyrolytic oil contained more fatty acid like PFAD than PKS oil. However, PKS pyrolytic oil had more glyceride, like CPO. Pyrolytic oils from JSC and PKS wastes feature in containing phenolic derivatives and heavy compounds compared to the palm oils; the phenolic compounds were associated with high lignin contents [7].

3.3. Pyrolytic oils' applicability as fuel

A recent alternative for green diesel production is based on hydrotreating, which can be used to convert not only plant-derived oils, such as soybean and CPO, but also various types of non-edible oils [25]. Its advantages over trans-esterification are its compatibility with current infrastructure, engine compatibility and feedstock flexibility [24]. Since 2005, UOP and ENI have developed Ecofining™ process based on conventional hydroprocessing. Analogous technologies have been developed by Neste oil and Petrobras [25]. Recently, SK innovation announced the development of the SK-HBD process with a high performance catalyst for converting CPO and PFAD [26].

In Table 4, the major chemical compounds and nitrogen impurities in the pyrolytic oils of JSC and PKS were compared with PFAD to assess the possibility of the pyrolytic oils as feedstocks in the hydrotreating process for diesel conversion. The pyrolytic oils contained more unsaturated fatty acid than PFAD. Yields of palmitic acid, major part of PFAD, were small in the pyrolytic oils. Fatty acids in JSC oil had more long chain compounds than PKS oil. JSC oil had more similar distributions of fatty acid compounds to PFAD than to PKS oil, despite PKS and PFAD originating from the same fruit. However, the carbon chain lengths of the pyrolytic oils are from C_{12} to C_{18}, similar to PFAD and within the C_{10} to C_{23} of typical diesel fuel. Nitrogen was distributed in various forms in the pyrolytic oils; their main compounds (over 1 wt.%) were also different. JSC oil was high in amide and imide derivatives; PKS oil contained more nitrile derivatives.

Table 4
Major chemical compounds of fatty acid and nitrogen impurities in pyrolytic oils and PFAD (wt.%).

Chemical compound		JSC	PKS	PFAD[a]
Fatty acid	Lauric/myristic acid ($C_{12}H_{24}O_2$/$C_{14}H_{28}O_2$)	–	11.3	–
	Palmitic acid ($C_{16}H_{32}O_2$)	9.9	6.3	45.6
	Stearic acid ($C_{18}H_{36}O_2$)	5.9	3.9	3.8
	Oleic acid ($C_{18}H_{34}O_2$)	33.3	19.5	33.3
	Linoleic acid ($C_{18}H_{34}O_2$)	18.2	9.4	7.7
Nitrogen impurities	Amide derivative	2.0	–	–
	Imide derivative	2.0	–	–
	Nitrile derivative	–	8.3	–

[a] Chongkhong et al.(2009) [27].

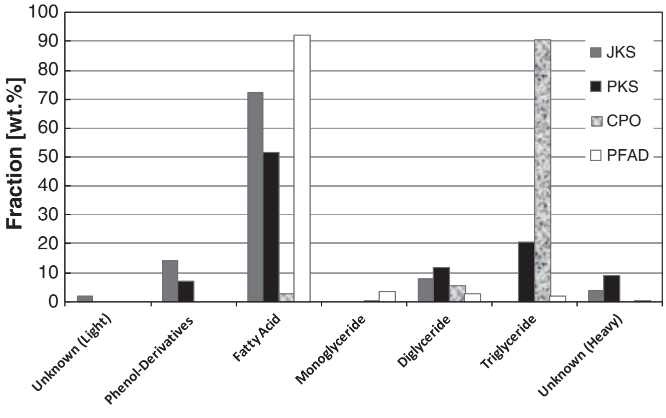

Fig. 8. Compound distributions of pyrolytic oils and palm oils.

These results suggest that the applications of JSC and PKS pyrolytic oils could be approached similar to PFAD. However, it is clear that they would require refining before hydrotreating because the crude pyrolytic oils contained small amounts of phenol derivatives and heavies. EFB pyrolytic oil has potential as a feedstock for the production of highly aromatic gasoline through catalytic deoxygenation or petrochemicals because of its high concentrations of phenolic derivatives [28]. In removal of nitrogen impurity for fuel use, denitrogenation catalyst specific to each oil could be designed or selected for efficient process because of their different main nitrogen compounds.

4. Conclusions

The pyrolysis of JSC, PKS and EFB was investigated in a fluidized bed reactor. The effects of bed temperature and gas flow rate on product yields and properties have been determined. Maximized liquid yield and fractionated oil yield of 48 wt.% and 32 wt.% were obtained at *ca.* 470 to 480 °C from JSC. The effects of fluidization quality in the fluidized bed on product yield were also determined. Pyrolytic liquid yield was maximized at 8–9 u_{mf} gas velocity, given the trade-off of vigorous bubbling and bed mixing that increased yield and decreasing heat transfer coefficient that reduced yield, which occurred with increasing gas velocity. EFB oil showed a uniform distribution of its components' boiling point, with an almost constant slope; JSC and PKS showed plateaus around 360 °C. The pyrolytic oils contained more oxygen and nitrogen and less sulfur than petroleum fuel oils; they showed lower HHVs. Pyrolytic oils from JSC and PKS showed high yields of fatty acid and glycerides compared to other lignocellulose biomass like EFB, which showed high yield of phenolic derivatives. In assessment of pyrolytic oils' applicability as fuel, JSC and PKS pyrolytic oils showed suitability for alternative feedstocks for biodiesel production using hydrotreating process, and EFB pyrolytic oil could be used to produce highly aromatic gasoline or petrochemicals.

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