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Torrefaction of Malaysian Palm Kernel Shell into Value-Added Solid Fuels

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***Abstract*—**This project aims to investigate the potential of torrefaction to improve the properties of Malaysian palm kernel shell (PKS) as a solid fuel. A study towards torrefaction of PKS was performed under various temperature and residence time of 240, 260, and 280°C and 30, 60, and 90 minutes respectively. The torrefied PKS was characterized in terms of the mass yield, energy yield, elemental composition analysis, calorific value analysis, moisture and volatile matter contents, and ash and fixed carbon contents. The mass and energy yield changes in the torrefied PKS were observed to prove that the temperature has more effect compare to residence time in the torrefaction process. The C content of PKS increases while H and O contents decrease after torrefaction, which resulted in higher heating value between 5 to 16%. Meanwhile, torrefaction caused the ash and fixed carbon content of PKS to increase, and the moisture and volatile matter to decrease.

***Keywords*—**biomass, palm kernel shell, pretreatment, solid fuel, torrefaction

I. Introduction

BIOMASS is considered as a sustainable and renewable energy sources with the highest potential to contribute to the energy needs of modern society and to replace the existing conventional fuel which is subject to depletion as they are consumed [1]-[3]. In the context of biomass for energy, it is often to mean the plant based material which is derived from the reaction between CO^2 in the air, water and sunlight, through photosynthesis to produce carbohydrates that form the building blocks of the biomass [4]. For ages, the energy stored in the chemical bonds of the biomass has been exploited by burning it as a fuel. One important factor considering the use of biomass as energy sources is to improve the global warming issue since burning new biomass contributes no new CO^2 to the atmosphere, because replanting biomass ensures that the CO^2 is absorbed and returned for a cycle of new growth [4].

However, several weaknesses of biomass have limited its wider application in energy generation. These include low heating value, high moisture content, high alkali metal content, hygroscopic nature, degradation and self-heating, smoke during combustion, low energy density, low combustion efficiency and low grindability properties [5]-[8]. Biomass is a high moisture fuel which consumes a considerable amount of energy during drying [8]. Furthermore, the dried biomass again picks up moisture due to its hygroscopic (water-absorbing) nature that leads to biomass degradation and self-heating, thus raising complications in storage. Also, a high oxygen content of biomass does not make it an ideal fuel for gasification (thermochemical conversion technology) [9]. The size reduction of biomass to produce a powder that can be burned in a coal-fired power station has also been identified to be a problem because of its low grindability properties [6].

Torrefaction is a pretreatment process which serves to improve the properties of biomass in relation to the thermochemical conversion technologies for more efficient energy generation. Torrefaction is a thermochemical pretreatment method that is maintained by an operating temperature ranging from 200-300°C [5]. It is carried out under atmospheric pressure, in the absence of oxygen [10] and in the flow of nitrogen gas. The process is characterized by low particle heating rates and by relatively long residence time [6], typically 1-3 hours.

Pimchuai et al. [8] reported a study on torrefaction of rice husks, sawdust, peanut husks, bagasse and water hyacinth under various temperature and residence time of 250, 270, and 300°C and 1, 1.5 and 2 hours respectively. Based on the study, the percentage of mass and energy yield decreased, the calorific value of the torrefied product increased and moisture and volatile matter contents decreased with the increase in the temperature and residence time, with the findings that temperature has more effects on torrefaction process than the residence time [8]. Meanwhile the ash and fixed carbon contents increased when the temperature increases. However, it majorly decreased when the residence time increases [8].

A study done by Gevers et al. [14] had focused on the torrefaction of pinewood at temperature and residence time of 230, 250, and 280°C and 1, 2 and 3 hours respectively. It was reported that the carbon content increased with the increase in the temperature and residence time, hydrogen and oxygen contents decreased with the increase in the temperature and residence time, while nitrogen content was almost constant [14].

Bridgeman et al. [7] studied the torrefaction of reed canary grass, wheat straw, and willow at 230, 250, 270, and 290°C and with residence time of 30 minutes. Based on the findings, increasing the torrefaction temperature resulted in increased carbon content, decreased hydrogen and oxygen contents, with nitrogen content almost constant [7].

Meanwhile, Uemura et al. [15] investigated the torrefaction of oil palm empty fruit bunch, mesocarp fiber and PKS at 220,

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250 and 300°C and residence time of 30 minutes. It was observed that the increase in torrefaction temperature resulted in higher calorific value, lower moisture, volatile matter and ash contents, and increased fixed carbon content [15].

This work aims to study the potential of torrefaction in improving the properties of Malaysian palm kernel shell as solid fuel via parametric study on temperature and residence time.

II. Methodology

A. Sample Preparation

The raw PKS is acquired from the palm oil mill. The raw PKS is then being grinded into a small particle size i.e. 250 µm. After grinding, the raw PKS is dried under temperature 105°C for 24 hours to remove its extrinsic moisture. The dried PKS is stored in a low humidity cabinet for further process and analyses.

B. Torrefaction Process

Torrefaction of PKS with 9 set of different torrefaction condition i.e. varied in temperature & residence time (240, 260, 280°C and 30, 60, 90 minutes) is done using tube furnace. The initial and final weights of the PKS are recorded for the evaluation of the mass yield after torrefaction using equation [6]:

$$mass\ \ yield\ \ (\%) = \frac{product\ \ weight}{raw\ material\ \ weight} \times 100\,\% \quad (1)$$

C. Ultimate Analysis

The ultimate analysis, i.e. the carbon (C), hydrogen (H), nitrogen (N), and sulphur (S) contents is carried out on raw and torrefied PKS by using an elemental (CHNS) analyzer. Oxygen (O) is determined using equation [16]:

$$O(\%) = 100 - C(\%) - H(\%) - N(\%) - S(\%) - ash\,(dry\,)(\%) \quad (2)$$

D. Calorific Value Analysis

The calorific value (HHV) of raw and torrefied PKS is measured using bomb calorimeter. The value is used to determine energy yield for each sample using the equation [6]:

$$energy\ \ yield\ \ (\%) = mass\ \ yield\,(\%) \times \frac{HHV_{\ product}}{HHV_{\ raw\ material}} \quad (3)$$

E. Proximate Analysis

The intrinsic moisture content, volatile matter, fixed carbon content, and ash content of raw and torrefied PKS are measured using Thermogravimetric Analyzer (TGA). The sample of 4.5-5.0mg is heated from 50–110°C at a heating rate of 60°C/min and with a nitrogen gas flowrate of 30 ml/min. Next, it is run isothermally for 5 minutes at 110°C, and is heated up to 950°C at a heating rate of 100°C/min under the same nitrogen flowrate. Subsequently the run is performed isothermally for 3 minutes at 950°C. Then the purge gas is switched to oxygen with the flowrate of 30 ml/min and the sample is held isothermally for another 15 minutes at 950°C.

III. Results And Discussion

A. The Properties of Raw PKS

Result of analysis of the raw PKS (dry) is summarized in TABLE I. The HHV difference occurring between the same biomass materials is because of physical environmental conditions and harvesting season of the PKS [15]. The difference in the HHV is also expected because of the size of the PKS used differs from other studies. The ultimate analysis result in TABLE I shows fairly close values with those reported in a previous study done by Uemura et al. [15].

TABLE I
Properties of Raw PKS

Properties	Value	Value from Uemura et al. [15]
HHV (dry)	18.81 MJ/kg	19.78 MJ/kg
Moisture content	2.88 %	-
C content	46.53 %	46.68 %
H content	5.85 %	5.86 %
N content	0.89 %	1.01 %
O content	42.32 %	42.01 %
VM content	84.86 %	-
Ash content	4.29 %	4.38 %
FC content	10.85 %	-

B. The Properties of Torrefied PKS

1. Mass yield

The mass yield of the torrefied PKS at different torrefaction conditions is shown in Fig. 1 and 2 for the study on the influence of temperature and residence time respectively. The percentage of mass yield decreased with the increase in the torrefaction temperature and residence time. This observation is consistent with the findings by Pimchuai et al. [8]. This could be explained by the results of proximate analysis where the decrease in the moisture and volatile matter contents leads to the decreases in mass yield. The significant mass loss at the beginning of the torrefaction process, is due to the decomposition of some reactive components of the hemicelluloses [8]. Whereas, the mass loss at higher residence time is associated with the decomposition of less reactive components of the hemicelluloses [8]. It is also being noticed from the results that the temperature has more significant effect on torrefaction than the residence time.

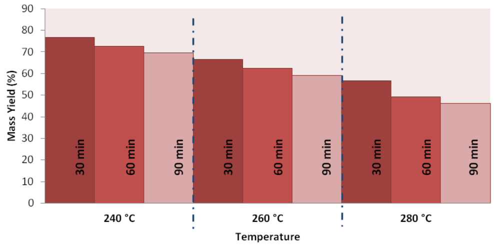

Fig. 1 Influence of temperature on the mass yield of torrefied PKS

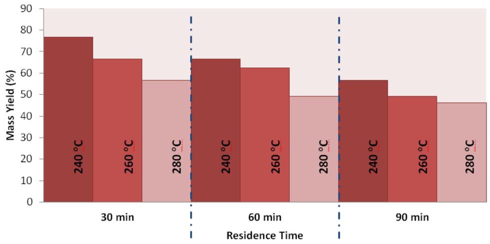

Fig. 2 Influence of residence time on the mass yield of torrefied PKS

2. Energy yield

The energy yield of the torrefied PKS at different torrefaction temperature and residence time is shown in Fig. 3 and 4 respectively. The percentage of energy yield decreases with the increase in the torrefaction temperature and residence time. This trend matches the results reported by Pimchuai et al. [8]. From the results in this study, it is observed that the temperature has larger effect on torrefaction than the residence time. The energy yield of the torrefied product is higher than the mass yield, thus, the energy densification of the torrefied PKS is achieved [17].

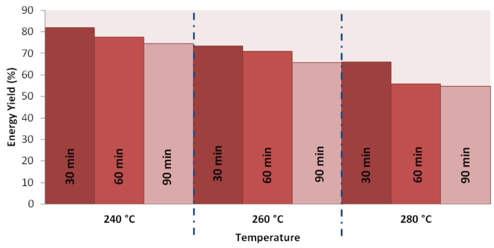

Fig. 3 Influence of temperature on the energy yield of torrefied PKS

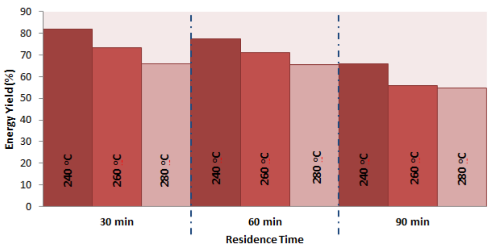

Fig. 4 Influence of residence time on the energy yield of torrefied PKS

3. Elemental composition

Carbon (C), hydrogen (H), nitrogen (N), sulphur (S) and oxygen (O) contents of the raw and torrefied PKS are summarized in TABLE II. The C:C bond increases as the C content increase, while C:H and C:O bonds decreases as the H and O contents decreases with the increase of torrefaction temperature and residence time. The C content increases by 10-20% with the increase in the torrefaction temperature and residence time. The percentage of H decreases by 9-29% with the increase of the torrefaction temperature and residence time. Meanwhile, the percentage of O decreases by 6-21% with the increase of the torrefaction temperature and residence time. The change in nitrogen content fluctuates with a slight difference of 0.13% and being considered as constant. The findings that the increases in C content, decreases in H and O contents, while the N content is constant, as the torrefaction temperature and residence time increases, are similar with those of Gevers et al. [14]. It is also found that the trend of the elemental composition of the torrefied PKS at every respective residence time is similar with the results reported by Bridgeman et al. [7]. The percentage of sulphur content is maintained low, i.e. below 1%, with the increase of the torrefaction temperature and residence time. Low sulphur content in the torrefied PKS allows it to be an environmental friendly fuel. Overall, it can be seen that temperature has more significant effect on the torrefied products than residence time.

4. Calorific value

The calorific value (HHV) for the torrefied and raw PKS are summarized in TABLE II. The HHV of torrefied PKS increase with the increase of the torrefaction temperature and residence time. This observation is consistent with the findings by Pimchuai et al. [8]. This could be explained by the results of ultimate analysis where an increase in the C:C concentration leads to an increase in the HHV. It is also found that the trend of the HHV of the torrefied PKS is similar with results reported by Uemura et al. [15]. Overall, the increase of the HHV of the torrefied PKS is about 4.72-16.17%. Similarly, the temperature imposes more significant effect than the residence time.

5. Proximate analysis

The moisture, volatile matters (VM), ash, and fixed carbon (FC) contents of the raw and torrefied PKS are summarized in TABLE II. The fixed carbon and ash contents of torrefied PKS increases, while the moisture and volatile matter contents decrease. This observation is also consistent with the findings by Pimchuai et al. [8]. It is also realized that the trend of the moisture, volatile and fixed carbon contents of the torrefied PKS is similar with the results reported by Uemura et al. [15]. The moisture content decreases by 15-64% with the increase in the torrefaction temperature and residence time. Similarly, the volatile matter content decreases with the increase in the torrefaction temperature and residence time with the change observed is approximately 10-20%. Ash content increases by

16-99% with the increase in the torrefaction temperature, however decreases with the increase in the residence time. The fixed carbon content increases by 85-208% with the increase in the torrefaction temperature, however decreases with the increase in the residence time. From the results, temperature has a more significant influence on the torrefied product than the residence time.

TABLE II
PROXIMATE, ULTIMATE, AND CALORIFIC VALUE ANALYSIS OF RAW AND TORREFIED PKS

Sample		Proximate analysis				Ultimate analysis					Calorific value
		Moisture (%)	VM (%)	FC (%)	Ash (%)	C (%)	H (%)	N (%)	S (%)	O (%)	HHV (MJ/kg)
Raw PKS		1.74	83.38	10.66	4.22	46.53	5.85	0.89	0.12	42.32	18.814
30 min	240°C	1.48	74.56	19.77	4.89	49.08	5.10	1.07	0.12	39.67	19.702
	260°C	1.19	73.77	22.04	6.21	49.26	4.37	1.02	0.07	39.00	19.715
	280°C	0.92	75.15	21.25	5.62	49.90	3.92	1.07	0.00	39.45	19.856
60 min	240°C	1.00	73.66	21.06	6.37	50.84	4.68	1.03	0.03	36.99	20.351
	260°C	1.02	70.84	22.83	6.82	50.50	4.36	1.12	0.02	37.11	21.085
	280°C	0.70	73.63	20.51	6.69	51.49	4.06	1.08	0.01	36.61	20.587
90 min	240°C	0.72	63.56	28,25	8.40	50.26	4.38	1.10	0.00	35.80	21.542
	260°C	0.68	70.84	22.72	6.09	51.16	4.23	1.10	0.02	37.36	20.913
	280°C	0.63	58.07	32.86	8.39	53.07	3.97	1.14	0.00	33.37	21.856

IV. CONCLUSION

Potential solid fuel i.e. torrefied Malaysian palm kernel shell (PKS) has been prepared using different temperatures and residence times. Torrefaction significantly improved the properties of PKS. The experimental and analyses results show that the mass and energy yields of torrefied PKS decrease with the increase of the torrefaction temperature and residence time. The C content increases, while H and O content decreases, while the N content is constant, with the increase of the torrefaction temperature and residence time. Meanwhile the S content of the torrefied PKS is maintained low i.e. below 1% which makes it as an environmental friendly fuel. The HHV of torrefied PKS increases within the range of 7-19% with the increase of the torrefaction temperature and residence time. The fixed carbon and ash contents of torrefied PKS increases, while the moisture and volatile matter contents decrease.

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