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Influence of Torrefaction on Gasification of Torrefied Palm Kernel Shell

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A B S T R A C T

In this study, torrefaction pretreatment on palm kernel shell (PKS) was investigated using fixed bed reactor. The PKS was torrefied at the temperatures of 210, 230, 250, 270 and 290 °C. The characteristics between untreated and torrefied PKS were compared. The results showed that, the mass and energy yield lessened, while the calorific value augmented with the increasing torrefaction temperature. Furthermore, with the rise of temperature, the oxygen composition, O/C ratio, oxygenated compounds and volatile matter of torrefied PKS decreased, but, the carbon and fixed carbon content increased. The composition of carbon in torrefied PKS was toward coal where equivalent calorific values was achieved. The gasification of torrefied PKS enhanced the product yield which produced higher gas, lower tar and char yield than the gasification of untreated PKS. Gasification of torrefied PKS increased the gas yield by 16.9 % than the untreated PKS. The tar and char yield of torrefied PKS decreased by 19.4 % and 25.9 %, respectively than the untreated PKS. Therefore, the torrefied PKS, by which their physical and chemical properties have been improved through torrefaction pretreatment is more suitable to be used in gasification and co-gasification as their influences are significant than the untreated PKS.

1. Introduction

Nowadays, the growing utilization of energy, worries on the worldwide environmental difficulties and lessening of fossil fuel, lead the nation to head for clean and renewable energy. This paper is an addition of the work formerly presented in 4th IET Clean Energy and Technology Conference 2016 [1]. Among of the main problems for fossil fuels are the discharge of contaminants such as carbon dioxide, sulfur and nitrogen oxide towards environment [2]. Therefore, biomass is one of the most attractive and broadly used renewable energy source, become important as an alternative energy resource due to little sulfur composition and neutral CO_2 supply [3].

Despite the great prospective of biomass, it has the drawbacks on its properties such as high moisture content, low energy density and hydrophilic characteristics [4-5]. Thus, these characteristics of biomass fuel are connected with some complications in biomass thermal conversion such as in gasification. Previous studied [6-7], revealed that high oxygen compound in biomass lower the gasification productivities compare with less oxygen, for example coal. Thus, alteration the properties of biomass preceding gasification is necessary.

A pretreatment step preceding to thermal conversion is required in the direction to reduce some of the aforementioned problems. Thus, torrefaction appears to be an effective route. Torrefaction involves pretreatment at temperature ranges of 200 to 300 °C in atmospheric surrounding. The pretreated biomass formed a fuel with low moisture and great energy content [2]. Previous studies also show other advantages of this torrefaction pretreatment, such as improving feedstock hydrophobicity, homogeneity and grindability [8-9].

Palm as the highest provider to biomass incomes in Malaysia has appealed huge consideration to achieve the renewable energy demands [10]. In 2016, Malaysia produced 4.19 MnT of PKS, as

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residues from oil palm industry [11]. Thus, transforming PKS to bio-fuel under a thermal conversion offers a greater advantage to substitute fossil fuels, and it minimizes the disposal problems related with the generation of agricultural by-products [12]. PKS exhibited great prospective as fuel to produce gas with enhanced hydrogen and energy content [13]. However, high moisture, low heating value and energy density inhibit the PKS as valuable fuel [14]. Accordingly, these complications can be handled through torrefaction.

Consequently, the research objective was to explore the influence of torrefaction temperature on the characteristic of torrefied PKS. Further, the gasification of torrefied PKS was investigated.

2. Methodology

2.1. Materials

PKS sample was obtained from oil palm factory in Penang, Malaysia. It was crushed and sieved to get particle sizes between 200 to 400 µm. The inherent moisture was removed by drying the sample in an oven for 24 hours at 105 °C.

2.2. Pretreatment

Torrefaction, which is a mild pyrolysis pretreatment was studied thru a fixed-bed reactor at an atmospheric pressure. The reactor has inner diameter and height of 0.06 m and 0.3 m, respectively. The electric furnace surrounding reactor tube was used to heat the reactor. Figure 1 displays a schematic diagram of the pretreatment system.

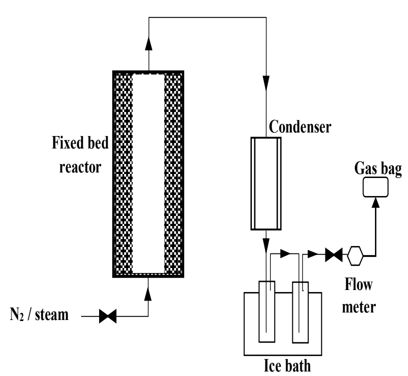

Figure 1. Schematic diagram of the reactor set-up

The sample weight of 5 g was positioned inside the reactor. The reactor was flowed with 500 ml/min nitrogen gas to generate an inert atmosphere. The reactor temperature was fixed at reaction temperatures (210, 230, 250, 270 and 290 °C) with heating rate and retention time of 10 °C/min and 1 hr, correspondingly. The torrefied PKS was weighted when the process was completed and reached the room temperature.

Mass and energy yield are main factors in the pretreatment. Energy yield represented the quantity of energy preserved after the pretreatment and is measured using mass yield of final product. Torrefied biomass has fewer energy yield than untreated biomass, due to reduce in volatile matter of torrefied biomass [15]. The mass yield (Y_m) and energy yield (Y_e) were examined via equations (1) and (2), correspondingly.

$$Y_m = (M_t / M_u) \times 100 \quad (1)$$

$$Y_e = Y_m \times (HHV_t / HHV_u) \quad (2)$$

where M_u = mass of untreated biomass, M_t = mass of torrefied biomass, HHV_u = heating value of untreated biomass and HHV_t = heating value of torrefied biomass.

2.3. Characterization

The elemental composition (C, H, N, S and O) was examined using CHNS-O elemental analyser. The proximate analysis was inspected via Mettler Toledo thermogravimetric analyser. The calorific value (CV) was measured using Leco bomb calorimeter. The functional groups were discovered using Perkin Elmer fourier transform infra-red (FTIR) spectroscopy. Table 1 listed the properties of untreated PKS.

Table 1. Properties of untreated PKS

Analysis	Value
Elemental composition (wt. %)	
Carbon	47.7
Hydrogen	5.5
Nitrogen	0.4
Sulfur	0
Oxygen[a]	46.4
Proximate analysis (wt. %)	
Moisture	10.6
Volatile matter	77.5
Ash	0.9
Fixed carbon	11.0
Calorific value (MJ/kg)	18.2

[a] By different

2.4. Gasification Experiment

Figure 1 displays the gasification system of PKS. The sample weight of 5 g was positioned inside the reactor. A nitrogen gas was flowed to the reactor for 10 min formerly the test. The sample was gasified at gasification temperature (800 °C) with heating rate of 50 °C/min. The nitrogen flow of 500 ml/min was continued to generate an inert condition. After the temperature of 800 °C had reached, the steam was streamed into the reactor and the nitrogen flow was stopped. The steam gasification of the sample was held for 45 min.

The volatile product and steam which left the reactor from the upper side were condensed in a tar trap. The solid residue was weighted as char. Tar yield in the tar trap was measured. The gas product was inspected using changed of total mass balances. The gasification was repeated for verification of the outcomes.

3. Result and Discussion

3.1. Mass and Energy Yield

Figure 2 presents the mass and energy yield of torrefied PKS under different torrefaction temperatures. The mass and energy yield reduces by increasing the temperature. The mass yield ranges from 88 to 65 % of torrefied PKS at temperature ranges of 210 to 290 °C. This displays that the conversion of PKS was increased from 12 to 35 %. The slight conversion at the temperature of 210 °C was reflected to the loss of moisture. Thus, the PKS torrefaction was insignificant at low temperature. At upper temperature between 230 to 290 °C, mass reduction was due to the major hemicelluloses and minor lignin decomposition [4]. Some authors [16-17] established that the main decomposition part during torrefaction was hemicelluloses.

The energy yield of torrefied PKS was considerably reduced to 75 % at pretreatment temperature of 290 °C. This observation was mostly due to the additional decomposition of cellulose. Accordingly, more than 75 % of energy yield was able to be reserved at the pretreatment temperature between 250 to 270 °C. Hence, torrefaction of PKS above 290 °C is not suggested in order to avoid the loss of energy yield below 75 %.

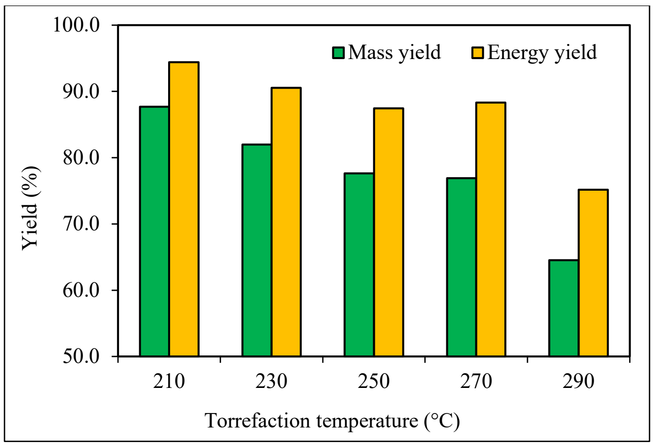

Figure 2. The influence of torrefaction temperature on mass and energy yield

3.2. Fixed Carbon, Volatile Matter and Calorific Value

Figure 3 presents the influence of pretreatment temperature on fixed carbon content and volatile matter of torrefied PKS. The fixed carbon content of torrefied PKS increased while volatile matter decreased notably with the rise in torrefaction temperature. At high temperature (290 °C), the fixed carbon of the torrefied sample improved above 50 % with comparison to the untreated sample. The torrefied sample showed huge reduction of volatile matter with close to 50 % with increasing reaction temperature up to 290 °C. The hemicellulose content in PKS is easy to degrade during torrefaction process. The results on the extensive volatile matter reduction were comparable to the work published by Uemura et al. [18], Matali et al. [19] and Sabil et al. [20] in their study of agricultural wastes.

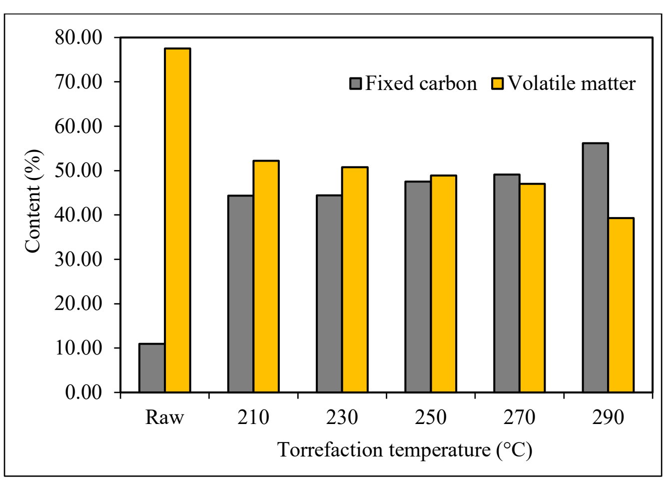

Figure 3. The influence of torrefaction temperature on fixed carbon and volatile matter

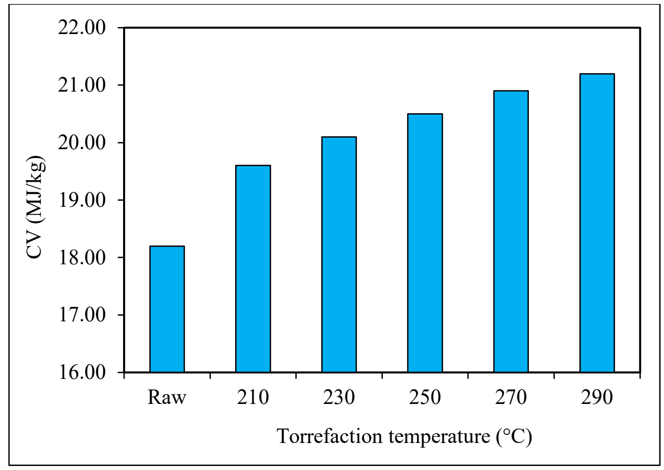

Figure 4. The influence of torrefaction temperature on calorific value

The CV of torrefied PKS is presented in Figure 4. The CV of torrefied PKS increased by rising the temperature. Improvement of CV is related with the rise of fixed carbon component. Accordingly, the PKS energy value enriched with pretreatment.

3.3. Carbon and Oxygen Content

The carbon and oxygen content of torrefied PKS are presented in Figure 5. Overall, the torrefied PKS displayed lower oxygen and higher carbon composition than untreated PKS by increasing the torrefaction temperature. The oxygen was reduced to 39 % and the carbon was increased up to 56 % at the highest pretreatment temperature of 290 °C. These outcomes appear to be in agreement with the earlier reports [21-22]. Moreover, O/C ratio of torrefied PKS reduced by rising the temperature. The reduction of the O/C ratio also indicates the measure of conversion efficiency and oxidation degree of torrefied product [4].

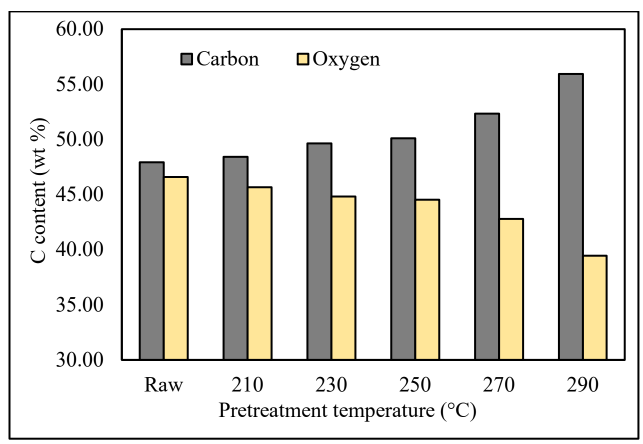

Figure 5. Carbon and oxygen content of torrefied PKS

3.4. Functional Group

Figure 6 shows the chemical structure alteration of PKS samples via FTIR. The spectrum shape was comparable for untreated and torrefied PKS, but the peak strength was dissimilar.

A broad band of 3300 cm^{-1} connected to -OH stretching which related to the alcohols and phenols. The -OH peak reduced considerably as the pretreatment temperature increased. The aliphatic methylene group was denoted at peak of 2920 cm^{-1}. The C=O bond which is associated with aldehydes, acids and ketones was detected at 1730 cm^{-1}. At greater pretreatment temperature, the peak intensity reduced due to the breakdown of hemicellulose. The C-O stretching and O-H alteration of organic components are assigned in the peak ranges of 1000 - 1500 cm^{-1}. Granados et al. [23] also found the similar trend which the intensity of these peaks were reduced with increasing torrefaction temperature. Peak of 700 cm^{-1} indicated the aromatic groups.

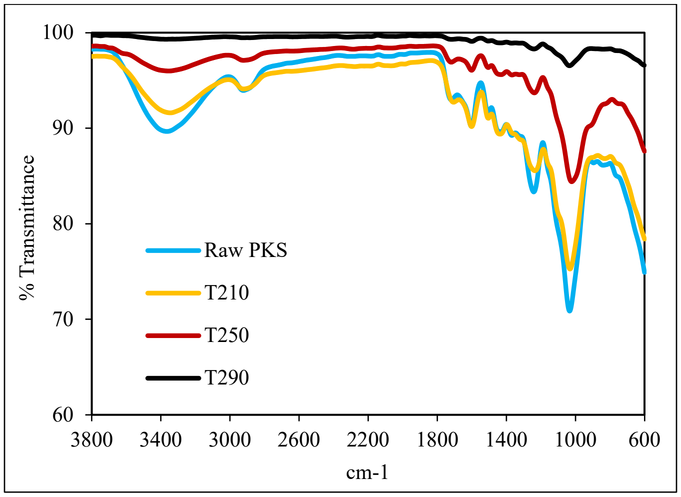

Figure 6. FTIR spectrum of PKS samples

3.5. Effect of Product Yield on Gasification of Torrefied PKS

Figure 7 shows the gasification product yield of untreated and torrefied PKS at gasification temperature of 800 °C. The torrefied PKS produced 16.9 % higher gas yield than the untreated PKS. The torrefied PKS revealed notable influence on the gas production to produce high gas yield compared to untreated PKS. This result was also in agreement with Berrueco et al. [24] which produced higher gas yield using torrefied sample.

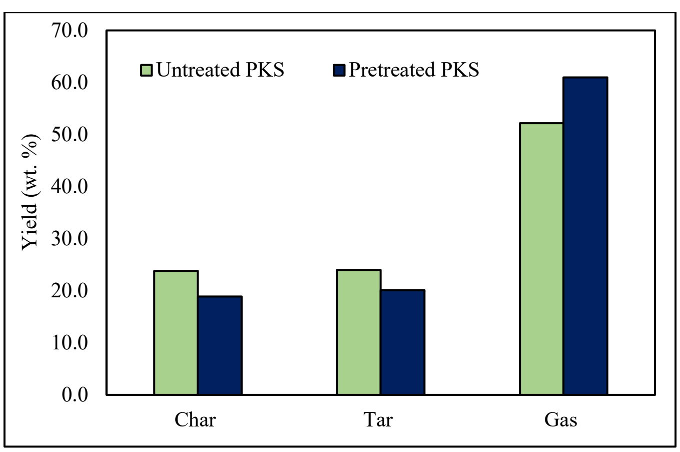

Figure 7. Gasification product yield of untreated and pretreated PKS

The tar yield reduced from 24.0 % to 20.1 % using for the torrefied PKS. The torrefied PKS had markedly reduced the tar yield about 19.4 % as an impact of the partial elimination of oxygenated components and volatiles through the torrefaction. Dudyunki et al. [25] also exhibited a comparable outcome as the effectiveness of using torrefied biomass to produce lower tar than the untreated biomass.

The gasification of torrefied PKS decreased the char yield from 23.8 % to 18.9 %. Low char yield using torrefied PKS was connected with the increased of solid conversion to gas product. Moreover, this event was influenced by the low moisture and oxygenated compound of torrefied PKS.

4. Conclusion

The influences of pretreatment temperature on torrefied PKS was investigated successfully. It was determined that the CV, fixed carbon and carbon content increased, however, mass and energy yield, volatile matter and oxygen content reduced, as the temperature augmented. Furthermore, oxygenated peak intensity in FTIR spectra decreased with increasing temperature. Therefore, PKS revealed a high value biofuel at reaction temperature from 250 °C to 290 °C. PKS torrefied at 250 °C showed significant mass and energy yield around 75 % and 85 %, respectively. The CV also increased more than 10 % compared to untreated PKS. The considerable reduction of oxygenated peak intensity was also found for torrefied PKS at 250 °C.

The gasification with torrefied PKS shows a positive effect in terms of product yield distribution. The torrefied PKS produced 16.9 % higher gas yield than the untreated PKS. The tar yield was reduced from 24.0 % to 20.1 % using the torrefied PKS. Also, the gasification of torrefied PKS decreased the char yield from 23.8 % to 18.9 %. Consequently, the torrefaction pretreatment, which improved the PKS properties, enhanced the gasification performance by producing high gas yield with low tar and char yield.

Conflict of Interest

The authors declare no conflict of interest.

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