

# Influence of Temperature and Blending Ratio on Product Yield for Co-gasification of Torrefied Palm Kernel Shell (TPKS) and Low-Density Polyethylene (LDPE)

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## Abstract

This study investigated the product yields produced from the co-gasification of torrefied palm kernel shell (TPKS) and low-density polyethylene (LDPE). Prior co-gasification, PKS was undergo pre-treatment process at different temperature. The optimum parameter for torrefaction was found at 250 °C for 60 min reaction time with 4.89 wt.% moisture content and 10.48 wt.% fixed carbon. Thus, the result indicated that TPKS a suitable fuel feedstock for further thermal conversion. Then, TPKS and LDPE were gasified at different temperature and blending ratio for 60 min reaction time. The results showed that, Co-gasification is significantly influenced by temperature. A higher gasification temperature improves the gasification rate by increasing carbon conversion. By varying temperature from 600 to 1000 °C, the tar production dropped significantly from 49.61 to 35.03 wt.%, while the gas yield grew significantly from 25.88 to 45.94 wt.%. However, as temperature increased from 800 to 1000 °C, tar yield increased from 26.58 to 35.03 wt.%. Meanwhile, char yield decreased from 24.50 wt.% to 19.02 wt.% when the temperature from 600 to 1000 °C. For the effect of blending ratio, through blending of TPKS and LDPE, the gas and char yield increase, while tar decrease with increase torrefied TPKS ratio. Additionally, it was found that the highest gas yield with low tar and char yield was obtained from the co-gasification of TPKS and LDPE at 50:50 blending ratios produce the than another blending ratio. Therefore, based on the effect of temperature and blending ratio on product yield shows that the optimum parameter to produce maximum gas yield with minimum tar and char yield are at 50:50 (TPKS: LDPE) blending ratio at 800°C for 60 minutes reaction time. The gas analysis exhibited in increasing H<sub>2</sub> composition when the reaction time increase for TPKS: LDPE compared than UnPKS:LDPE.

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The large amount of carbon content is consistent with the high H<sub>2</sub> production in TPKS compared to UnPKS. As a result, the pretreatment of PKS enhanced the H<sub>2</sub> production during co-gasification of TPKS and LDPE.

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## 1. Introduction

One of the most abundant sustainable energy sources on Earth, biomass has a wide range of globally accessible alternative energy sources that can displace conventional fossil fuels because of their abundance and many benefits for the economy and environment as carbon-neutral sources of energy. Due to the large amount of agricultural waste biomass that Malaysia produces, there is a lot of potential for using biomass to generate electricity in this nation. The cultivation of oil palm, which can be a significant renewable energy source, makes up the majority of agricultural activity in Malaysia [1]. Other residues such as the oil palm trunk (OPT), palm frond (OPF), empty fruit bunch (EFB), and palm kernel shell (PKS) are produced because the primary output of oil palm agriculture is the palm oil itself. PKS, a byproduct of the manufacture of palm oil, is utilized in the processes of producing energy and biofuels [2]. The production of PKS waste will need to be used for a variety of purposes, particularly because of its alleged low carbon content [3]. PKS is easier to locate, has a lower sulphur level, and has a higher calorific value. Therefore, organic crude fuels, or unconventional fuels, must be used in place of conventional fuels to reduce the instantaneous greenhouse gas emissions caused by fossil fuels [4].

Global plastic manufacturing has expanded over time as a result of the widespread use of plastics in commercial applications. Plastics are used in a wide range of industrial and domestic applications since they are now considered necessary materials and have several applications in every sector of industry. Nevertheless, the ongoing need for plastics leads to an accumulation of plastic garbage in landfills, which takes up a lot of room and exacerbates environmental issues. Recycling used plastic is anticipated to be the most efficient method. However, the recycling approach degraded the sustainability of the operation by contaminating the water and requiring a significant personnel cost for the separation process. Since plastics are made of petroleum, the demand for plastics has increased, which has resulted in the depletion of petroleum as a non-renewable fossil fuel [5]. As a result, there has been a lot of interest in the methods for turning waste plastics into fuels and chemicals with additional value through in-depth study and technological development. Among plastics, LDPE's high effective H/C ratio (~2) and molecular chain structure make it a good choice for fuel-ranged hydrocarbon production, or oil. Given that petroleum was the primary raw material used in the production of plastic, the thermal process of recovering plastic to biofuel held significant promise. In addition, the generated biofuel had a higher calorific value than the fuel purchased [5].

Thermochemical conversion is a process that can transform waste plastic and biomass energy into products or fuels with additional value [1]. Thermochemical conversion proves to be a highly effective technique for transforming raw materials into biofuels. Processes such as pyrolysis, combustion, liquefaction, and gasification are typically favored due to their adaptability to a wide range of feedstocks and their shorter processing duration. Gasification is a desirable method among the different thermochemical conversion pathways for converting biomass and polymers into syngas with added value, such as carbon monoxide (CO) and hydrogen (H<sub>2</sub>). According to Sulaiman et al. [6] gasification is a process for converting solids become combustible gases (CO, CH<sub>4</sub>, and H<sub>2</sub>) by combustion processes in high temperatures on gasifier reactor with limited air supply, the gas produced (syngas) can be used as fuels, chemicals or to producing electrical energy. In addition to the primary gaseous products, condensable liquids high in water and biochemicals are produced during gasification. Higher temperatures limit the production of tar, which makes cleaning and gas recovery relatively easy [7]. Hence, in this research, co-gasification of TPKS and LDPE was studied to determine the product yield and gases composition by using fixed bed reactor system.

## 2. Methods

### 2.1 Sample Preparation

This study used one type of oil palm biomass, namely palm kernel shell (PKS) and one type of plastic waste namely low-density polyethylene (LDPE). The untreated biomass, PKS was collected from Setiakawan Kilang Kelapa Sawit, Kulim, Kedah. Meanwhile, LDPE was purchase from Vistec Sdn Bhd. The untreated PKS was crushed into particle size of 300 µm to 450 µm and then was dried at 105 °C for 12 hours. Then, Until the analyses were completed, every prepared sample was kept in an airtight container. Untreated PKS was subjected to room pressure torrefaction pre-treatment in fixed bed reactor. The electric furnace encircling the reactor for maintaining its temperature. 5 g of raw PKS was added to the reactor. Nitrogen gas was then flushed into the reactor for ten minutes prior to the experiment. A steady nitrogen flow rate of 0.5 L/min was maintained inside the reactor to create an inert atmosphere. The temperature of the reactor was then increased to the necessary torrefaction temperature and holding period while keeping the nitrogen flow rate constant at 100 ml/min. After

the torrefaction process completed, the heater was shutting off and the reactor was let to standard temperature. After the pretreated sample reached room temperature, its final weight was calculated. Next, in order to calculate the yield of torrefied PKS (TPKS), the solid product was weighed.

## 2.2 Co-gasification of TPKS and LDPE

The co-gasification of TPKS and LDPE was performed under an atmospheric pressure in a fixed-bed reactor. A sample weighing around 5 g at a variable blending ratio was added to the reactor. Prior to the experiment, nitrogen gas was pushed through the reactor for 10 minutes. Next, using a heating rate of 50 °C/min, the sample was heated to the required gasification temperature. The reactor's inert atmosphere was created by maintaining a constant nitrogen flow rate of 0.5 L/min. The nitrogen flow was halted and the reactor was filled with steam generated by the steam generator once it reached the gasification temperature. A tar trap condensed the volatile product and steam that emerged from the reactor's upper side. After that, every 15 minutes from the start of the steam gasification process, gas bag was used to capture the dry gas. After the completion of the process, the reactor was allowed to cool to room temperature with the furnace turned off. After reaching room temperature, the char's weight was determined. The tar product in a tar trap was weighed. Based on the overall mass balances taking into account the tar and char yield, the gas yield was computed by difference. The calculations of char, tar and gas yields was calculated according to the equations (1), (2) and (3) respectively.

$$\% \text{ char yield} = \text{mass of char (g)}/\text{mass of sample (g)} \times 100 \quad (1)$$

$$\% \text{ tar yield} = \text{mass of tar (g)}/\text{mass of sample (g)} \times 100 \quad (2)$$

$$\% \text{ gas yield} = 100 - (\% \text{ tar yield} + \% \text{ char yield}) \quad (3)$$

## 2.3 Gas Analysis

The gas composition was analysed using gas chromatography with thermal conductivity detector (GC-TCD). The produced gases of H<sub>2</sub>, CO, CO<sub>2</sub> and CH<sub>4</sub> was quantitatively analysed by GC-TCD using purified argon as carrier gas. The CO, H<sub>2</sub> and CH<sub>4</sub> was analysed by a molecular sieve column. The sample injection volume is 10 µl and were splitted at 21.2:1. The detector temperature was set at 250 °C. The oven programming was set at 60 °C and held for 15 min.

## 3. Results and Discussion

### 3.1 Proximate Analysis of Torrefied PKS

Proximate analysis used to determine the characteristics and quality of torrefied PKS before undergo further thermal conversion process. The proximate analysis was shown in Table 1 for untreated PKS and torrefied PKS. The volatile matter generally decreased as the temperature of torrefaction increased but fixed carbon shows the opposite trend. This is mostly because increasing the torrefaction temperature causes an increase in the devolatilization rate, which makes the decomposition of hemicellulose and lignin more significant [8]. The quantity of material lost during heating biomass to a specific temperature and duration is known as volatile matter. The quantity of carbon contained in biomass is indicated by fixed carbon (FC) [9,10]. To ensure that fixed carbon would keep rising after torrefaction, a great deal of volatile matter was lost throughout the torrefaction process. Volatile levels were correlated with fixed carbon levels [11]. As a result, the solid product's gross calorific value increased [12].

Typically, when the torrefaction temperature increases, the amount of ash increases as well, leading to mass loss and the buildup of significant concentrations of metallic elements. Lower total heat was produced by solid fuels because of their high ash concentration [13,14]. The thermal conversion of biomass was significantly improved by low ash content, especially when the biomass contained potassium or halides like chlorine. The ash-forming inorganic component did not degrade along with the mass reduction that took place throughout the torrefaction process, which is what led to this rise.

The calorific value of biomass was impacted by its moisture content. The amount of heat required for combustion to occur increased as solid fuels' water content increased, requiring more energy [15]. Compare to untreated PKS, the moisture content of torrefied PKS is significantly decrease when the torrefaction temperature increase. The high amount of fixed carbon and low moisture content levels can help determine whether treated PKS is a good fuel feedstock. Thus, optimum parameter for torrefied PKS was 250 °C torrefaction temperature at reaction time of 60 min with 4.89 wt. % moisture content and 10.48 wt.% fixed carbon.

**Table 1** Proximate analysis at torrefied PKS at 60 minutes reaction time

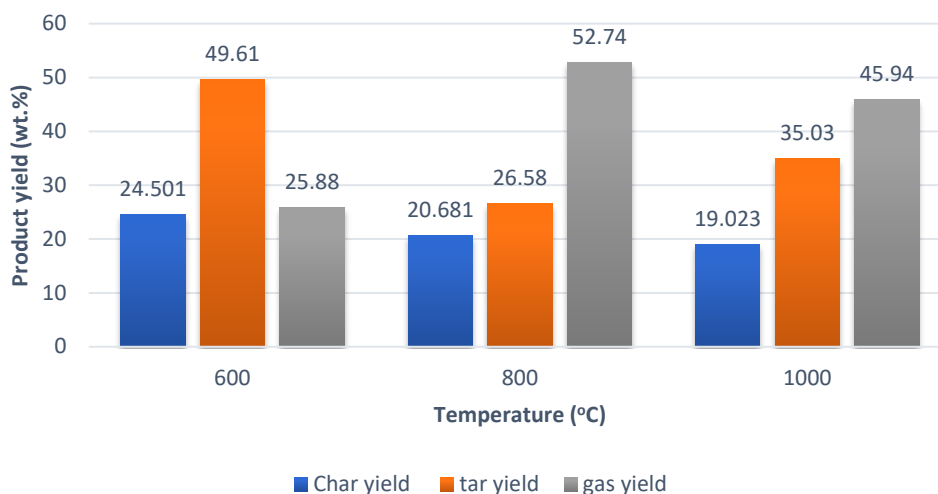
Sample	Volatile matter (wt.%)	Ash (wt.%)	Fixed Carbon (wt.%)	Moisture Content (wt.%)
Untreated PKS	51.05	33.61	9.01	6.33
200 °C	50.21	34.32	10.07	5.41
250 °C	48.83	35.8	10.48	4.89
300 °C	43.11	42.72	11.13	3.03

### 3.2 Effect of Temperature on Product Yield of Co-gasification

The co-gasification of TPKS and LDPE (TPKS: LDPE) is significantly influenced by temperature. An increase in gasification temperature speeds up gasification by increasing carbon conversion [16]. Co-gasification of products yield as function of temperature at 50:50 blending ratio and 60 min reaction time are shown in Figure 1. Within the experimental parameter range that was considered, the gas was substantially more abundant than tar and char. In contrast, it was discovered that tar was the second-highest product, especially at lower temperatures [17]. The gas yield significantly rose from 25.88 to 45.94 wt.% when the temperature increased from 600 to 1000 °C, whereas the bio-tar drastically fell from 49.61 to 35.03 wt.%. Tar and char conversion in relation to increasing heating carrier temperature may be responsible for the increase in gaseous yield. Consequently, increased amounts of tar and char could potentially undergo transformation into gas through thermal cracking and the boudouard reaction, respectively [17]. Elevated temperatures might promote the breakdown of the C-C and C-O bonds, leading to the formation of smaller particles and an increased chance of their conversion into reduced gas particles [18].

Tar yield varied from 49.61 to 26.58 wt.% within a temperature range of 600 to 800 °C. However, as temperature increased from 800 to 1000 °C, tar yield increased from 26.58 to 35.03 wt.%. Meanwhile, char yield decreased from 24.50 wt.% to 19.02 wt.% over the temperature range of 600 to 1000 °C. This is caused by the fact that the char yield decreased due to the rapid and thorough degradation of lignocellulosic components at higher temperatures. Lower temperature helps to increase char yield. The reason for the decrease in tar and char yield after 600 °C could be that temperatures over that point favour gaseous yield [19].

In general, tar cracking and boudouard reactions enable the endothermic process of turning tar and char into gaseous products [20]. As a result, a higher reactor temperature would promote the thermodynamic conversion of tar and char into gas, lowering the amount of bio-tar and char in the finished product. On the other hand, according to Mishra et.al, [16] in char gasification, the gasification temperature is crucial. The gas shift reactions of water, boudouard, and oxidation show an essentially linear relationship with rising bed temperature.

**Fig. 1** Product yields of co-gasification at different temperature for 60 minutes

### 3.3 Effect of Blending Ratio on Product Yield of Co-gasification

Figure 2 demonstrated the co-gasification of TPKS: LDPE at 800 °C for 60 min reaction time with different blending ratios of 10%, 50% and 90% TPKS. As shown in Figure 2, through blending of torrefied PKS and LDPE (TPKS: LDPE), the gas and char yield increase, while tar decrease with increase torrefied PKS ratio. This may have resulted from the co-gasification process's high biomass blending ratio producing excess volatiles. [21]. Numerous

studies have found that since many plastic wastes, such as polyethylene glycol terephthalate (PET), polypropylene (PP), polystyrene (PS), and polyethylene (PE) are rich in hydrogen and low in oxygen, they could be an appropriate co-reagent when used with biomass during co-gasification [18]. In addition, the blending of LDPE to the biomass will result in the occurrence of two processing processes. The first step was the thermal decomposition of the LDPE waste and biomass, which produced heavy and light hydrocarbons, char, and volatiles. The second step entails high-temperature reactions mostly at 650 – 1000 °C with volatile substances and steam that mostly yield hydrocarbons and char [22].

Additionally, it was shown that, when compared to other blending ratios, the product yields from the co-gasification of TPKS: LDPE at 50:50 blending ratios produce the maximum gas production with the lowest char and tar yield. According to Buentello-Montoya et al. [23], combining plastics with biomass enhanced the gas yield and encouraged the production of CO and H<sub>2</sub>. The greatest H<sub>2</sub> generation and efficiency were also obtained by simulating a plastic combination with a composition similar to LDPE. According to Buentello-Montoya et al. [23], gasification of plastics produces better gas than gasification of other wastes, and the hydrogen contents in the feedstock are crucial in defining the products. Additionally, the plastic improved the process's efficiency for converting carbon [23]. Therefore, the ideal parameter to create maximum gas yield with lowest tar and char yield is at 50:50 (TPKS: LDPE) blending ratio at 800°C for 60 minutes of reaction time, based on the effect of temperature and blending ratio on product yield.

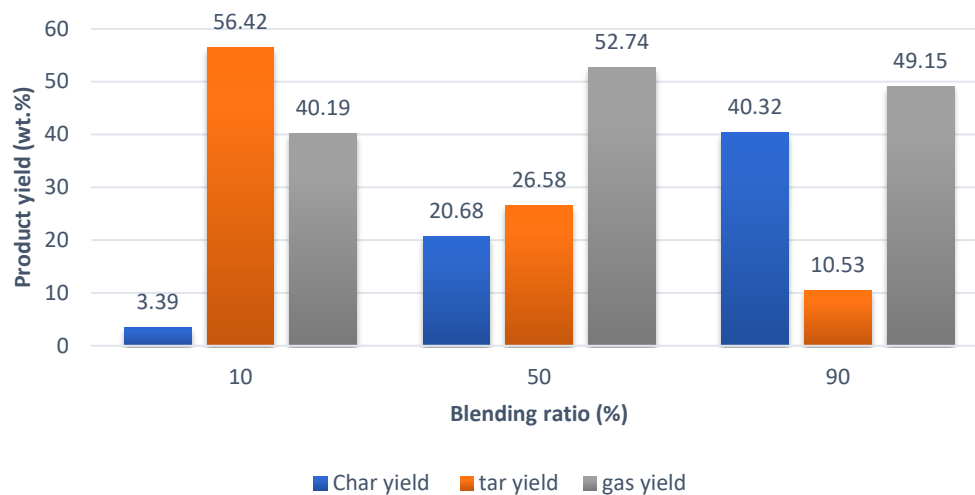


Fig. 2 Product yields of co-gasification at different blending ratio for 60 minutes

### 3.4 Gases Composition of Co-gasification at Optimum Parameter

The amount of volatile matter and fixed carbon in the gas had an impact on gas composition. Typically, thermal decomposition converts volatile matter, which is mostly made of carbon and hydrogen, into hydrocarbons, CH<sub>4</sub>, and H<sub>2</sub> [20]. In contrast, oxidation and partial oxidation reactions using oxygen sources transform fixed carbon into CO and CO<sub>2</sub> forms. In fact, both endothermic and exothermic reactions take place simultaneously during gasification, resulting in the main components of the final gaseous products including H<sub>2</sub>, CO, CO<sub>2</sub>, and CH<sub>4</sub> [24]. The effect of gases composition on co-gasification of UnPKS:LDPE and TPKS:LDPE at reaction time 20, 40, and 60 minutes was shown in Figure 3. From figure 3 (a), the composition of H<sub>2</sub> was increased drastically when the reaction time increase for TPKS: LDPE from 7.28% to 31.65% within 20 to 40 min. However, H<sub>2</sub> composition was slightly decrease to 21.9% at 60 min. The H<sub>2</sub> composition of UnPKS:LDPE was increase continuously 5.42% at 20 min to 6.03% at 40 min and 9.44% of 60 min. The large amount of carbon content is consistent with the high H<sub>2</sub> production in TPKS compared to UnPKS [25]. The majority of the H<sub>2</sub> produced in a co-gasification reactor comes from the reaction of carbon and steam. As a result, the pretreatment of biomass increased both its carbon content and its ability to produce H<sub>2</sub> gas [26].

This offers a great opportunity to apply pretreated biomass for the production of hydrogen [27]. The production of CH<sub>4</sub> composition for TPKS: LDPE was highest at 20 min of 76.65% however, at 60 minutes it decreases drastically to 29.31%. Meanwhile, UnPKS:LDPE contain higher CH<sub>4</sub> at 60 minutes than TPKS:LDPE. The composition of CO are not present in TPKS: LDPE from 20 min until 60 min but present in UnPKS:LDPE at 40 min and 60 min. Figure 3(d) shows the composition of CO<sub>2</sub> increase as increase reaction time for UnPKS:LDPE. At 60 min reaction time, UnPKS:LDPE shows the highest CO<sub>2</sub> production of 10.60% at longer reaction time of 60 min. Meanwhile, CO<sub>2</sub> production of TPKS: LDPE was increased at 20 min to 40 min from 3.14% to 7.24%, however, TPKS: LDPE showed the significant reduction of 3.72% at longer reaction time.

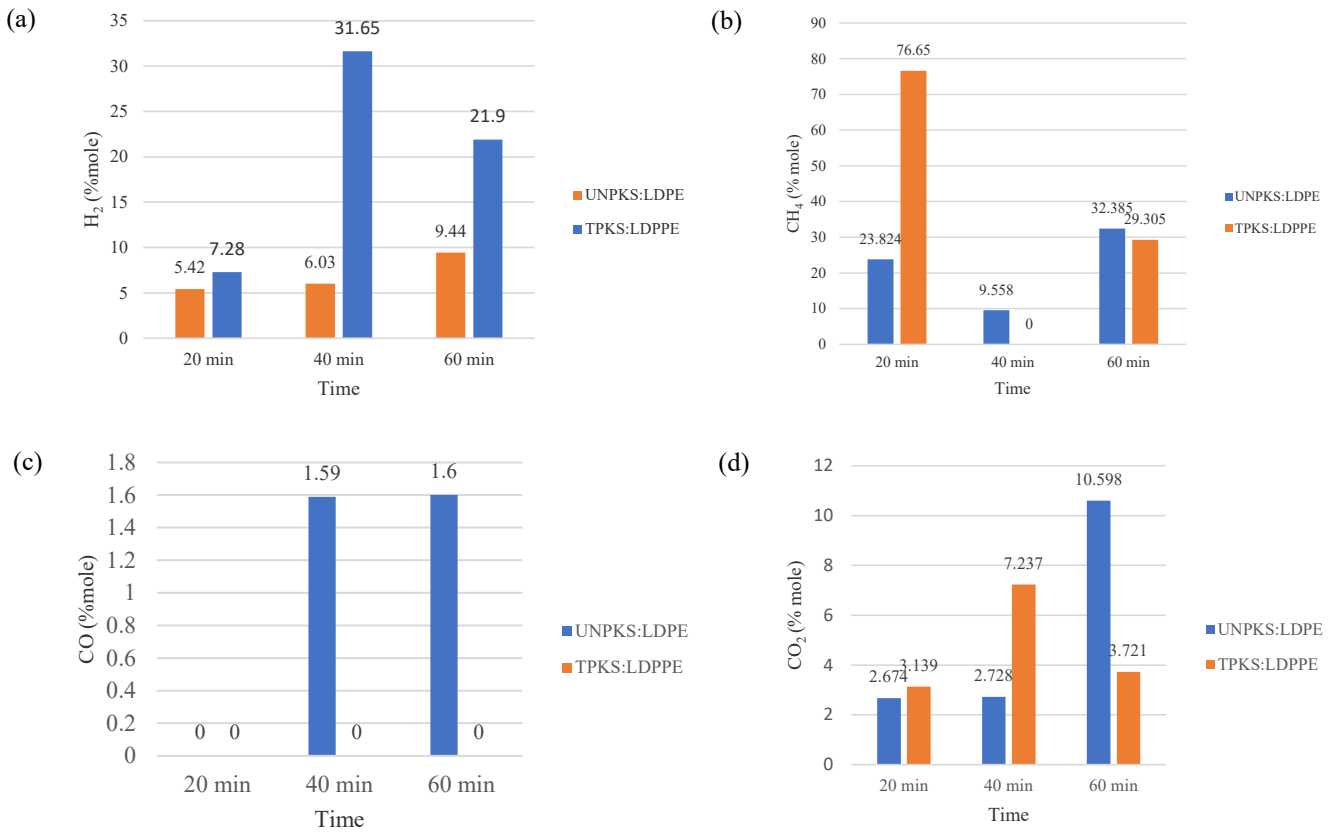


Fig. 3 (a) H<sub>2</sub>, (b) CH<sub>4</sub>, (c) CO, (d) CO<sub>2</sub> gases composition of co-gasification at optimum condition

#### 4. Conclusion

This study presents the product yields produce from the co-gasification of TPKS and LDPE. Prior co-gasification, PKS was undergo pre-treatment process in order to improve the quality of biomass. Then, TPKS and LDPE were gasified at different temperature and blending ratio for 60 min reaction time. The findings exhibited that; temperature plays an important role in co-gasification. The optimum parameter to produce maximum gas yield with minimum tar and char yield are at 50:50 (TPKS: LDPE) blending ratio at 800 °C for 60 minutes reaction time. The gas analysis showed that H<sub>2</sub> composition for TPKS: LDPE was increased drastically compared than UnPKS:LDPE with increase reaction time. When compared to an untreated sample, the treated sample's high carbon content accounts for its significant H<sub>2</sub> generation. Consequently, the pretreatment of PKS altered it's characteristic particularly increased the carbon content. Therefore, the pretreatment of biomass offers a great opportunity during the co-gasification for the production of hydrogen.

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#### Conflict of Interest

No conflict of interests regarding the publication of the paper.

#### Author Contribution

Nur Rahimah Ibrahim and Razi Ahmad suggested the idea of this work, wrote the manuscript and made final improvements. Razi Ahmad and Mohd Azlan Mohd Ishak proofread, edited, and made improvements to this article.

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