IOP Conference Series:
Earth and
Environmental Science

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To cite this article: Nur Rahimah Ibrahim *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1303** 012007

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

Nur Rahimah Ibrahim [1], Razi Ahmad [1,2,*], Mohd Azlan Mohd Ishak [3,4]

[1]Faculty of Civil Engineering Technology, Universiti Malaysia Perlis, Perlis, Malaysia.
[2]Water Research and Environmental Sustainability Growth (WAREG), Center of Excellence (COE), Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia.
[3]Fossil and Biomass Energy Research Group, Universiti Teknologi MARA, Perlis Branch, Arau Campus, Arau, Perlis, Malaysia.
[4]Faculty of Applied Science, Universiti Teknologi MARA, Perlis Branch, Arau Campus, Arau, Perlis, Malaysia.

*Corresponding author e-mail: razi@unimap.edu.my

Abstract. This study investigates 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 ºC 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 futher thermal conversion. Then, TPKS and LDPE were gasified at temperature of 600, 800 and 1000 ºC and blending ratio of 10:90, 50:50, 90:10 (TPKS:LDPE) for 60 min reaction time. Based on the findings found that, temperature plays an important role in co-gasification. Higher gasification temperature increases the carbon conversion which improves gasification rate. By varying temperature from 600 to 1000 ºC, the gas yield increased whilst tar yield decreased sharply. 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. Furthermore, it was observed that the product yields obtained from the co-gasification of TPKS and LDPE at 50:50 blending ratios produce the highest gas yield with low char and tar yield 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 ºC for 60 minutes reaction time.

1. Introduction

Biomass is one of the largest sustainable energy sources in the world that has a variety of alternative energy sources which are available globally. Due to their accessibility and advantages for the environment as a carbon source with CO_2 neutrality, it can be utilised to replace conventional fossil fuels [1]. Given that Malaysia produces 127 million tonnes of agricultural waste biomass, using biomass for energy production in this nation has a lot of promise [2]. Oil palm cultivation makes up the majority of agricultural activity in Malaysia and is a significant source of renewable energy [3]. Since palm oil is the primary end product of oil palm agriculture, additional waste products are also produced, including empty fruit bunches (EFB), mesocarp fibre (MF), palm kernel shells (PKS), oil palm trunks (OPT), and oil palm fronds (OPF). Palm kernel shell (PKS), a byproduct of the manufacture of palm oil, is utilised in the production of energy and biofuels [4]. Waste palm kernel shells (PKS) must be used for a variety of purposes, especially given their alleged minimal carbon footprint [5]. PKS has higher calorific value (17.30-20.35 MJ/kg), lower sulphur content (0.06-0.95 wt%) and can be found easily. Thus, organic crude fuels (unconventional fuels) must be substituted for conventional fuel in order to lessen the immediate fossil fuel greenhouse gases [6].

The global plastic has produced 600 metric tonnes of plastic over the years due to the numerous commercial uses for plastics [3]. Plastics are used in a wide range of industrial and domestic areas since they have become indispensable materials and their industrial applications are constantly expanding. However, the ongoing need for plastics leads to an accumulation of plastic garbage in landfills, which takes up a lot of area and exacerbates environmental issues. Recycling used plastic is anticipated to be the most efficient method. However, the recycling method resulted in water contamination and significant manpower costs for the separation process, which decreased the process's sustainability. The increased demand for plastics, which were made of petroleum-based materials, resulted in the exhaustion of petroleum [7]. The processes for converting waste plastic into fuels and chemicals with additional value are therefore very interesting and are the subject of extensive research and technological advancement. Among the polymers, LDPE has a molecular chain structure and a high effective H/C ratio. that make it excellent for manufacturing fuel-ranged hydrocarbons. Since petroleum was the primary raw material used to make plastic, recovering plastic and turning it into biofuel through thermal processing had enormous promise. Besides, the biofuel produced had high calorific value of 51.19 kJ/kg compared to the commercial fuel [8].

Biomass energy and plastics waste able to be transformed into value-added fuels or products through thermochemical conversion [3]. Thermochemical conversion is an efficient method to convert raw materials into biofuels. Pyrolysis, combustion, liquefaction, and gasification are normally preferred due to their versatility to afford almost all types of feedstocks and shorter processing time. Gasification is one of the many thermochemical conversion processes that has promise for converting biomass and polymers into syngas with added value, such as hydrogen (H_2) and carbon monoxide (CO). According to Sulaiman et al. [9] gasification is a process for converting solids become combustible gases (CO, CH_4, and H_2) 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. Apart from the main gaseous products, gasification also results in condensable liquids. Higher temperatures prevent tar from forming, which makes cleaning and recovering the gas relatively easy [10].

Fixed-bed reactors, which can be categorized into vertical and horizontal varieties, are widely used in small-scale operations or pilot trials because they are the most straightforward, reliable, developed, and efficient gasifier. Heat from external sources, like electric heating systems, causes the thermal degradation of biomass. Vacuum pumps or inert gases like nitrogen, argon, and helium are used to drive volatiles out of the reactor; these volatiles are subsequently condensed back into bio-oil by cooling devices.

Even though research has been done on the co-gasification of plastics and pretreated biomass, it is still not as widespread as the co-gasification of plastics and untreated biomass. Additionally, there are few studies that looked into the co-gasification of polymers and oil palm biomass as a biomass feedstock. M. Basha et. al [3] did research on the steam co-gasification of polystyrene and untreated palm kernel shell. Conversely, mixing of plastics with untreated biomass increase extensively the volatility of the fuel. This converts in higher tendency to tar production, consequently, reducing the gases production.

Hence, in this research, prior co-gasification, PKS was undergo torrefaction as pre-treatment process at different temperature. Then, co-gasification of torrefied PKS and LDPE was studied in order to determine the product yield 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, palm kernel shell (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 ºC for 12 hours.

2.2. Pre-treatment of PKS

Using a vertical fixed bed reactor with an ambient pressure system, a height of 300 mm, and an internal diameter of 60 mm, untreated PKS was first torrefied. The reactor was heated from the outside by an electric furnace. The 5g of untreated PKS were placed in the reactor. Prior to the experiment, the reactor was flushed with nitrogen gas for 10 minutes. To maintain an inert atmosphere inside the reactor, a nitrogen flow rate of 0.5 L/min was maintained at all times. Then, at a steady nitrogen flow rate of 100 ml/min, the reactor's temperature was raised to the necessary torrefaction temperatures of 200, 250, and 300 ºC.

2.3. Proximate analysis of TPKS

The proximate analysis was carried out using thermogravimetric analyser (TGA). In TGA, about 20 mg of sample was used and heated from room temperature to 900 °C at a rate of 10 K /min under the flow of N_2 at a rate of 200 cm^3min^{-1}. The thermogravimetric (TG) curve and differential thermogravimetric curve (DTG) will be evaluated for the ash, moisture, fixed carbon, and volatile matter.

2.4. Co-gasification of TPKS and LDPE

The co-gasification of TPKS and LDPE was performed under an atmospheric pressure in a vertical fixed-bed reactor. Approximately 5 g of sample at different blending ratio of TPKS:LDPE (10:90, 50:50, 90:10) was positioned within the reactor, weighed, and placed. Prior to the experiment, nitrogen gas was used to flush the reactor for ten minutes. The sample was then heated at a rate of 50 °C/min to the required gasification temperature. A nitrogen flow rate of 0.5 L/min was always kept in the reactor to ensure an inert atmosphere. When the reactor reached the gasification temperature, the nitrogen flow was halted and the steam generated by the steam generator was added to the reactor. The volatile product and steam that were released from the reactor's upper side were condensed using a tar trap. After that, every 15 minutes starting at the start of the steam gasification, the gas bag was used to collect dry gas. The reactor was let to cool to room temperature when the procedure was finished and the furnace was shut off. Once the char had warmed to room temperature, its weight was determined. Weighing was done on the tar product in a tar trap. On the basis of the overall mass balances and 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 [11].

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

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

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

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. Table 1 demonstrated the result of proximate analysis for untreated PKS and torrefied PKS. Generally, it can be seen that when torrefaction temperature increase, the volatile matter decreased but fixed carbon shows the opposite trend. This is principally brought on by the fact that as the temperature of torrefaction rises, the rate of devolatization increases and more hemicellulose and lignin are broken down [1]. Volatile matter is the quantity of substance lost when biomass is heated for a specific period of time and at a specific temperature. The amount of carbon present 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 [14]**.** As a result, the solid product's gross calorific value increased [15].

Typically, as the temperature of torrefaction increases, the amount of ash also grows, causing mass loss and the accumulation of high levels of metallic elements. The thermal conversion of biomass was significantly improved by low ash content, especially if the biomass had halides or potassium 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 moisture content of biomass had an effect on its calorific value. The amount of heat required for combustion to occur increased as solid fuels' water content increased, requiring more energy [16]. Compare to untreated PKS, the moisture content of torrefied PKS is significantly decrease when the torrefaction temperature increase. Moisture content and the amount of fixed carbon can help determine whether treated PKS is an appropriate 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 of 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 [17]**.** 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 highest product yield at lower temperatures. The gas yield increased significantly from 25.88 to 45.94 wt% when the reactor temperature was raised from 600 to 1000 oC, whereas the bio-tar yield dropped significantly from 49.61 to 35.03 wt%. The rise in gaseous yield could be attributed to tar and char conversion in relation to growing heating carrier temperature. As a result, Due to the thermal cracking process and the boudouard reaction, higher tar and char can both be transformed into gases [18]. However, higher temperatures may encourage the disintegration of the C-C and C-O bands, resulting in smaller particles and a higher probability of them becoming reduced gas particles [19].

Tar yield varied from 49.61 to 26.58 wt.% within a temperature range of 600 to 800 ºC. However, as temperature increased from 800 to 1000 ºC, 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 ºC. The char yield decreased as a result of the lignocellulosic components' quick and thorough breakdown at higher temperatures. Lower temperature helps to increase char yield. The fact that temperatures above 600 ºC favoring gaseous yield may be the cause of the drop in both char and tar yield after 600 ºC [20].

In general, tar cracking and boudourad reactions enable the endothermic process of turning tar and char into gaseous products [21]. Therefore, the amount of bio-tar and char in the final product would decrease as a result of a higher reactor temperature that would thermodynamically favour the conversion of tar and char into gas. On the other hand, according to Mishra et.al, [17] in char gasification, the gasification temperature is crucial. As the temperature of the bed rises, water gas shift reaction, oxidation, and boudouard which exhibit an almost linear relationship, increase the conversion of carbon during the gasification reaction.

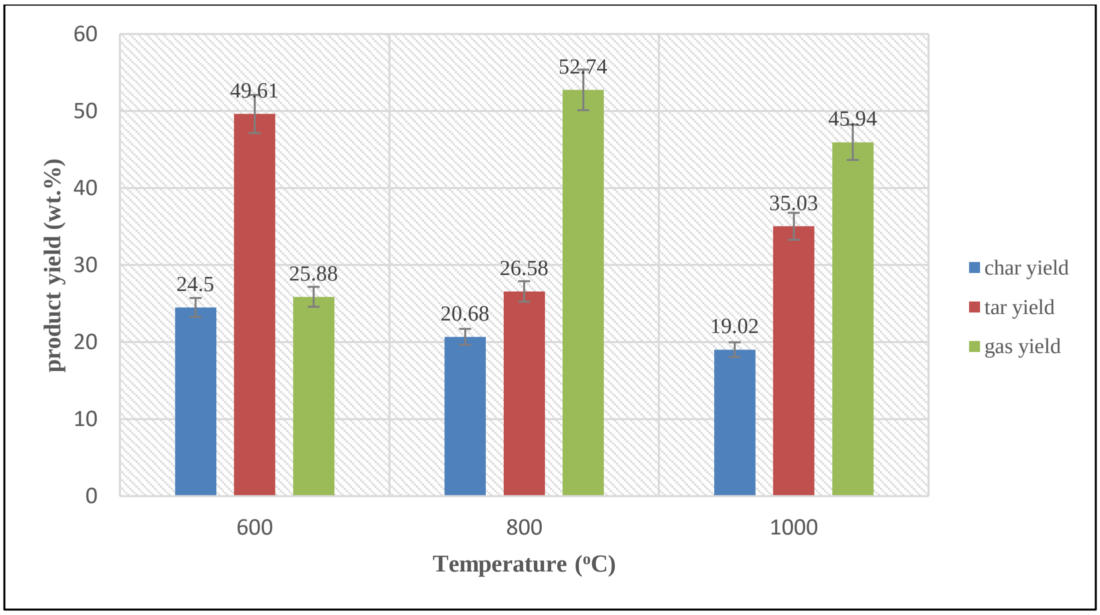

Figure 1. Product yields of co-gasification at different temperature for 60 minutes

3.3. *Effect of blending ratio on product yield of co-gasification*

Figure 2 demonstrated the co-gasification of TPKS:LDPE at 800 ºC 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 is likely caused by the co-gasification process's excessive volatile generation at high biomass blending ratios [21]. Numerous studies have discovered that plastic waste could be an appropriate co-reagent with biomass during co-gasification since many plastic wastes, including polypropylene (PP), polyethylene (PE), polyethylene glycol terephthalate (PET), and polystyrene (PS) are rich in hydrogen and low in oxygen. [19]. In addition, the addition of LDPE to the biomass feedstock resulted in the occurrence of two processing processes. The first step was the thermo-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 ºC with volatile substances and steam that mostly yield hydrocarbons and char [23].

Additionally, it was shown that the co-gasification of TPKS:LDPE at 50:50 blending ratios produces the maximum gas production with the lowest char and tar yields compared to other blending ratios. Buentello-Montoya et. al, [24] stated that, plastics' presence facilitated the synthesis of H_2 and CO, while combining biomass with plastics boosted the gas yield. Furthermore, an LDPE-like plastic mixture was also simulated, producing the best H_2 production and efficiency. Buentello-Montoya et. al [24] also stated plastic waste can be gasified to produce more gas than other types of waste because the amount of hydrogen in the feedstock determines the final output. Additionally, the plastic improved the process' efficiency for converting carbon [24]. 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.

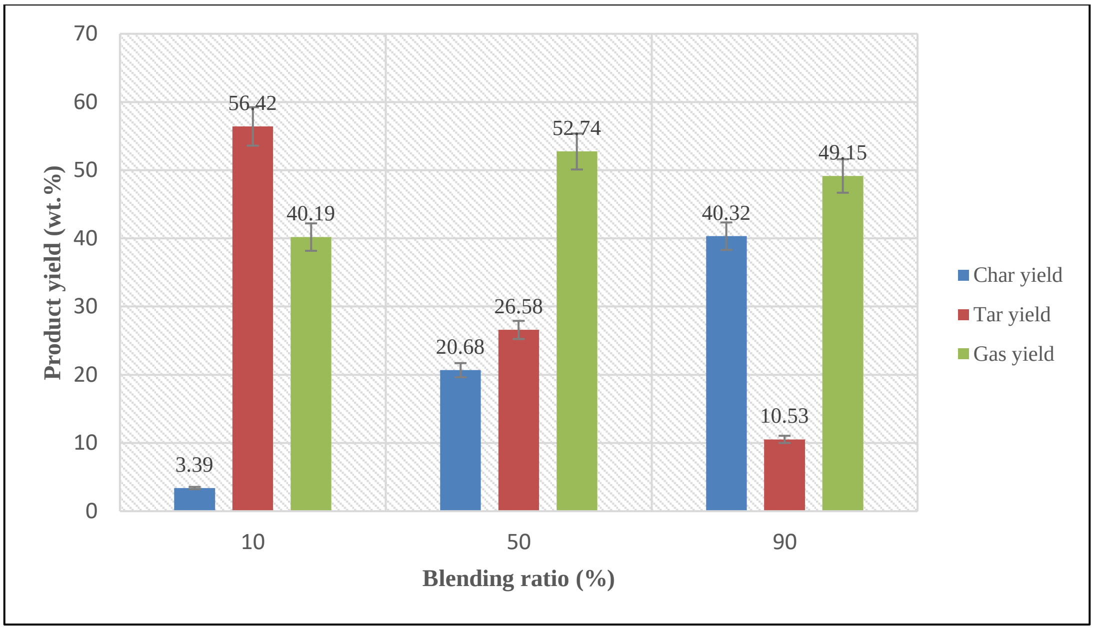

Figure 2. Product yields of co-gasification at different blending ratio (TPKS:LDPE) for 60 minutes

4. Conclusion

This study presents the product yields produce from the co-gasification of TPKS and LDPE. Prior co-gasification, PKS undergo pre-treatment to enhance the quality of the biomass. Then, TPKS and LDPE were gasified at different temperature and blending ratio for 60 min reaction time. Based on the findings found that, temperature is a key factor 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.

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