Gasification of raw and torrefied empty fruit bunch using bubbling fluidized bed

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Abstract. An experimental study of bubbling fluidized bed gasification process using empty fruit bunch (EFB) as a feedstock has been performed in order to study the effect of gasification temperature on gasification performance. Two types of EFB have been used, which are raw EFB and torrefied EFB at 300 °C. The composition of the synthesis gas, gas yield, low heating value (LHV), cold gas efficiency (CGE), and carbon conversion (CC) was determined and analyzed. In terms of synthesis gas, the composition of hydrogen and carbon monoxide gases were increased while methane and carbon monoxide gases were decreased for raw and torrefied EFB when the temperature is increased from 650 to 900 °C. Meanwhile, the synthesis gas yield was significantly enhanced and reached the maximum value of 1.21 and 1.45 MJ/Nm³ for raw and torrefied EFB respectively, which indicates that the torrefaction process improves the synthesis gas yield. Besides, the LHV for the torrefied EFB at highest gasification temperature is 11.08 MJ/Nm³ which is higher than raw EFB (10.81 MJ/Nm³). However, the value of CGE and CC of torrefied EFB are lower than raw EFB with the different about 3% and 5% respectively.

1. Introduction
Currently, the world is depending on the fossil fuel as the energy resources which mostly utilized as the transportation fuel. Besides, the utilization of the fossil fuel itself will contributes to the climate changes and global warming. Thus, it is important to find another alternative source in order to reduce the dependency of fossil fuel. Biomass is one of the bioenergy resources which provide clean and green renewable energy for the consumers. Biomass is an organic matter which derived from living things and it can be converted into fuels or useful chemical by biological and thermochemical conversions. The oil palm waste is one of the biomass resources which consists of empty fruit bunch (EFB), palm kernel shell (PKS), palm mesocarp fibre (PMF) and oil palm fronds (OPF). The palm oil industries in the world or even in Malaysia generate over millions ton of wastes either in solid or liquid residues. From palm oil plantation, only 10% of them are being utilized while 90% of them are wastes [1]. However, approximately only 10% of the wastes are utilized commercially for new products like bio-fertilizers [2]. Currently, PKS and PMF are being utilized for the steam production as fuels while the rest are being left rotten. Therefore, a proper waste management and utilization is necessary in order to reduce the amount of waste and also to maintain the sustainability of the environment [3]. One of the methods is using thermochemical conversion technology such as biomass gasification which converting solid biomass into liquid and gases product through series of oxidation reaction.

Gasification is one of the processes used to produce synthesis gases which consist of hydrogen (H₂), carbon monoxide (CO), methane (CH₄) and carbon dioxide (CO₂). Gasification process usually is
conducted at high temperature (>600 °C) with the present of the gasifying agent such as air and/or steam using the gasifier. There are several types of gasifier that can be used to conduct the gasification process. One of the widely used gasifier is bubbling fluidized bed since it can gives good temperature distribution and higher reaction rates compare to other gasifiers [4]. Even though it has complex operation, it also has large fuel inventory which provides safety, reliability and stability. In addition, the bubbling fluidized gasifier gives more advantages as it gives higher cold gas efficiency as well as specific capacity and lower residence time which suitable and easier to evaluate the gasification performances.

Although many of gasification experiments have been performed but it is important to note that most of previous studies use raw biomass as the gasification feedstock. However raw biomass usually content high moisture content and low values of fixed carbon and ash which reduce the efficiency of the gasification performances. In order to improve the quality of the biomass, the pre-treatment process is needed by using the torrefaction method [5]. This method removes the moisture content of the biomass by carrying out at torrefaction temperature in the range of 200 – 300 °C under the absence of the oxygen which resulting into increment of fixed carbon, volatile matter and ash content [6]. As consequence, torrefied biomass is considered more uniform compared to raw biomass and make it more easier to be utilized as feedstock in the gasification process [7]. This study focuses on utilization of two different types of EFB namely raw and torrefied EFB at 300 °C, as the biomass feedstock. The objective of this work is to study the production of synthesis gas and the gasification performances of raw and torrefied EFB by varying the gasification temperature. The synthesis gas composition is evaluated and the gas yields, lower heating value (LHV), cold gas efficiency (CGE) and carbon conversion (CC) are determined and analyzed by varying the reactor temperature from 650 to 900 °C.

2. Materials and methods

2.1. Sample preparation

The biomasses used in this study were raw Empty Fruit Bunch (EFB) and torrefied EFB. The raw EFB were obtained from Lepar Hilir Palm Oil Mill, Kuantan, Pahang. Initially, the biomass samples were dried using an oven for about 4 hours at 105 °C to reduce the moisture content and also to avoid biomass degradation that influence the quality of the sample. Then, the sample were grinded and sieved to the particle size of 0.5 to 1.0 mm. Accordingly, the torrefied EFB has been obtained based on torrefaction experiment of raw EFB at temperature of 300 °C with a residence time of 30 minutes. The torrefaction process was carried out using a vertical-stainless steel reactor with 39.7 cm long and 1.9 cm internal diameter as shown in figure 1. The grinded and dried sample was placed in the reactor. The reactor was flushed for 5 minutes with 10 mL/min nitrogen in order to create the inert atmosphere. After that, the biomass sample was heated by an electric furnace to the desired temperature of 300 °C for 30 minutes and then it was cooled to ambient temperature. Finally, the torrefied biomass was placed in air-tight container to keep the value of the moisture content from increasing [8].

The properties of proximate analysis, ultimate analysis and high heating value (HHV) for raw and torrefied EFB are shown in table 1. The moisture content is reduced after the torrefaction process from 15.77 wt% to 4.63 wt% due to the drying process which contributing to the loss of the water content in the biomass. Besides, the value of the volatile matter also decreased from 67.01 to 48.44 wt%. Meanwhile, the value of fixed carbon and ash are increased due to the breakdown of hydrocarbon bonds which contributing to the volatile loss and further increasing the fixed carbon and ash content. For the ultimate analysis, the result shows that the percentage of carbon and nitrogen were increasing and the other gases shows opposite trends. Moreover, the HHV value also increased from 15.49 to 19.60 MJ/kg due to the lower moisture content and loss of more volatiles. Both results of proximate and ultimate analysis as well as HHV show that the biomass properties are improved by using torrefaction process.
Figure 1. Schematic diagram of vertical tubular reactor.

Table 1. The proximate and ultimate analysis of the raw and torrefied EFB.

| Proximate and Ultimate Analysis (wt%) | Raw EFB | Torrefied EFB at 300 °C |
|--------------------------------------|---------|-------------------------|
| Moisture Content                     | 15.77   | 4.63                    |
| Volatile Matter                      | 67.01   | 48.44                   |
| Fixed Carbon                         | 13.37   | 39.23                   |
| Ash                                  | 3.85    | 7.70                    |
| C                                    | 43.53   | 54.63                   |
| H                                    | 7.20    | 5.63                    |
| N                                    | 1.73    | 6.37                    |
| S                                    | 0.46    | 0.21                    |
| O                                    | 47.09   | 36.04                   |
| HHV (MJ/kg)                          | 15.49   | 19.60                   |

2.2. Gasification experimental setup

Experimental set-up used for the gasification process is shown in figure 2. The fluidized reactor was made from stainless steel with a bed diameter of 60 mm and height of 850 mm. Silica sand was used as a bed material in the fluidized bed reactor. The feedstock was fed into the reactor using a screw feeder conveyor at a rate of 0.25 to 0.4 kg/h. Steam was used as the gasifying agent and flushed into the bottom of the reactor. The fluidized bed reactor was heated to the desired gasification temperature using an electric furnace. Eight different gasification temperatures were used in this work (650, 700, 750, 800, 850 and 900 °C) to study the effects of gasification temperature on the production of synthesis gas. The produced gas exited at the top of the reactor and entered the cyclone separator for separating tar and ash. The gas exited the cyclone and underwent a cleaning and drying process using a dry ice trap and cotton filter. The dry and clean gas was then collected using a gas sampling bag and analysed using an Agilent 6890N gas chromatograph with a thermal conductivity detector (GC–TCD). The standard gas mixture was used as calibration for GC–TCD and nitrogen gas was used as the carrier gas for the analysis.
2.3. Product gas analysis

In this work, the gasification performance is evaluated by determining the synthesis gas yield, lower heating value (LHV), cold gas efficiency (CGE) and carbon conversion (CC) for both raw and torrefied EFB. The volume of the gas produced from the experimental work was used to obtain synthesis gas yield that is expressed as

$$\text{Syn}_{\text{yield}} = \frac{\text{Vol}_{\text{gas}}}{\text{Mass}_{\text{feedstock}}}$$ (1)

One of the energy contents in biomass is expressed as lower calorific value which includes all the sensible energy except for the heat of condensation of water. The LHV of the synthesis gas was calculated from the gas composition recorded at different temperature for both raw and torrefied EFB. The LHV of product gas is defined as

$$\text{LHV}_{\text{yield}} = (30x_{\text{CO}} + 25.7x_{\text{H}_2} + 85.4x_{\text{CH}_4}) \times 4.2$$ (2)

where \(x\) is represents the mole fraction of the gas species. Furthermore, CGE is a crucial index to evaluate the performance of the biomass gasification [9]. The CGE is calculated by

$$\text{CGE}(\%) = \frac{\text{LHV}_{\text{gas}} \times \text{Syn}_{\text{yield}}}{\text{HHV}_{\text{feedstock}}} \times 100$$ (3)

where HHV is the higher heating value of feedstock. In addition to CGE, carbon conversion (CC) is also analysed and expressed as

$$\text{CC}(\%) = \left[ 1 - \frac{m_{\text{product gas}}(y_{\text{CO}_2}^{12\text{CO}_2} + y_{\text{CO}}^{12\text{CO}} + y_{\text{CH}_4}^{12\text{CH}_4})}{m_{\text{fuel}}C} \right] \times 100$$ (4)

where \(y\) is the mass fraction of the gas species. CC is the parameter that determines the solid feed converted into the permanent gases.

3. Results and discussion

3.1. Effect of gasification temperature on synthesis gas composition

The gas chromatography analysis was performed in order to determine each of the synthesis gas composition which are \(\text{H}_2\), \(\text{CO}\), \(\text{CH}_4\) and \(\text{CO}_2\). Figure 3 shows the effect of the gasification temperature on each of the synthesis gas produced. Based on figures 3 to 6, increment of gasification temperature from 650 to 900 °C contributes to the increase of hydrogen percentage from 15.28 mol% to 29.40 mol%.
for raw EFB and 10.40 mol% to 21.50 mol% for torrefied EFB respectively. Moreover, the percentage of the carbon monoxide showed some increment for both raw and torrefied EFB which are from 36.42 mol% to 54.94 mol% and 36.74 mol% to 54.67 mol% respectively. The higher temperature is known to favour the reactants in endothermic and products in exothermic reactions [10]. Thus, the increasing of carbon monoxide can be clarified by taking into account the endothermic reduction reaction that will reach the equilibrium at higher temperature. The endothermic reactions involved in this process are water-gas shift reaction \((\text{C} + \text{H}_2\text{O} \leftrightarrow \text{CO} + \text{H}_2 \Delta H^\circ = +131.4 \text{ kJ/mol})\) and Boudouard reaction \((\text{C} + \text{CO}_2 \leftrightarrow 2\text{CO} \Delta H^\circ = +176.6 \text{ kJ/mol})\) which produce the hydrogen and carbon monoxide that contributes to the increasing of the percentage of both gases. Meanwhile, the percentage of carbon dioxide is decreased when the reactor temperature is increased. This could be explained from the increasing of the hydrogen and carbon monoxide where the carbon dioxide would be consumed in Boudouard reaction [7]. Besides, the torrefied EFB shows higher percentage of carbon monoxide compare to raw EFB. This is due to the improvement in the carbon content of torrefied EFB from 43.5% to 54.6% as shown in table 1 which improving carbon conversion to produce more carbon monoxide. However, the torrefied EFB produced smaller amount of hydrogen, carbon dioxide and methane compared to the raw EFB with the different is lesser than 8% due to the reduction of the volatile matter from 67% to 48.4%. Generally, the biomass with lower volatile matter have lower reactivity in gasification applications. This shows that the torrefaction method is insignificant for the production of those gases.

![Figure 3. Composition of H₂ for raw and torrefied EFB at different temperature.](image-url)
Figure 4. Composition of CO for raw and torrefied EFB at different temperature.

Figure 5. Composition of CO₂ for raw and torrefied EFB at different temperature.
3.2. Synthesis gas yields, lower heating value (LHV), cold gas efficiency (CGE) and carbon conversion (CC)

The synthesis gas yields, LHV, CGE and CC are essential criteria for measuring the efficiency of the biomass conversion for the gasification application. As shown in figure 7, the synthesis gas yield for both raw and torrefied EFB are increased when the temperature is increased. This is due to the further cracking of liquid and enhanced char reaction with gasifying agent which reduce the amount of liquid and char. However, the synthesis gas for torrefied EFB is higher than the raw EFB as the volume of gases produced for torrefied EFB is higher than raw EFB. In addition, the LHV for torrefied EFB is slightly higher than raw EFB which is not more than 0.3 MJ/Nm$^3$ as shown in figure 8. Referring to equation (4), the LHV is depending on the mole fractions of carbon monoxide, hydrogen and methane which are higher in torrefied EFB compare to raw EFB. Moreover, the carbon conversion of both raw and torrefied EFB as shown in figure 9 are increased due to the increment of the rate of devolatilization.

From the torrefaction method, the HHV for EFB has been increased from 15.49 to 19.60 MJ/kg which explains the increment of carbon conversion rate. Moreover, the CGE of torrefied EFB will be affected as well as shown on the equation (3). As shown in figure 10, the maximum CGE of raw EFB (84.26%) is slightly higher than torrefied EFB (81.88%) but both are increased with the increasing of temperature. The CGE is defined as ratio of the flow of energy in the gases and energy in biomass. Referring to equation (3), the CGE is increased when the syngas yield and LHV are increased but shown a decrement when the value HHV is increased.

![Figure 6. Composition of CH₄ for raw and torrefied EFB at different temperature.](image-url)
Figure 7. Comparison of synthesis gas yields between raw and torrefied EFB in increasing temperature.

Figure 8. Comparison of lower heating value between raw and torrefied EFB in increasing temperature.
4. Conclusion
Bubbling fluidized bed gasification experiments were conducted at different gasification temperature using raw and torrefied EFB as the feedstocks. Experimental results show that the increasing temperature from 650 to 900 °C would increase the performances of the gasification in terms of synthesis gas yield, lower heating value, cold gas efficiency and carbon conversion. Meanwhile, with the increasing of temperature, the compositions of hydrogen and carbon monoxide are increased while methane and carbon dioxide compositions are decreased. Torrefied EFB at 300 °C produces higher amount of carbon monoxide compare to other gases which are 54.9% at gasification temperature of 900 °C. In terms of feedstock comparison, it shows that the EFB undergo torrefaction process produces a higher synthesis
gas yield and LHV compare to raw EFB. However, the value of CGE and CC for torrefied EFB are lower compared to raw EFB.

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