Gasification Performance and Tar Generation Comparison From Fluidized Bed Gasification of Raw and Torrefied Empty Fruit Bunch

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Abstract. This paper presents the effects of gasification temperature and steam to biomass ratio on gasification performance and tar generation. Fluidized bed gasifier is used for gasification process with steam employs as gasifying agent. Two types of feedstock were used namely raw and torrefied empty fruit bunch (EFB). Experimental results show the synthesis gas yield, lower heating value (LHV), cold gas efficiency (CGE) and tar generation are steadily increased for both feedstock when gasification temperature is increased from 600 and 1000 °C. Meanwhile only yield of synthesis gas is increased when steam to biomass ratio is increased from 0.51 to 1.51. LHV, CGE and tar initially show increment trends but start to decrease beyond steam to biomass ratio of 1.02. Torrefied EFB shows superior performance in terms of producing more synthesis gas, better energy and efficiency compare to raw EFB. However, tar generated from torrefied EFB is higher than raw EFB. Based on tar component analysis, it has been found that 6 tertiary tar components are detected which consists of naphthalene,acenaphthylene, fluorene, phenanthrene, anthracene and pyrene for both feedstock. In overall, torrefied EFB shows potential as fuel feedstock for gasification process based on high synthesis gas yield with considerable amount of tar generation.

1. Introduction
Biomass gasification is one of the widely used thermochemical conversion methods for converting biomass into energy product. This is due to the fact that its ability to reduce the green house gases (GHG) emissions and at the same time overcome disposal problem of biomass waste. Theoretically, biomass gasification is conducted at high temperatures between 600 and 1000 °C with the presence of gasifying agents such as air, steam or combination of both. The main product from gasification is synthesis gas which consists of hydrogen (H₂), carbon monoxide (CO), carbon dioxide (CO₂) and traces of methane [1]. The produced synthesis gas is then can be utilized in combined heat and power production. However, synthesis gas is not the only product produced from gasification but other by-products are also generated such as particulates alkali metals, chlorine, sulfur and tars [2]. In gasification process, removal of tar is one of the challenges during gasification process. Usually tar is identified as black and
sticky material which may condenses at reduced temperature, thus contributing to the blocking and fouling process equipments such as engines and turbines [3].

To date most studies and experimental work on biomass gasification focuses on the effects of operating condition on synthesis gas production and gasification performance. For example, Bach et al. studied the effects of gasification temperature and steam to biomass ratio on product gas composition, heating value of cold gas and cold gas efficiency using raw and torrefied spruce [4]. Gasification performances of raw and torrefied bamboo in downdraft fixed bed gasifier have been investigated at different equivalence ratio and steam supply ratio [5]. Effect of gasification temperature on synthesis gas production gasification performance has been performed by Halim et al. using raw and torrefied palm mesocarp fibre [6]. Kirsanovs et al. investigated the influence of air supply organization, fuel supply and fuel moisture for maximizing synthesis gas calorific value and gasification process efficiencies [7]. However only limited work can be found on tar generation study from gasification process. Atnaw et al. studied tar generation from downdraft gasification of oil palm fronds [8]. Gasification of empty fruit bunch in an entrained flow gasifier has been investigated where oxygen has been added together with steam for maximizing hydrogen gas with low tar content [9]. However it is important to note both works employ only raw biomass as feedstock and the effect of torrefaction in feedstock is not considered in their works. Usually biomass undergo pretreatment process such as torrefaction process is preferable since it has lower moisture content and high energy density compare to untreated biomass. The effect of temperature, equivalence ratio and biomass composition on tar yields have been performed by Horvat et al. [2]. Two types of feedstock have been used which are raw and torrefied *Miscanthus x giganteus* where yields and composition of tar have been analyzed as a function of temperature and equivalence ratio.

Therefore, the objective of this work is to evaluate tar generation with gasification performance at different gasification temperature and different steam to biomass ratio. Fluidized bed gasifier is used since it provides minimum fluidization velocity to ensure intense mixing of hot bed material [10]. Meanwhile steam is used for gasifying agent. Two different types of empty fruit bunch are used namely raw EFB without pre-treatment and torrefied EFB at temperature of 300°C. Based on both feedstock, tar generation as well as gasification performance in terms of synthesis gas yield, lower heating value (LHV) and cold gas efficiency (CGE) are compared and evaluated. Tar component generated from gasification of raw and torrefied EFB is characterized and analyzed.

2. Materials and Methods
Prior to gasification, empty fruit bunch (EFB) underwent torrefaction process at temperature of 300°C with residence time of 30 minutes according to a procedure described previously [11]. The properties of proximate analysis, ultimate analysis and high heating value (HHV) for raw and torrefied EFB are shown in Table 1.

| Table 1. Properties of raw and torrefied EFB [11] |
|-----------------------------------|-----------------|-----------------|
| **Properties**                    | **Raw EFB**     | **Torrefied EFB at 300°C** |
| Moisture Content (as received) (wt %) | 15.77          | 4.63           |
| Volatile Matter (as received) (wt %) | 67.01          | 48.44          |
| Fixed Carbon (as received) (wt %) | 13.37          | 39.23          |
| Ash (as received) (wt %)          | 3.85           | 7.70           |
| **Ultimate Analysis (as received) (wt %)** |                  |                 |
| C (as received) (wt %)            | 43.53          | 54.63          |
| H (as received) (wt %)            | 7.20           | 5.63           |
| N (as received) (wt %)            | 1.73           | 6.37           |
| S (as received) (wt %)            | 0.46           | 0.21           |
| O (by difference) (as received)   | 47.09          | 36.04          |
| HHV (MJ/kg)                       | 15.49          | 19.60          |
As shown in Table 1, the moisture content of torrefied EFB is significantly reduced from 15.77 wt% to 4.63 wt%. In addition the fixed carbon and carbon content is greatly increased from 13.37 wt% to 39.23 wt% and 43.53 wt% to 54.63 wt% respectively. Moreover, the energy content indicates the HHV of torrefied EFB is increased from 15.49 to 19.6 MJ/kg. This indicates the properties of EFB is further upgraded by using torrefaction process. Thus both raw and torrefied EFB are then used as feedstock for gasification process. Gasification experimental set-up is shown in Figure 1. The details of this setup can be found in our previous work [11]. In this work, the operating conditions for fluidized bed gasification is shown in Table 2. The operating conditions are selected based on the normal range of operating conditions for performing biomass fluidized bed gasification where the range of gasification temperature is between 600 and 1000°C as well as range of gasifying agent to feedstock ratio is set between 0.1 to 1.5 [2,10].

The dry and clean gas was then collected using a gas sampling bag and analysed using an Agilent 6890N gas chromatograph with mass spectroscopy (GC–MS). The standard gas mixture was used as calibration for GC–MS and nitrogen gas was used as the carrier gas for the analysis. For tar collection, the impinger inside dry ice trap is rinsed with isopropanol solvent and the tar sample in liquid form is then collected using flask. Subsequently it is heated to temperature between 80 and 90°C for 40 to 60 min using rotary evaporator in order to remove the solvent. Finally the amount of tar is weighed for determining tar generation. For tar component analysis, the tar is analyzed using Agilent 6890N GC–MS where the temperature program was initiated at 30°C for 5 min before it is heating to temperature of 300°C. In this work, tar generation is assumed mainly from acid, aldehyde and ketone functional groups since EFB is part of ligno-cellulosic biomass [2].

![Figure 1. Schematic diagram of fluidized bed gasification [11]](image-url)

| Table 2. Operating conditions used for fluidized bed gasification |
|---------------------------------------------------------------|
| Parameters | Values |
| Feeding rate | 0.25 – 0.4 kg/hr |
| Gasification temperature | 600, 800 and 1000°C |
| Steam to biomass ratio | 0.51, 1.02, 1.51 |

In addition of tar generation, the gasification performance is also evaluated in terms of synthesis gas yield, lower heating value (LHV) and cold gas efficiency (CGE). Synthesis gas yield for both raw and torrefied EFB is calculated based on the volume of the gas produced from the experimental work and is expressed as
\[ S_{\text{yield}} = \frac{V_{\text{gas}}}{M_{\text{fuel}}} \]  

(1)

LHV is the indicator for energy contents in biomass and is defined as

\[ LHV_{\text{yield}} = (30x_{\text{CO}} + 25.7x_{\text{H}_2} + 85.4x_{\text{CH}_4}) \times 4.2 \]  

(2)

where \( x \) is represents the mole fraction of the gas species. Meanwhile the efficiency of gasifier is measured by using CGE where it is calculated by

\[ \text{CGE} (\%) = \frac{LHV_{\text{gas}} \times S_{\text{yield}}}{HHV_{\text{fuel}}} \times 100 \]  

(3)

where HHV is the higher heating value of feedstock.

3. Results and Discussions

3.1. Effect of temperature on syngas yield, gasification performance and tar generation

The effect of gasification temperature at fixed steam to biomass ratio of 1.02 on gasification performance and tar generation for both raw and torrefied EFB are shown in Figure 2. The main indication from Figure 2 is torrefied EFB shows better performance in terms of synthesis gas yield, LHV and CGE compare to raw EFB. Only at gasification temperature of 1000°C both feedstocks show similar performance in terms of LHV and CGE. As consequence, tar generation from gasification of torrefied EFB is superior compare to raw EFB at all investigated gasification temperature. The highest tar generation for raw and torrefied EFB is 15.74 g tar/kg biomass and 19.21 g tar/kg biomass at gasification temperature of 1000°C. This is due to effect of steam as gasifying agent and low moisture content of torrefied EFB (4.63 wt%) compare to raw EFB (15.77 wt%).

![Figure 2. Synthesis gas yield, LHV, CGE and tar generation at different temperature](image-url)
Based on tar steam reforming reaction [12]:

\[
C_nH_x + nH_2O \rightarrow (n + x/2)H_2 + nCO
\]  

(4)

Although steam as gasifying agent is able to convert tar \((C_nH_x)\) into hydrogen and carbon monoxide but the presence of high moisture content in raw EFB enable higher rates of tar steam reforming reaction compare to torrefied EFB. In addition, ash content for EFB as shown in Table 1 has been increased from 3.85 wt% to 7.7 wt% due to torrefaction process. However it does not contributes to any tar reduction and thus not a determining factor during tar evolution [13].

3.2. Effect of steam to biomass ratio on syngas yield, gasification performance and tar generation

The effect of steam to biomass ratio at fixed gasification temperature of 800°C on gasification performance and tar generation for both raw and torrefied EFB are shown in Figure 3. Synthesis gas yield shows an increment trends for both feedstock as the steam to biomass ratio is increased. This indicates that more steam supply into the gasification contributes to the rise of synthesis gas production. However different trends are observed in LHV and CGE. Initially both LHV and CGE are increased but start to decrease once the steam to biomass ratio is beyond 1.02. Although yield of synthesis gas has been increased but the efficiency and energy of product gas is not improved. By increasing steam to biomass ratio beyond 1.02, more steam presence in gasification compare to biomass which contributing to more dilution of the producer gas by steam. As consequence it is lowering the energy content of synthesis gas and efficiency of gasifier.

![Figure 3. Synthesis gas yield, LHV, CGE and tar generation at different steam to biomass ratio](image)

In terms of tar generation, torrefied EFB produces more tar compare to raw EFB. Initially torrefied EFB produces 18.04 g tar/kg biomass and slightly increased to 18.33 g tar/kg biomass when steam to biomass ratio is increased from 0.51 to 1.02. However tar generated from torrefied EFB gasification starts to decrease once the steam to biomass ratio is operated at 1.51. This is may due to the amount of steam in gasification process. As the steam to biomass ratio is increased, more tar is converted into hydrogen and carbon monoxide compositions which contributing to the increment of synthesis gas yield but only slight
increment of tar generation is observed. However once steam to biomass ratio is operated beyond 1.02, the amount of steam is in excessive compare to biomass feedstock and thus more tar is converted into other synthesis gas component which explains decrement trends for tar generation. Similarly torrefied EFB produces more tar compare to raw EFB due to low moisture content which reducing the amount of tar converted into synthesis gas composition due to tar steam reforming reaction.

3.3. Tar component analysis

The main product and by-products of fluidized bed gasification using raw and torrefied EFB is shown in Table 3. In overall, not much different of synthesis gas composition except CO composition obtained from torrefied EFB is significantly higher than raw EFB. This contributes to more synthesis gas yield from torrefied EFB (1.38 Nm³/kg) compare to raw EFB (1.31 Nm³/kg). Total amounts of ash and char show superior performance of torrefied EFB compare to raw EFB. This indicates more torrefied EFB is converted into product and by-product components. This also contributes to more tar generation of torrefied EFB (8.34 g) compare to only 5.23 g of tar generated using raw EFB. Since the feed flow rate used is between 0.25 and 0.4 kg/hr, thus raw EFB produced tar in the range of 13.08 and 20.92 g tar/kg biomass compare to between 20.85 and 33.36 g tar/kg biomass. These ranges obtained is in accordance to the acceptable range of tar generation which is between 10 and 70 g tar/kg biomass [15]. This indicates that torrefied EFB has the potential to be utilized as a feedstock of gasification process since it produces better synthesis gas yield compare to raw EFB with acceptable tar generation.

Table 3. Products and by-products analysis of gasification at gasification temperature of 1000°C and steam to biomass ratio of 1

| Product Classification | Parameters          | Raw EFB | Torrefied EFB at 300°C |
|------------------------|---------------------|---------|------------------------|
| Main Products          | H₂ composition (vol %) | 29.39   | 26.43                  |
|                        | CO composition (vol %) | 44.10   | 50.21                  |
|                        | CO₂ composition (vol %) | 20.71   | 19.78                  |
|                        | CH₄ composition (vol %) | 5.79    | 3.56                   |
|                        | Synthesis gas yield (Nm³/kg) | 1.31    | 1.38                   |
| Residue                | Ash weight (g)       | 19.35   | 23.16                  |
|                        | Char weight (g)      | 39.53   | 45.65                  |
| Side products          | Tar weight (g)       | 5.23    | 8.34                   |

The tar generated from raw and torrefied EFB gasification is characterized using GC-MS in order to determine components available in tar by-product. Normally tar generated from gasification may consists of acids, alcohols, aldehydes, ketones, esters, heterocyclic derivatives and phenolic compounds [14]. The list of detectable tar component obtained from raw and torrefied EFB gasification is shown in Table 4. In overall all 6 components represent most of the observable peak from GC-MS spectrum and are identified as tertiary tar. No primary or secondary tar is detected from raw and torrefied EFB gasification indicating that the primary and secondary tar may quickly decompose during gasification [9].

Table 4. Tar component analysis

| Tar Compounds | GC-MS Retention Time (min) |
|---------------|---------------------------|
| Naphthalene   | 16.75                     |
| Acenaphthylene| 23.50                     |
| Fluorene      | 26.95                     |
| Phenantherene | 32.25                     |
| Anthracene    | 32.64                     |
| Pyrene        | 36.78                     |
4. Conclusions
Fluidized bed gasification using raw and torrefied EFB has been performed at different gasification temperature and steam to biomass ratio. Steam was used as gasifying agent. Experimental results show the gasification temperature is more dominant operating condition where all yield of synthesis gas, LHV, CGE and tar generation is increased when the gasification temperature is increased. However, only synthesis gas yield is increased at all investigated steam to biomass ratio for both feedstock. LHV, CGE and tar generation reach maximum values at steam to biomass ratio of 1.02 and start to decrease afterwards. Torrefied EFB shows better performance in terms of production more synthesis gas but with high tar generation. 6 components tar are detected from GC-MS which belongs to tertiary tar group from both feedstock. However the tar generation is considered low based on the ratio of tar generated and feedstock flow rate. This indicates the torrefied EFB has the potential to be used as fuel source for gasification process.

5. References
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Acknowledgements
This work was financially supported by Fundamental Research Grant Scheme (FRGS/1/2019/TK02/UMP/02/2) under Ministry of Higher Education Malaysia via Research and Innovation Department, Universiti Malaysia Pahang (UMP)