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Torrefaction of Empty Fruit Bunch in the Presence of Combustion Gas

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Abstract

Torrefaction is a mild thermochemical treatment of biomass between 473-573 K in inert atmosphere. The poor economic feasibility of torrefaction due to continuous supply of inert gas hinders the commercialization of this technology. The present study investigates torrefaction of oil palm empty fruit bunch (EFB) in a vertical tubular reactor under the presence of gas from charcoal combustion. The combustion gas consisted of nitrogen, carbon dioxide, oxygen, carbon monoxide and hydrogen at percentages of 75.5, 16.4, 4.0, 3.5 and 0.3 vol%, respectively. In the present study, the thermal energy generated through charcoal combustion was directly utilized for torrefaction of EFB. Torrefaction experiment was carried out at 461 – 494 K for 30 min. The mass and energy yields and properties of torrefied biomass were investigated. Torrefaction in the presence of combustion gas resulted in an increase in the energy density and carbon content of torrefied EFB. The SEM cross-sectional observation of EFB torrefied in combustion gas showed presence of hollow porous structure like honeycomb. The result of torrefaction in combustion gas was compared with torrefaction carried out at 493 K for 30 min in a mixture of CO_2 (12.0 vol%), O_2 (9.0 vol%) and N_2 (balance) from gas cylinder.

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Keywords: Torrefaction; Empty Fruit Bunch; Combustion Gas; Mass and Energy Yields; Calorific Value; Elemental Analysis.

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1. Introduction

The depletion in the fossil fuel resources and environmental issues caused by global greenhouse gas emission has moved the attentions of industrialist towards producing energy from renewable sources [1]. Lignocellulosic biomass is categorized as a potential feedstock in producing fuels due to its non-edible property and abundance.

In 2014, Malaysia was the second largest producer of palm oil, producing 21.0 million metric tons or 35.4% of the total world supply and Indonesia was the world's largest producer of palm oil, producing 33.0 million metric tons of oil, or 55.6% of the total world supply [2]. A total of 451 palm oil mills are operating in Malaysia [3]. Being the world second largest producer and exporter of palm oil, Malaysia's palm oil industry generates a vast quantity of biomass from its plantation and milling activity.

The palm oil mills utilize mesocarp fibre and palm kernel shell as fuel for the boiler to generate steam and electricity in palm oil mills through direct combustion [4]. Empty fruit bunches (EFB) have not been optimally used due to its high moisture content (up to 70 wt%), low heating value, presence of minerals, and bulkiness which are unfavorable for transportation and handling. In order to address those drawbacks, EFB is required to be pretreated to improve its quality. A low temperature treatment at 473-573K under an inert atmosphere, known as torrefaction, is a promising technology in improving the energy density and shelf life of biomass. Over the past few years, torrefaction research has been widely reported for lignocellulosic biomass under inert atmosphere [5, 6]. Utilization of flue gas generated from the palm oil mills boilers as carrier gas could save a considerable quantity of energy and inert gas. In light of this idea, recently some studies have been reported for torrefaction under oxygen and carbon dioxide since these two are the representative components in flue gas. Uemura et al. [7] and Chen et al. [8] investigated biomass torrefaction in the presence of oxygen at various concentrations. Uemura et al. [9] and Chen et al. [10] also investigated torrefaction of biomass in oxygen and carbon dioxide. Lu et al. [11] torrefied oil palm fiber and eucalyptus using air as torrefaction gas. However, still there has been no report for torrefaction in real combustion gas.

In the present study, torrefaction of EFB was carried out in a vertical tubular reactor in the presence of combustion gas from burning charcoal. The mass yield, energy yield and properties of EFB torrefied in combustion gas were investigated. Thus, the main objective of the present study is to elucidate the effect of torrefaction using real combustion gas on the mass and energy yields and characteristics of torrefied EFB.

2. Experimental

2.1. Biomass samples

Empty fruit bunches (EFB) were collected from a nearby palm oil mill in January 2016. The moisture content of the raw EFB was 74.9 wt%. After drying in an oven at 378 K for 24 h, the EFB were chopped into smaller chips with an average dimension of 2.0 cm x 0.5 cm x 1.0 cm using a mechanical cut-off machine. The moisture content of the dried EFB was 7.1 wt%. The EFB were stored in an air-tight container prior to analysis and experimental work. The physiochemical properties of the EFB used in this study are listed in Table 1.

Table 1. Physicochemical properties of EFB.

Proximate Analysis (wt %)	
Moisture	7.1
Volatile Matter	92.5
Ash Content	6.8
Fixed Carbon	0.7
Elemental Analysis (wt %)	
Carbon	44.6
Hydrogen	6.7
Nitrogen	0.1
Oxygen	34.8
HHV [MJ/kg]	15.2

2.2. Torrefaction experiment

Torrefaction of the EFB chips was carried out in a vertical tubular type reactor made of stainless steel with an internal diameter of 10 cm and a height of 20 cm. The entire set-up is illustrated in Fig 1. Prior to the experimental work on torrefaction of the biomass, a certain amount of charcoal pieces (240.37 g) was placed at the bottom of the reactor and ignited. Throughout the experiment, the flow rate of the compressed air was controlled and regulated at a flow rate of 5.0 L(NTP)/min via a mass flow controller. The reactor was equipped with an electric igniter in order to provide the ignition source for combustion. The duration of active combustion with the propagation of flame from the solid charcoal took place for approximately 40 min. Charcoal was partially consumed during this phase. When charcoal combustion phase entered glowing combustion or the flame combustion phase was finished, torrefaction experiment started as follows. A prescribed amount of EFB (6.03 g) was placed on a grid biomass stand made of stainless steel with a diameter of 5.5 cm and a height of 8.5 cm. The stand was placed in the reactor once a stable red glowing combustion phase was achieved. The reactor temperature was recorded every 5 min. The torrefaction was carried out at a temperature range of 461 – 494 K. Gas released from the torrefaction reactor was collected in a gas sampling bag to analyse the gas composition by GC-TCD. After torrefaction for 30 min, the reactor was purged with nitrogen gas at a flow rate of 5.0 L(NTP)/min till the temperature cooled down to 337 K. The torrefied sample was then recovered, weighed and stored in an airtight vessel until it was characterized.

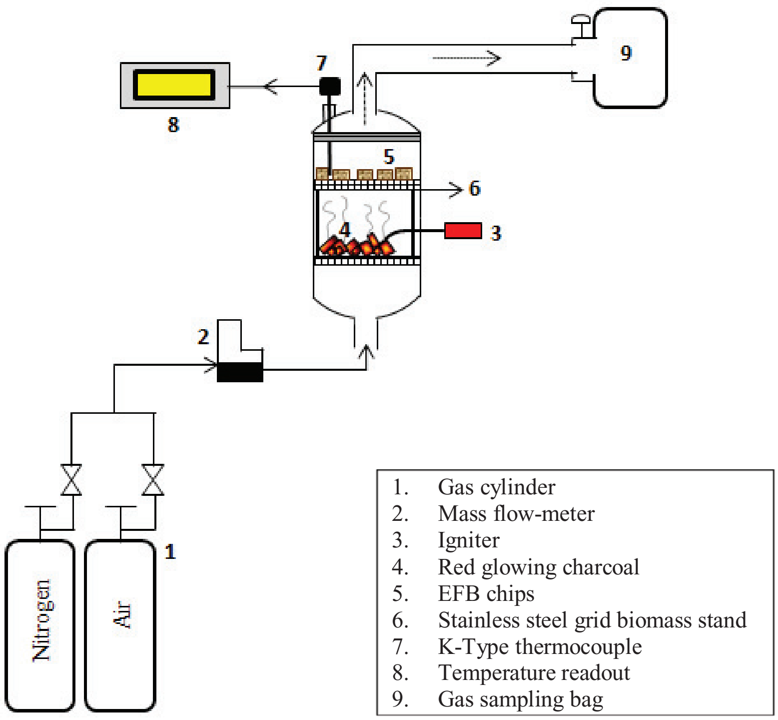

Fig. 1. Schematic diagram of torrefaction reactor.

As a comparison, EFB was also torrefied for 30 min at 493 K in a mixture of air, carbon dioxide and nitrogen, which were all supplied from commercially-available gas cylinders. The procedure was described elsewhere [9].

2.3. Measurement

EFB with an average dimension of 2.0 cm x 0.5 cm x 1.0 cm were used in this study. The mass and calorific value were measured before and after torrefaction. The calorific value was measured using a bomb calorimeter (C2000, IKA Werke). The energy yield used in this study is in high heat value (*HHV*) basis, which included the latent heat of the vapour emitted from the sample upon combustion. The equations employed in quantifying the mass yield and the energy yield from the torrefaction result are shown below:

$$\text{Mass Yield} = \frac{M_t}{M_0} \times 100 \quad (1)$$

$$\text{Energy Yield} = \frac{M_t}{M_0}\frac{HHV_t}{HHV_0} \times 100 \quad (2)$$

where M is the mass of sample, the subscripts 0 and t represent the initial value before torrefaction and final value after torrefaction, respectively.

The composition of the combustion gas was quantified using a gas chromatography with a thermal conductivity detector (GC-TCD; Shimadzu GC-8A) with column packings of MS-5A and Porapak Q. The elemental analysis of untorrefied and torrefied biomass samples was carried out by using a CHN analyzer (Series II CHNS/O Analyzer 2400, Perkin Elmer). Morphological differences in cross sections of untorrefied and torrefied biomass samples were observed by a scanning electron microscope (SEM; Hitachi, TM3030). The cross section of the sample was coated with a thin layer of gold using a sputter coater before SEM measurements.

3. Results and Discussion

3.1. Combustion Gas Composition

Table 2 shows the composition of the combustion gas. The combustion gas composition analysis was repeated thrice.

Table 2. Composition of combustion gas.

Combustion gas component	N_2	CO_2	O_2	CO	H_2
Concentration (vol %)	75.5 (±0.28)	16.4 (±0.39)	4.0 (±0.02)	3.5 (±0.11)	0.3 (±0.01)

As shown in Table 2, the combustion gas consists of nitrogen, carbon dioxide, oxygen, carbon monoxide and hydrogen. Based on this analysis, the presence of CO and H_2 gas at low concentrations was identified. The concentration of oxygen in this combustion gas was 4.0 vol%. This value shows the concentration of oxygen is lowered compared with that in air due to consumption of oxygen during charcoal combustion. On the other hand, the concentration of carbon dioxide in this combustion gas was 16.4 vol%. The total volume percentage of oxygen and carbon dioxide in combustion gas was 20.4 vol%, which is comparable with the flue gas composition for pulverized coal combustion reported by Werther et al. [12].

3.2. Temperature Profile

The thermal energy for the torrefaction process in this study was generated from the stable combustion of charcoal. Temperature plays a dominant role on the mass yield, energy yield and product quality of torrefied EFB. The three stages involved in the present torrefaction experimental work are heating, torrefaction and cooling. Torrefaction of biomass is carried out at temperatures typically between 473-573 K [5]. Fig. 2 shows the temperature profile of the biomass bed during temperature rise, torrefaction and cooling down stage. As shown in Fig. 2, EFB was placed on the biomass stand when a stable combustion phase was achieved, that is at 2 min.

Torrefaction of EFB in combustion gas took place at a temperature range of 461 to 494 K with a residence time of 30 min. Combustion gas was collected in a gas sampling bag from 5 to 8 min as shown by region (I) in Fig. 2.

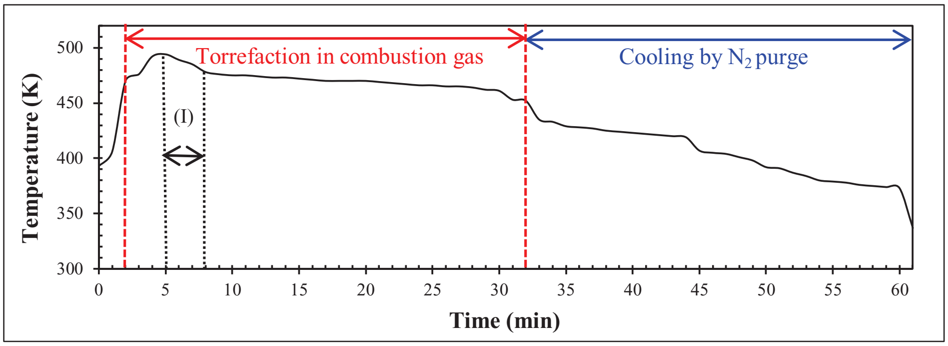

Fig. 2. Temperature profile of torrefaction bed with time.

3.3. Mass and Energy Yields

Torrefaction of EFB was carried out in combustion gas with the presence of 16.4 vol% CO_2 and 4.0 vol% O_2. Fig. 3 illustrates the difference appearance of EFB before and after torrefaction under combustion gas atmosphere. After torrefaction, the colour of EFB becomes black.

(a) **(b)**

Fig. 3. Appearance of EFB (a) before and (b) after torrefaction in combustion gas.

Fig. 4 shows the relationship of the mass and energy yields of EFB torrefied in combustion gas and non-inert gas from gas cylinder. The mass yield of EFB torrefied in combustion gas is 64.5%. Mass loss in the torrefaction temperature range of 473 - 573 K is dominated by dehydration and devolatization in the reaction regime of hemicellulose component [5]. According to Wang et al. [13], the presence of oxygen in torrefaction process resulted in higher mass loss than inert atmosphere due to oxidation of lignocellulosic biomass. Thus, the mass loss 35.5% in the present study is supposed to be a total effect of dehydration, devolatilization and partial oxidation. In Fig. 4, the mass yield of torrefied EFB in combustion gas is slightly lower compared to mass yield of EFB torrefied in CO_2 and O_2 from gas cylinder. This could be correlated with interactions between the combustion gas components and biomass. Further investigation must be carried out to elucidate this finding.

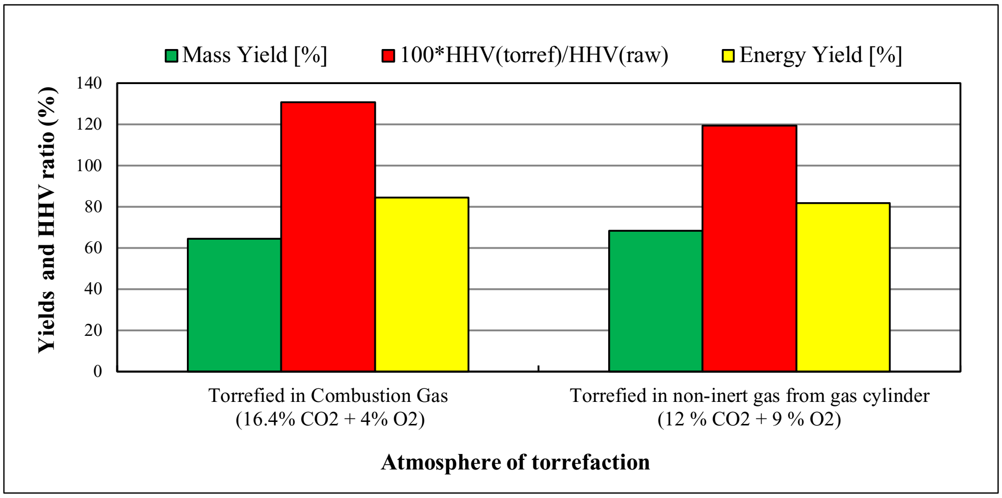

Fig. 4. Torrefaction in combustion gas and a mixture of CO_2 and O_2 (N_2 balance): Mass and energy yields, and *HHV* ratio.

One of the important parameters in evaluating the economic viability of torrefaction process is the calorific value and energy yield. The calorific value of EFB after torrefied in combustion gas is 19.8 MJ/kg with an energy yield of 84.4%. The energy yield and calorific value ratio of torrefied EFB in combustion gas is higher than EFB torrefied with cylinder gas (12 vol% CO_2 + 9 vol% O_2).

3.4. Elemental Analysis

Elemental analysis is an important characterization method to analyse on the chemical properties of the sample. Fig. 5 presents the elemental composition of EFB before and after torrefaction in combustion and non-inert gas from gas cylinder respectively.

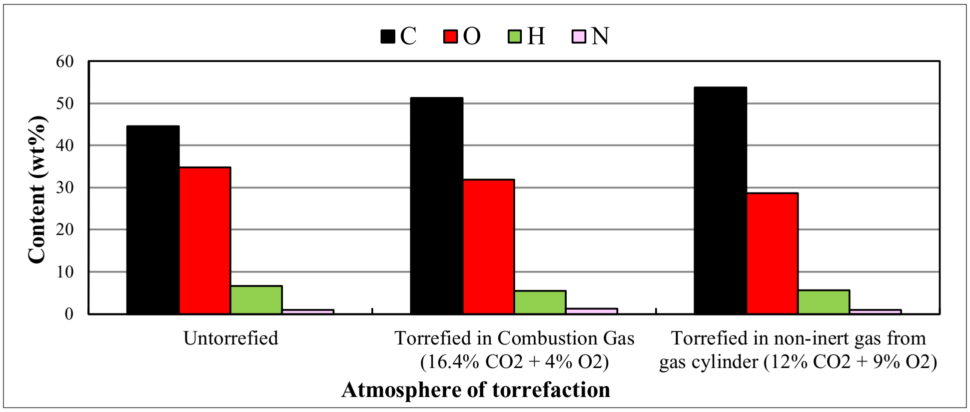

Fig. 5. Torrefaction in combustion gas and a mixture of CO_2 and O_2 (N_2 balance): Elemental composition.

Fig. 5 shows that carbon has a significant rise when torrefied under non-inert atmospheres regardless of the gas sources: combustion gas or cylinder gas. EFB torrefied in combustion gas resulted lower oxygen and hydrogen contents than untorrefied EFB sample. This decrease in hydrogen and oxygen is resulted from the dehydration and devolatization from the biomass during torrefaction [14]. Higher loss of oxygen and hydrogen compared to carbon is corresponding to the increase in calorific value of the biomass. The carbon content of EFB torrefied in combustion gas is slightly lower compared to EFB torrefied in non-inert gas from gas cylinder. This difference may be attributed to fluctuations in the combustion gas temperature during 30 min of torrefaction reaction time.

3.5. Morphological Changes

The cross-sectional morphology of EFB before and after torrefaction was examined by SEM observation. Fig. 6 compares the cross sectional morphology of untorrefied and torrefied EFB under combustion and non-inert gas from gas cylinder. All images are taken at a magnification of 1000.

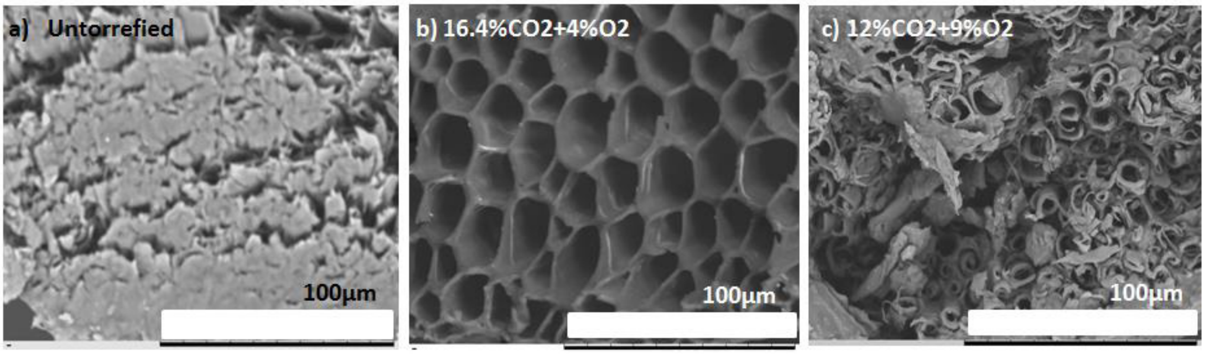

Fig. 6. SEM observation of raw and torrefied EFB (cross section); (a) Untorrefied, (b) EFB torrefied in combustion gas, (c) EFB torrefied in 12.0 vol% CO_2 + 9.0 vol% O_2 from gas cylinder (N_2 balance).

The morphology of untorrefied EFB shows a rather flat surface with slight disorder. The presence of this disorder in Fig. 6(a) might be resulted from the cutting effect during sample preparation. The cross section of torrefied EFB under combustion gas in Fig. 6(b) shows a porous structure like honeycomb. On the other hand, in Fig. 6(c) the cross section of EFB torrefied using CO_2 + O_2 cylinder gases shows a tiny-sized porous structure in comparison with Fig. 6(b). The distinctive difference in the morphology of EFB torrefied in combustion gas and cylinder gas implies that thermal radiation from glowing charcoal at the bottom of the reactor (See Fig. 1) may have decomposed the hemicellulose and some weak part of lignin components in EFB more significantly compared to the torrefaction in cylinder gas.

4. Conclusion

Torrefaction of EFB was carried out in combustion gas at 461 – 494 K for 30 min to investigate the effect of real flue gas from boilers on torrefaction behaviour including the mass and energy yields, elemental composition, and microscopic morphology. The effect of combustion gas on the mass and energy yields and characteristics of EFB were analysed. This study showed that utilization of combustion gas as torrefaction gas and thermal energy sources resulted in 64.5% of mass yield and 84.4% of energy yield. The carbon content and calorific value of torrefied EFB increased by 15.1% and 30.9%, respectively. The difference on the microscopic cross-sectional morphology of EFB before and after torrefaction may be attributed to hemicellulose decomposition by convective thermal energy from gas and irradiative thermal energy from glowing charcoal.

The comparative analysis of torrefaction by combustion gas with torrefaction using cylinder gas (12 vol% CO_2 + 9 vol% O_2) at 493 K showed that torrefaction using combustion gas as torrefaction gas can be carried out without any significant problem for the yields and quality. The result also proved that utilization of combustion gas for torrefaction may be able to generate an economically more viable and sustainable torrefaction process.

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