Dry and wet torrefaction of empty fruit bunch to produce clean solid fuel for cooking application

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Abstract. Empty fruit bunch (EFB) is one of the biomass source in Indonesia which has abundant availability generated from palm oil industry. The aim of the present work is to study the dry and wet torrefaction of EFB in a fixed bed reactor for green energy production in a cooking application. The feedstock used in these experimental works was empty fruit bunch. The collected EFB has a high moisture content which was then dried in the sun for three days in order to remove some of the water content. The samples were then crushed into smaller particle size to make it easily put into the reactor. The results showed that the higher the reaction temperature and holding time, the lower the solid yields. The dry torrefaction of EFB can produce around 34-91\% of the solid product. The results also showed that increasing the dry torrefaction temperature resulted in the increase of heating value. Wet torrefaction has the similar trend with the dry torrefaction. The solid product from wet torrefied EFB which can be obtained is in the range of 64-83\%. Dry torrefied EFB produced higher energy yield than that of wet torrefied EFB. The difference reaction medium, temperature, and pressure resulted in different energy yield.

1. Introduction
As the largest economy in South East Asia region (ASEAN), Indonesia needs more sustainable and environmentally friendly energy supply to ensure the high and stable economic growth. Therefore, there will be an urgent need for renewable energy especially bioenergy since Indonesia has a huge potential for this energy source. Bioenergy which is produced from biomass plantation sources such as palm oil, paddy, sugarcane, and wood was traditionally used in the rural area for cooking application. However, the low efficiency and high emission of this technology make this system has no longer applied in the community. We need to upgrade both the fuel quality and stove technology to obtain a better quality of the cooking process.

Not only in Indonesia, nowadays biomass become one of the alternative energy used in the world. Various biomass sources have been generated in Indonesia such as empty fruit bunch, palm kernel shell [1], bagasse, jatropha curcas [2][3], wood waste, cocoa pod husk [4][5], etc. However, the high low
heating value and high moisture content of biomass make it a difficult energy source which needs special treatment in logistics, transport, and thermal conversion [6]. One of the solutions to increase the density of biomass and offers several advantages is by applying pelletization or briquetting process. However, biomass pellet still has some limitations including high energy cost, durability, and hygroscopic nature.

Torrefaction, which is divided into two process methods i.e. dry and wet torrefaction, is one of the technologies that can be employed to overcome such problems. Torrefaction is a thermal processing step which is done by heating up the biomass in the temperature range of 200–300°C in an inert atmosphere. The improved heating value, ease of size reduction, and low moisture content of torrefied solid biomass is the final product of this process [7]. Various biomass materials have been torrefied and studied such as palm kernel shell [1], empty fruit bunch [8][9], bamboo [10][11], and microalgae residue [12].

Empty fruit bunch (EFB) is one of the biomass source in Indonesia which has abundant availability generated from palm oil industry. As the biggest producer country of crude palm oil in the world, Indonesia has the land area of palm oil plantation reached more than 11 million hectares which produce more than 31 million tonnes of crude palm oil. [13]. Sulaiman et al. [14] investigated the effect of temperature and time on the calorific value, mass yield, and CHN analysis of EFB. The results show that temperature has a higher impact towards torrefaction as compared to residence time in terms of calorific value, mass yield, and carbon content. Wet torrefaction of hydrothermal treatment of EFB has been investigated by Novianti et al. [15] to produce solid fuel and organic fertilizer. The results showed that the treated EFB has the higher carbon content, lower ash content and lower deposition tendency compared to raw EFB.

![Figure 1](image.png)

**Figure 1.** Mass balance of palm oil processing industry [16].

EFB can be generated from the oil palm industry around 21% of fresh fruit bunch as shown in Figure 1. Thus, the utilization of EFB as a solid fuel via dry and wet torrefaction is an attractive method to produce high quality solid biofuel. The aim of the present work is to study the dry and wet torrefaction of EFB in a fixed bed reactor for green energy production in a cooking application.

2. Experimental

2.1. Materials

The feedstock used in these experimental works was empty fruit bunch. EFB was collected from PTPN V Sei Paar, Riau province, Sumatera, Indonesia. The collected feedstocks have a high moisture content which was then dried in the sun for three days in order to remove some the water content. The samples were then crushed into smaller particle size to made it easily put into the reactor. Evaluation of
calorific value was then conducted for untreated and treated EFB to study the effect of dry and wet torrefaction processes. The physical appearances of EFB can be seen in Figure 2.

![Figure 2](image)

**Figure 2.** EFB sample used in the experiments.

2.2. Torrefaction set-up

The dry torrefaction experimental works were conducted in a fixed bed reactor which is electrically heated around the side wall of the reactor. The reactor was made of stainless steel which has the diameter and height of 10 cm and 45 cm respectively. A temperature probe (K-type thermocouple) was put on the outer surface of the side wall of the reactor to measure the torrefaction temperature which is controlled by the temperature controller. A double-tube glass condenser was installed at the outlet of the reactor to condense the torrefaction gas into the liquid product. The non-condensable gas was discharged out from the condenser. A schematic diagram of the experimental apparatus is shown in Figure 3.

![Figure 3](image)

**Figure 3.** A schematic diagram of dry torrefaction apparatus.

In each experiment, 250 g of sample was placed in the reactor. In these experiments, the reactor was first heated up to a certain temperature. Two main parameters of torrefaction which are temperature and holding time were taken into account to evaluate their effects on torrefaction performance. Four different torrefaction temperature i.e. 200°C, 250°C, 300°C and 350°C, and holding time i.e. 30, 45 and 60 minutes were chosen for the experiments. After the experiments were finished, the solid residue in the
reactor was cooled down and collected as a torrefaction product for calorific value analysis by using a
bomb calorimeter. The liquid product was condensed and collected in the oil tank. The gaseous product
was calculated by the difference between the total feedstock weight, and liquid and solid weights.

Wet torrefaction or hydrothermal treatment process has also been conducted using EFB sample. The
material with the mass of 100 g was placed in a 2.5 L reactor and mixed with the distilled water with
biomass to water ratio of 1:5. Figure 4 illustrates the reactor for wet torrefaction experiments. The reactor
was heated up by using an electrical heater until a certain set temperature and then held at this
temperature for 30 minutes. Wet torrefaction process temperature was varied from 160°C, 180°C, and
200°C. The solid products produced from this process were separated from the liquid by using cloth
filter and then dried in an electric oven for about 5 hours. Furthermore, the final solid products were
then analyzed for their calorific value.

\[
\text{Mass yield} \text{ (%) } = \frac{m_{\text{torrefied}}}{m_{\text{raw}}} 
\]

\[
\text{Energy yield} \text{ (%) } = \frac{HV_{TP} \times \text{ mass yield} \text{ (%) }}{HV_{RB}} 
\]

3. Result and Discussion

3.1. Dry torrefaction of EFB
Dry torrefaction of EFB has been carried out to study the influence of temperature and holding time on
product distribution and characteristics including the energy content. Figure 5 illustrates the effect of
temperature and holding time on mass yield. The figure showed that the higher the temperature and holding time, the lower the solid yields. The torrefaction of EFB can produce around 34-91% of solid product depending on the torrefaction temperature and holding time. The similar results have also been obtained in previous studies using palm kernel, palm kernel shell [1], microalgae residue [12] and bamboo [10]. Sulaiman et al. [14] studied the dry torrefaction of EFB at the higher temperature and holding time. The biomass has three major components including cellulose, hemicellulose, and lignin. These components were initiated to decompose when the temperature was increased up to more than 200°C.

Figure 5. Effect of dry torrefaction temperature and holding time on the mass yield of the empty fruit bunch.

Figure 5 also showed that when the temperature increase from 200°C to 250°C, there was a significant reduction of the solid yield compared with the temperature of 300°C and 350°C. It means that between these temperatures, the decomposition process was drastically and intensively increase. Furthermore, the torrefaction phenomena between these temperatures should be deeply investigated in the future to obtain the best temperature for torrefaction. On the other hand, the increase of holding time resulted in a linear decrease of solid fraction.

Figure 6. The physical appearance of EFB torrefaction products at various temperature.

The physical appearance of torrefied EFB as the effect of temperature and holding time were shown in Figure 6 and 7. It can be seen that at 200°C the colour was still brown. It means that the samples were torrefied in a small portion. The drying process was the most decomposition reaction at this temperature. When the temperature increase, the colour becomes darker which means that more pyrolysis reaction has occurred. The solid product appearance at 350°C was less than 40% which is similar to the charcoal
product. Figure 7 illustrates the effect of holding time on the physical appearance of solid products. The colour change as the effect of holding time was not significant like in temperature.

![Figure 7. The physical appearance of EFB torrefaction products at various holding time.](image)

The calorific value of biomass materials is a key parameter showing the quality of solid products. The calorific value of EFB as the effect of temperature was presented in Figure 8. It showed that increasing the torrefaction temperature resulted in the increase of heating value. Figure 8 also showed that when the temperature increase from 200°C to 250°C, there was a significant increase of the heating value compared with the temperature of 300°C and 350°C. It was consistent with the solid fraction result which means that at this temperature much more volatile matter has been released converting to liquid and gaseous products.

![Figure 8. Effect of torrefaction temperature on the heating value of EFB at 60 minutes holding time.](image)

3.2. Wet torrefaction of EFB

Wet torrefaction or hydrothermal treatment of EFB has also been conducted to evaluate the effect of temperature on product distribution and characteristics including the energy content. Figure 9 presented the effect of hydrothermal (HT) temperature on the solid yield. The figure showed that the higher the temperature, the lower the solid yields. The solid product which can be obtained is in the range of 64-
83% depending on the reaction temperature. The similar results have also been obtained by other researchers [17][18]. Wet torrefaction decreased the fraction of volatile matter in combustible carbon. This process can also remove up the ash content and reduce the chlorine and potassium significantly [18].

![Figure 9. Effect of hydrothermal (HT) temperature on the solid yield of EFB at 30 minutes holding time.](image)

Figure 9. Effect of hydrothermal (HT) temperature on the solid yield of EFB at 30 minutes holding time.

Figure 10 illustrated the physical appearance of EFB after hydrothermal treatment as the effect of temperature. The results showed that the colour was still brown in all condition. These results showed different appearance compared with the torrefied EFB. This is due to the different temperature and medium used in the hydrothermal treatment and dry torrefaction. The intensity of the reaction occurred in the biomass was mainly depended on the reaction medium (hot gas or compressed hot water) which finally affected the final product [19].

![Figure 10. The physical appearance of EFB hydrothermal products at 160°C, 180°C, and 200°C.](image)

Figure 10. The physical appearance of EFB hydrothermal products at 160°C, 180°C, and 200°C.

The calorific value of EFB after hydrothermal treatment is shown in Figure 11. The figure showed that there is the slight increase of the calorific value of EFB after treatment. It means that wet torrefaction of EFB has not upgraded the energy content of EFB significantly. In general, wet torrefaction has been applied to the high moisture content of biomass to easily remove the water content in the biomass by breaking the inbound water which can not be removed by mechanical treatment. Wet torrefaction can
also be used to remove some ash materials in the biomass resulted in the different characteristics of biomass when burning in the furnace.

![Graph showing the effect of hydrothermal (HT) temperature on the heating value of EFB at 30 minutes holding time.](image)

**Figure 11. Effect of hydrothermal (HT) temperature on the heating value of EFB at 30 minutes holding time.**

3.3. Energy yield of torrefied EFB

The energy yield of torrefied EFB comparing the dry and wet torrefaction processes is illustrated in Figure 12. The energy yield is defined by the ratio of energy content between torrefied and its raw biomass [20] and was calculated using equation 2 for each process condition. The linear correlation was based on many previous torrefaction data calculated by Chen et al. as presented in Figure 12 [20] and has a formula:

\[
\text{Energy yield (\%)} = 0.975 \times \text{solid yield (\%)} + 11.682
\]  

(3)

![Graph showing the plot of solid yield versus energy yield from dry and wet torrefaction of EFB.](image)

**Figure 12. The plot of solid yield versus energy yield from dry and wet torrefaction of EFB.**

The results show that the solid yield versus energy yield of EFB is close to the linear correlation formulated by Chen et al. The decrease in solid yield linearly decreases the energy yield of biomass. Figure 12 also showed that dry torrefied EFB produced higher energy yield than that of wet torrefied EFB. The difference reaction medium, temperature, and pressure resulted in different energy yield. Comparative study of three different methods of solid fuel upgrading has been done by Yeoh et al. using
thermal (dry torrefaction), hydrothermal (wet torrefaction) and vapothermal [19]. Vapothermal process resulted in the highest energy densification followed by dry torrefaction and then wet torrefaction.

4. Conclusion

Dry and wet torrefaction to produce green solid fuel from empty fruit bunch has been conducted to upgrade the energy content of the fuel. The results showed that the higher the reaction temperature and holding time, the lower the solid yields. The dry torrefaction of EFB can produce around 34-91% of the solid product. The results also showed that increasing the dry torrefaction temperature resulted in the increase of heating value. Wet torrefaction has the similar trend with the dry torrefaction. The solid product from wet torrefied EFB which can be obtained is in the range of 64-83% depending on the reaction temperature. Wet torrefaction also slightly increased the calorific value of EFB which means that wet torrefaction has not upgraded the energy content of EFB significantly. Dry torrefied EFB produced higher energy yield than that of wet torrefied EFB. The difference reaction medium, temperature, and pressure resulted in different energy yield.

References

[1] M. Syamsiro, B. B. Sitompul, U. B. Surono, B. Prabowo, and M. K. Biddinika, “Alternative solid biofuel production from palm oil residue wastes employing dry torrefaction,” in AIP Conference Proceedings, 2018, vol. 1983, no. 1, p. 20028.
[2] N. A. Pambudi, S. Torii, M. Syamsiro, H. Saptoadi, and I. M. Gandidi, “Emission factor of single pellet cake seed Jatropha curcas in a fix bed reactor,” J. Brazilian Soc. Mech. Sci. Eng., vol. 34, no. 2, pp. 184–192, 2012.
[3] N. A. Pambudi, T. Laukkanen, M. Syamsiro, and I. M. Gandidi, “Simulation of Jatropha curcas shell in gasifier for synthesis gas and hydrogen production,” J. Energy Inst., vol. 90, no. 5, pp. 672–679, 2017.
[4] M. Syamsiro, H. Saptoadi, B. H. Tambunan, and N. A. Pambudi, “A preliminary study on use of cocoa pod husk as a renewable source of energy in Indonesia,” Energy Sustain. Dev., vol. 16, no. 1, pp. 74–77, Mar. 2012.
[5] M. Syamsiro, H. Saptoadi, and B. H. Tambunan, “Experimental investigation on combustion of Bio-pellets from Indonesian cocoa pod husk,” Asian J. Appl. Sci., vol. 4, no. 7, pp. 712–719, 2012.
[6] J. Kiel, F. Verhoeff, H. Gerhauser, W. Van Daalen, and B. Meuleman, “BO 2 -technology for biomass upgrading into solid fuel - an enabling technology for IGCC and gasification-based BtL,” in 4th International Conference on Clean Coal Technologies, 2009, no. April, pp. 1–10.
[7] P. Bergman, A. Boersma, and J. Kiel, “TORREFACTION FOR ENTRAINED-FLOW GASIFICATION OF BIOMASS,” in The 2nd World Conference and Technology Exhibition, 2004, no. May, pp. 10–14.
[8] K. M. Sabil, M. A. Aziz, B. Lal, and Y. Uemura, “Effects of torrefaction on the physicochemical properties of oil palm empty fruit bunches, mesocarp fiber and kernel shell,” Biomass and Bioenergy, vol. 56, pp. 351–360, 2013.
[9] K. Kaminaka, Y. Matsumura, W. Noaman Omar, and Y. Uemura, “Process evaluation for torrefaction of empty fruit bunch in malaysia,” J. Japan Pet. Inst., vol. 57, no. 2, pp. 88–93, 2014.
[10] M. Li, X. Li, J. Bian, C. Chen, Y. Yu, and R. Sun, “Effect of temperature and holding time on bamboo torrefaction,” Biomass and Bioenergy, vol. 83, pp. 366–372, 2015.
[11] W. Yan, S. Perez, and K. Sheng, “Upgrading fuel quality of moso bamboo via low temperature thermochemical treatments: Dry torrefaction and hydrothermal carbonization,” Fuel, vol. 196, pp. 473–480, 2017.
[12] W. Chen, M. Huang, J. Chang, C. Chen, and W. Lee, “An energy analysis of torrefaction for upgrading microalga residue as a solid fuel,” Bioresour. Technol., vol. 185, pp. 285–293, 2015.
[13] Anonym, “Statistik Perkebunan Indonesia,” Jakarta, 2016.
[14] M. H. Sulaiman, Y. Uemura, and M. T. Azizan, “Torrefaction of Empty Fruit Bunches in Inert Condition at Various Temperature and Time,” Procedia Eng., vol. 148, pp. 573–579, 2016.

[15] S. Novianti, A. Nurdiawati, I. N. Zaini, H. Sumida, and K. Yoshikawa, “Hydrothermal treatment of palm oil empty fruit bunches: an investigation of the solid fuel and liquid organic fertilizer applications,” Biofuels, vol. 7, no. 6, pp. 627–636, 2016.

[16] P. Papilo, I. Kusumanto, and K. KunaiIfi, “Assessment of agricultural biomass potential to electricity generation in Riau Province,” IOP Conf. Ser. Earth Environ. Sci., vol. 65, no. 012006, pp. 1–13, 2017.

[17] S. Novianti, M. K. Biddinika, P. Prawisudha, and K. Yoshikawa, “Upgrading of Palm Oil Empty Fruit Bunch Employing Hydrothermal Treatment in Lab-scale and Pilot Scale,” Procedia Environ. Sci., vol. 20, pp. 46–54, 2014.

[18] A. Nurdiawati et al., “Evaluation of Hydrothermal Treatment of Empty Fruit Bunch for Solid Fuel and Liquid Organic Fertilizer Co-Production,” Energy Procedia, vol. 79, pp. 226–232, 2015.

[19] K. H. Yeoh, S. A. Shafie, K. A. Al-attab, and Z. A. Zainal, “Upgrading agricultural wastes using three different carbonization methods: Thermal, hydrothermal and vapothermal,” Bioresour. Technol., vol. 265, no. April, pp. 365–371, 2018.

[20] W. Chen, J. Peng, and X. T. Bi, “A state-of-the-art review of biomass torrefaction, densification and applications,” Renew. Sustain. Energy Rev., vol. 44, pp. 847–866, 2015.