Evaluation of biogas potential from empty fruit oil palm bunches

S Suhartini, N Hidayat and I Nurika
Department of Agro-industrial Technology, Faculty of Agricultural Technology, Universitas Brawijaya, Malang, 65145, Indonesia

E-mail: ssuhartini@ub.ac.id

Abstract. Indonesia experiences an increasing demand for energy, triggering the development of renewable energy, particularly from biomass resources. Empty fruit oil palm bunches (EFOB) residue is one of the potential lignocellulosic biomass highly abundant for further application in bioenergy generation such as biogas. This study was aimed to investigate and evaluate the potential of EFOB for biogas production using anaerobic digestion (AD) route. The biogas production in AD of EFOB was investigated in a batch experiment operated at an inoculum to substrate ratio (R_I/S) of 6:1 for 30 days under the temperature of 37 °C. The results showed that the specific methane potential (SMP) of EFOB (without any pre-treatment) was 0.110 m^3/kgVS added. Using the anaerobic digestion scenario modeling, it was indicated that EFOB is a potential feedstock for biogas production using AD technology, either for electricity or biomethane production. The model also indicated that biogas and methane generation from AD of EFOB can contribute to enhancing the GHG emissions savings from replacing the use of fossil fuels or other non-renewable energy sources. Yet, the problem of high lignin content in EFOB has hindered the optimal biogas production. Therefore, the next stage of this study was to integrate biological pre-treatment to improve the efficacy of AD process.

1. Introduction
Nowadays, Indonesia experiences an increasing demand for energy, followed by a high price of fossil fuel-based energy [1]. This is due to a decrease in the supply of non-renewable energy include fossil fuels and coals [2]. The effort to develop new and renewable energy sources is critical, such as biomass. Indonesia, however, has many challenges and hindrances in valorizing biomass for bioenergy generation [3]. Supported with biomass potential of 146.7 million tonnes annually with an estimated energy equivalent of 32,653.8 MW in 2016 [4], there is a huge opportunity to further advance biomass valorization for bioenergy.

Biomass is defined as any organic and biodegradable materials derived from plant, dead animal, microorganism or waste [5]. Oil palm production in Indonesia was approximately 28 million tonnes in 2014 [6]. Each tonne of fresh fruit oil palm bunches contains 23% empty fruit oil palm bunches (EFOB), 12% of fiber, and 5% oil palm shells [7]. Therefore, EFOB is considered as highly available biomass in Indonesia, accounted for 6.44 million tonnes [8]. Several studies have reported that EFOB, as lignocellulosic biomass, contains moisture content in the range of 60-70%, potential to be used as feedstock for bioenergy production such as biogas [9-10].

Anaerobic digestion (AD) is biological degradation process of organic material occurred under anaerobic condition [11], resulted in methane (CH_4), carbon dioxide (CO_2) and residual organic (i.e.
Biogas is composed of methane and carbon dioxide, and the high quality of biogas has higher methane concentration, usually in the range of 50-70% [13]. Furthermore, digestate can be valorized as biofertilizer, soil conditioner, or cultivation media. AD can be carried out using single-stage or two-stage systems [14]. The use of AD technology is aligned with the concept of the bio-based economy by enhancing the benefits from waste for preserving the environment and providing a renewable energy source, such as for electricity and biomethane. Therefore, this study was aimed to investigate and evaluate the potential of EFOB for biogas production using anaerobic digestion (AD) route.

2. Materials and methods

2.1. Feedstocks and inoculums
EFOB was freshly collected from the oil palm industry in Blitar City. The samples were directly stored in plastic and kept at room temperature upon arrival at Bioindustry Laboratory, Universitas Brawijaya. The EFOB sample was sliced with a size of 1 cm in length. The parameters analyzed include proximate analysis (i.e. moisture content/MC, ash, total solids/TS, and volatile solids/VS). Inoculum for the BMP test was prepared from digestate taken from a full-scale mesophilic digester treating cattle manure at Balai Besar Pelatihan Peternakan in Batu City. Digestate was collected in a 5-liter container. The digestate was sieved through a 1 mm screen to remove larger particles. Digestate was degassed for 48 hours at a temperature of 37 °C to remove the residual biogas. The inoculum was analyzed for pH, MC, ash, TS, and VS. The characteristic of inoculum used in this research is shown in table 1.

| Parameters | Values |
|------------|--------|
| pH         | 7.6    |
| TS (%WW)   | 2.41   |
| VS (%WW)   | 1.82   |
| VS (%TS)   | 75.63  |
| MC (%WW)   | 0.59   |
| Ash (%WW)  | 97.59  |

Note: WW = wet weight

2.2. BMP test set-up
A manual BMP system using water bath (37 °C) was used and operated for 28 days in batch condition, carried out according to procedures described by Suhartini et al. [15]. Control blank samples were prepared to measure the indigenous methane production from the inoculums. The positive control (α-cellulose) samples were prepared to test the activity of the inoculum. Samples of EFOB were tested in this study. All samples were prepared in triplicates with an inoculum to substrate ratio (I/S ratio) of 6. The BMP test was carried out using 250-ml serum bottle with a working volume of 40 ml. The biogas production was measured as pressure using a Digitron 2026P absolute pressure meter (Electron Technology, UK) on a daily basis.

2.3. AD modeling scenario
The AD modeling scenario used in this study consisted of two scenarios: (1) AD with combined heat and power (CHP) unit to transform biogas to electricity (AD with CHP or MCE), and (2) AD with biogas upgrading unit to convert biogas into biomethane (AD with biogas upgrading or MCB). The calculation of the carbon and energy balance was carried out using a model developed at the University of Southampton [16], with the organic loading rate (OLR) in the range of 2-5 kg VS/L/day. The system boundary includes AD process, transportation for feedstock and digestate, biogas storage, pasteurization (for digestate), digestate dewatering and application (i.e. composting) and biogas with
CHP unit or biogas with upgrading unit. This system is classified as a complex system. The selected parameters applied in the model were based on the experimental results works and from the literature. The digester operation was in a mesophilic condition.

2.4. Analysis
TS, VS, MC and ash determination were based on Standard Method 2540 G [17]. pH was measured using a digital pH meter, calibrated in buffers at pH 7 and 9.2. Biogas production was calculated by converting pressure readings to gas volume in the headspace at standard temperature and pressure (STP) of 273.15 K and 101.325 kPa. Elemental analysis was performed using an elemental analyzer (628 Series Elemental Determinator, LECO). Biogas production was calculated by converting pressure readings to gas volume in the headspace at standard temperature and pressure (STP) of 273.15 K and 101.325 kPa, following Walker’s formula [18]. The specific methane potential (SMP) was calculated using the equation reported by Strömberg et al. [19].

3. Results and discussion
3.1. Physical characteristics of EFOB
The characteristics of EFOB used in this study are shown in table 2. It can be seen that EFOB is categorized as organic waste, as indicated by a high value of VS (91.73%TS). This result confirmed the suitability of EFOB to be used as feedstock in AD process. Gelegenis et al. [20] found that the VS concentration of any biomass feedstock affects the volume of biogas produced.

| Table 2. EFOB physical characteristics. |
|-----------------------------------------|
| Parameter | Value  |
| TS (%WW)  | 88.59  |
| VS (%WW)  | 81.26  |
| VS/TS (%TS) | 91.73 |
| MC (%WW)  | 11.41  |
| Ash (%WW) | 7.33   |

3.2. BMP test results
Prior and after BMP test, inoculum, positive control α-cellulose, and tested waste samples were measured for the pH and temperature as baseline data to investigate whether there was any impact of pH on the AD process. The pH values at the start and end of BMP test decreased from 7.7 to 7.3. This value was still well within the ideal values for the optimum AD process of 6.8 – 8.0 [21]. Thus, the pH data indicated that the AD of EFOB can be operated normally without any inhibition detected. Unstable AD process can be seen from any sharp decrease or increase in pH values of lower than 6.0 or higher than 8.0 [22]. The BMP test results show that almost all samples experienced an adaptation period until day 2. After that, the samples enter the logarithmic growth phase indicated by a rapid increase of biogas production, started from day 2 to day 5. Then, followed by a stable phase, where biogas production is relatively consistent/stable.
Specific methane production (SMP) values indicate the potential of methane produced based on the weight of organic matter contained by biomass samples. Figure 1 shows that SMP from positive α-cellulose control is 0.197 m³ CH₄/kgVS_added, this value is still far below the standard value. For example, SMP of the α-cellulose sample reported in CROPGEN study (online database for BMP test results from various biomass feedstocks) and Chynoweth et al. [23] showed a value of 0.370 m³ CH₄/kgVS_added. Theoretically, based on the molecular composition (C₆H₁₀O₅), SMP of give the value of α-cellulose is 0.415 m³ CH₄/kgVS_added [24]. A similar or closer value with the theoretical SMP demonstrated that the inoculum has an excellent ability in degrading organic matter contained in α-cellulose. However, if the SMP value was much lower, it indicates a lack of microbial activity and
ability in the inoculum. This study shows the latter response where the SMP value was still lower. Therefore, future work with the BMP test maybe with the addition of nutrients, as suggested by Angelidaki et al. [25], hoping to enhance the ability of microbial consortia in inoculum to break down the organic material in the sample feedstocks.

Figure 1 also shows that during day 0 to day 1, the adaptation process occurred. Then, high methane production occurs from day 2 to day 4. Then, followed by entering the stationary phase where methane production was relatively stable. This condition was evident for positive control and EFOB sample. As for EFOB, the trend shows less methane production, possibly due to its high fiber and lignin content, which is considered to limit methane production. Further pre-treatment to reduce lignin is therefore advisable, either using chemical or biological options.

Figure 1. Specific methane production from EFOB against blank inoculum and positive control.

3.3. Energy and carbon balance from AD modeling scenario

3.3.1. Energy balance. In this study, the input digester used was 100,000 tonnes of untreated EFOB for all scenarios. The biogas and methane produced were similar for all scenarios, with the value of 16,252,721 m³ biogas and 7,651,600 m³ methane, respectively. In the case AD with CHP scenario, the biogas/methane produced generated electricity of 94,969 GJ and generated heat of 135,670 GJ. While, in the case of AD with biogas upgrading, the generated electricity and heat were lower at the value of 18,656 GJ and 26,651 GJ, with additional energy in biomethane of 213,677 GJ.

A summary of energy balance for the scenarios based on electricity production using a CHP unit and biomethane production using a biogas upgrading unit is shown in table 3 and 4. It can be seen that for all the scenarios considered, the energy available from AD of EFOB is enough to provide both energy needs for the operation of the digester plant. Furthermore, the models also show that the electricity and heat produced from AD of EFOB were also able to export this energy for other purposes or stakeholders. Similar trends were also observed in all AD with biogas upgrading scenarios which indicated potential production of biomethane. These findings indicate that EFOB is potential to be used as feedstock in AD system for producing biogas/methane, which later converted into electricity, heat or biomethane. The bioenergy from AD of EFOB can be further used to substitute the use of fossils fuels. Previous research reported by Nieves et al. [26] has also highlighted that biomethane production from 1-tonne oil palm empty fruit bunches can replace approximately 337 L of gasoline or diesel used in the transportation sector.
Table 3. Summary energy balances for electricity and heat production (AD with CHP scenarios at OLR 2-5 kg VS/l/day).

| Details                      | Units       | MCE2     | MCE3     | MCE4     | MCE5     |
|------------------------------|-------------|----------|----------|----------|----------|
| Energy balance total         | GJ year⁻¹   | 160,256  | 163,401  | 164,979  | 166,102  |
|                              | GJ tonne⁻¹ waste | 1.60     | 1.63     | 1.65     | 1.66     |
| Energy balance electrical    | GJ year⁻¹   | 51,011   | 52,864   | 53,793   | 54,454   |
|                              | GJ tonne⁻¹ waste | 0.51     | 0.53     | 0.54     | 0.54     |

Table 4. Summary energy balances for biomethane production (AD with biogas upgrading scenarios at OLR 2-5 kg VS/l/day).

| Details                      | Units       | MCB2     | MCB3     | MCB4     | MCB5     |
|------------------------------|-------------|----------|----------|----------|----------|
| Energy balance total         | GJ year⁻¹   | 160,174  | 163,319  | 164,897  | 166,020  |
|                              | GJ tonne⁻¹ waste | 1.60     | 1.63     | 1.65     | 1.66     |
| Energy balance biomethane    | GJ year⁻¹   | 159,948  | 161,801  | 162,730  | 163,391  |
|                              | GJ tonne⁻¹ waste | 1.60     | 1.62     | 1.63     | 1.63     |

Figure 2 shows a comparison of energy balances for electricity and biomethane production from AD of EFOB. The total energy available for export from the AD with CHP scenarios was in the range of 1.60-1.66 GJ/tonne EFOB. These values were the same as that of the AD with biogas upgrading scenarios. However, when taking into account electricity and biomethane only as exportable energy, it can be seen that the AD with CHP scenarios gave lower value in the range of 0.51 – 0.54 GJ/tonne EFOB. This was due to the production of heat from CHP unit was much higher, indicating its potential of biogas as heat sources. Wu et al [27] found that biomass waste from the oil palm industry, including EFOB, can generate electricity and heat which can be used as a sustainable and renewable energy source for the factory as well as provide extra energy for surrounding neighborhood area.

3.3.2. Carbon balance (GHG emissions). Table 5 shows carbon balances or emission balance for electricity and biomethane production from AD of EFOB. The total emission from all scenarios was relatively the same with the value of 0.021 tonne CO₂ eq/tonne EFOB. However, the total emission saving from AD with CHP scenarios was slightly higher.

Table 5. GHG emission balances for electricity and biomethane production (AD with CHP or with biogas upgrading scenarios at OLR 2-5 kg VS/l/day).

| Scenarios                                  | MCE2 | MCE3 | MCE4 | MCE5 |
|--------------------------------------------|------|------|------|------|
| **AD with CHP scenarios**                  |      |      |      |      |
| total emissions                            | 0.021| 0.021| 0.021| 0.021|
| emission saving (total)                    | 0.189| 0.189| 0.190| 0.190|
| emission balance (electricity)             | 0.092| 0.093| 0.093| 0.093|
| balance (electricity + heat)               | 0.155| 0.156| 0.156| 0.157|
| **AD with biogas upgrading scenarios**     |      |      |      |      |
| total emissions                            | 0.021| 0.021| 0.021| 0.021|
| emission saving (total)                    | 0.173| 0.173| 0.174| 0.174|
| emissions balance (biomethane)             | 0.138| 0.139| 0.139| 0.139|
| emissions balance (biomethane + heat)      | 0.138| 0.140| 0.140| 0.141|
Figure 2. Comparison of energy balances for electricity and biomethane production from AD of EFOB: (a) electrical energy and heat; (b) electrical energy only; (c) biomethane and heat; and (d) biomethane only.

It can also be seen from figure 3 that the model indicated AD with CHP scenarios resulted in higher total GHG emissions saving (electricity and heat) compared to the AD with biogas upgrading scenarios. The findings also showed that an increase in OLR was also parallel to increase the total emissions savings, which possibly due to higher energy generated. Higher bioenergy production is also indicating that an increase in their potential to replace fossil fuels or other non-renewable energy, as well as reducing the GHG emissions. Patthanaissarunakool et al. [28] demonstrated that valorization of palm oil biomass as bioenergy sources can contribute to the reduction of carbon emission. They further added that such an approach is highly potential for mitigating the climate change impact on the environment.
Figure 3. Potential emission savings from electricity (a) and biomethane (b) production with and without the use of heat.

4. Conclusion

EFOB has a high organic content of more than 90% VS. The BMP test results demonstrated that EFOB has SMP of 0.110 m$^3$/kgVS$_{added}$. A lower SMP value was due to a high lignin content in EFOB, which limiting the optimal biogas production. The AD modeling indicated that EFOB is a potential feedstock for biogas production using AD technology, as it can provide energy in the form of electricity, heat or biomethane, as well as an organic residue (digestate) as biofertilizer. Based on the assumptions used, the AD modeling also showed that AD of EFOB combined with CHP operating at mesophilic condition was a potential option than AD with biogas upgrading scenarios if the heat can be fully applied to substitute fossil fuels. Improving the efficacy process of AD of EFOB is necessary due to problems of high lignin content. Biological pre-treatment is proposed as an environmentally friendly option as to tackling the lignin problem in EFOB. Yet, in depth studies are still required to optimize the process.

References

[1] Kumar S 2016 Assessment of renewables for energy security and carbon mitigation in Southeast Asia: the case of Indonesia and Thailand Appl. Energy. 163 63–70
[2] Azam M, Khan A Q, Zaman K and Ahmad M 2015 Factors determining energy consumption: evidence from Indonesia, Malaysia and Thailand Renew. Sustain. Energy Rev. 42 1123–31
[3] Simangunsong B C H, Sitanggang V J, Manurung E G T, Rahmadi A, Moore G A, Aye L and Tambunan A H 2017 Potential forest biomass resource as feedstock for bioenergy and its economic value in Indonesia Forest Policy Econ. 81 10–7
[4] MEMR 2016 Perkembangan Penyediaan dan Pemanfaatan Migas Batubara Energi Baru Terbarukan dan Listrik (Development provision and utilisation of Fossil Fuels, Coal, Renewable Energy and Electricity). Report. Centre of Data and Information Technology for Energy and Mineral Resource. Ministry of Energy and Mineral Resources of Republic of Indonesia, Jakarta. Retrieved from http://www.esdm.go.id/publikasi/kajian-energi-indonesia/doc_download/1612-perkembangan-penyediaan-dan-pemanfaatan-migas-batubara-ebt-dan-listrik.html. Accessed on 13 May 2019. [In Indonesian]
[5] BULKOWSKA K, MIARUSZ Z, EWA G and ARTUR K 2016 Biomass for Biofuels (Boca Raton, Florida: CRC Press)
[6] Tarkono T and Ali H 2015 Pemanfaatan serat tandan kosong kelapa sawit (TKKS) dalam produksi eternit yang ramah lingkungan (Utilisation of empyr furit oil palm bunches (EFOB)
fiber for production of environmentally friendly eternites) Jurnal Sains Teknologi & Lingkungan 1(1) 1–7 [in Indonesian]

[7] O-Thong S, Boe K and Angelidaki I 2012 Thermophilic anaerobic co-digestion of oil palm empty fruit bunches with palm oil mill effluent for efficient biogas production Appl. Energy 93 648–54

[8] Indonesia Statistics 2012 Indonesia Dalam Angka (Indonesia in Number) (Jakarta: Badan Pusat Statistik Republik Indonesia) [in Indonesian]

[9] Kim S H, Choi S M, Ju H J and Jung Y Y 2013 Mesophilic co-digestion of palm oil mill effluent and empty fruit bunches Environ. Technol. 34(13–14) 2163–70

[10] Yacobi S, Shirai Y, Hassan M A, Wakisaka M and Subash S 2005 Baseline study of methane emission from open digesting tank of palm oil mill effluent Chemosphere 59 1575–81

[11] Pullen T 2015 Anaerobic Digestion – Making Biogas – Making Energy (London: Routledge)

[12] Tariq J R, Long D A, Chen J P, Hung Y T and Zou S W 2009 Anaerobic digestion Handbook of Environmental Engineering vol 8, ed L K Wang, N C Pereira et al (Totowa, New Jersey: Humana Press)

[13] Ibrahim M M, Narasimhan J V and Ramesh A 2015 Comparison of the predominantly premixed charge compression ignition and the dual fuel modes of operation with biogas and diesel as fuels Energy 89 990–1000

[14] Speece R E 2008 Anaerobic biotechnology and odor/corrosion control for municipalities and industries (Nashville, Tenn: Archæ Press)

[15] Suhartini S, Lestari Y P and Nurika I 2019 Estimation of methane and electricity potential from canteen food waste IOP Conf. Series: Earth Environ. Sci. 230 1–6

[16] Salter A and Banks C J 2009 Establishing an energy balance for crop-based digestion Water Sci. Technol. 59 1053–60

[17] Eaton A D et al 2005 Standard methods for the examination of water and wastewater 21st ed. (Washington, D.C.: APHA-AWWA-WEF)

[18] Walker M, Zhang Y, Heaven S and Banks C J 2009 Potential errors in the quantitative evaluation of biogas production in anaerobic digestion processes Bioresour. Technol. 100(24) 6339–46

[19] Strömberg S, Nistor M and Liu J 2014 Toward eliminating systematic errors caused by the experimental condition in biochemical methane potential (BMP) tests Waste Manage. 34(11) 1939–48

[20] Gelegenis J, Georgakakis D, Angelidaki I and Mavris V 2007 Optimization of biogas production by co-digesting whey with diluted poultry manure Renew. Energy 32(13) 2147–60

[21] Ciobăla A E, Ionel I, Dumitrel G A and Popescu F 2012 Comparative study on factors affecting anaerobic digestion of agricultural vegetal residues Biotechnol. Biofuels 5(1) 1–9

[22] Espinoza-Escalante F M, Pelayo-Ortiz C, Navarro-Corona J, González-García Y, Boríes A and Gutiérrez-Pulido H 2009 Anaerobic digestion of the vinasses from the fermentation of Agave tequilana Weber to tequila: the effect of pH, temperature and hydraulic retention time on the production of hydrogen and methane Biomass Bioenerg. 33(1) 14–20

[23] Chynoweth D P, Owens J M and Legrand R 2001 Renewable methane from anaerobic digestion of biomass Renew. Energy 22(1–3) 1–8

[24] Lim S J and Fox P 2013 Biochemical methane potential (BMP) test for thickened sludge using anaerobic granular sludge at different inoculum/substrate ratios Biotechnol. Bioprocess Eng. 18(2) 306–12

[25] Angelidaki I, Alves M, Bolzonella D, Borzacconi L, Campos J L, Guwy A J, Kalyuzhnyi S, Jenicek P and Van Lier J B 2009 Defining the biomethane potential (BMP) of solid organic wastes and energy crops: a proposed protocol for batch assays Water Sci. Technol. 59(5) 927–34
[26] Nieves D C, Karimi K and Horváth I S 2011 Improvement of biogas production from oil palm empty fruit bunches (OPEFB) Ind. Crops Prod. 34(1) 1097–1101

[27] Wu Q, Qiang T C, Zeng G, Zhang H, Huang Y and Wang Y 2017 Sustainable and renewable energy from biomass wastes in palm oil industry: A case study in Malaysia Int. J. Hydrogen Energy 42(37) 23871–7

[28] Patthanaissaranukool W, Polprasert C and Englande Jr A J 2013 Potential reduction of carbon emissions from crude palm oil production based on energy and carbon balances Appl. Energy 102 710–7

Acknowledgment
Thanks are due to Ministry of Research and Higher Education for research funding support through Basic Research 2019.