Enhanced biogas production by mesophilic and thermophilic anaerobic co-digestion of palm oil mill effluent with empty fruit bunches in expanded granular sludge bed reactor

R Fitrah, A Ahmad and I Amri
Department of Chemical Engineering, University of Riau, HR Subrantas Rd. km 12.5 Pekanbaru 28293

E-mail: adri@unri.ac.id

Abstract. This study aimed to utilize Palm Oil Mill Effluent (POME) and preheated Empty Fruit Bunches (EFB) as a source for enhanced biogas production in Expanded Granular Sludge Bed (EGSB) Reactor. The reactor was operated continuously for 48 days with 2 days hydraulic retention time (HRT), POME: EFB mixing ratios of 1: 0 ; 0.10 ; 0.15 ; 0.20 ; temperature of 35 ± 2°C and 55 ± 2°C. The best improved was achieved from co-digestion of POME with EFB at a mesophilic temperature of 35 ± 2°C and mixing ratios of 1: 0.10, highest total biogas volume achieved was 7,400 ml (0.1359 – 0.1619 m³ CH₄/kg COD removed), Volatile Fatty Acid (VFA) /Total Alkalinity (TA) ratios 0.1418 – 0.1582, and COD removal 61.97 – 78.87 %. The Methane content was 46.10 %. Under a Thermophilic temperature of 55 ± 2°C and mixing ratios of 1: 0, 10, the highest total biogas volume achieved was 1.350 ml (0.0859 – 0.1358 m³ CH₄/kg COD removed) VFA/TA ratios increased to 0.4498 – 0.6685 with COD removal 61.97 – 74.65 %.

1. Introduction
The growth of Indonesia’s population would encourage the increase in electricity consumption. In the year 2018, United Nations (UN) stated that Indonesia’s population had reached 266.79 million. The number will continue to increase and reached its peak in the year 2062 with 324.76 million inhabitants [1, 2].

The demand for electricity would increase from 283,000 MWh in 2018 to 819,000 MWh in 2030. The Ministry of Energy and Mineral Resources try to build the new power plants with the aim of fulfilling electrification ratio of Indonesia 100% in 2025 with the target power plant sourced from renewable energy for 23% [3]. Riau Province has potential renewable energy resources to meet this 23 % target by utilizing Palm Oil industrial waste into electricity. By 2016, 20,942,857 m³ of Palm Oil Mill Effluent (POME) and 8,028,095 tons of Empty Fruit Bunches (EFB) is generated from 7.33 Million tonnes of CPO produced in Riau Province. It is the largest among another province in Indonesia.

Biogas utilization from POME was environmentally friendly because it can reduce Greenhouse Gas emissions. EFB has been used by researchers as a co-substrate with POME to enhance the biogas production [4-7].

O-Thong et al. (2012) reported the effect of pretreatment method EFB in co-digestion with POME in biogas production rates as well as the ability of biodegradable [4]. A second substrate is mixed in a 320 ml serum bottle in batch conditions. The maximum Biomethane production rates from this study were 82.7 m³ CH₄/ton mixture (ratio of 6.8:1), Biomethane yield of 392 ml CH₄/g VS at the
temperature of 55°C and HRT 45 days. O-Thong (2012) also stated that EFB and POME blends have the potential of great biomethane [4]. Kim et al. (2017) reported the co-digestion POME with EFB in mesophilic temperature [5]. A second substrate was mixed in a 150 ml serum bottle in batch condition. The maximum Biomethane production rates from this study were 50 ml CH₄/g VSS. The Biomethane generated was 350 ml CH₄/g COD with substrate ratio 1:0.31, the temperature of 35°C, HRT of 16 days and pH 7.6. ] Kim et al. (2017) reported that co-digestion EFB and POME is one of the appropriate methods of controlling pollution and recover energy in the oil palm industry [5]. Ohimain and Izah (2014) reviewed the performance of various types of anaerobic biodigester in terms of biogas production using Nigeria’s POME historical data from 2004 to 2013 [2]. From these data, it is known the Expanded Granular Sludge Bed (EGSB) reactor generated the highest Biomethane in the shortest HRT when compared to other types of the anaerobic biodigester.

This research aimed to utilize POME and preheated EFB as a source for enhanced biogas production in (EGSB) reactor as well as determine the best variations of temperature and substrate ratio to get the highest volume of biogas production.

2. Materials and methods

2.1. Materials and experimental setup

The materials used in this study were POME obtained from Sei Galuh Palm Oil Mill and EFB from Sei Rokan Palm Oil Mill of PT. Perkebunan Nusantara V, granular sludge from PT. Insansandang Internusa’s UASB reactor, Nitrogen and 10% NaCl solution. Other materials included K₂Cr₂O₇ 0.05 M solution; Ag₂SO₄ 0.05 M; FAS; H₂SO₄ 0.02 N; NaOH 0.1 N; Ferroin, PP and MO indicators. The total volume of EGSB reactor used in this study was 30,570 ml with the effective volume of 19,820 ml. The following is a schematic setup of the EGSB reactor.

![Figure 1. EGSB reactor schematic setup.](image)

**Research variables**

**Dependent variables**

1. Size of the EFB < 1 mm [5]
2. The effective volume of the reactor was 19,820 ml
3. HRT of 2 days
Independent variables
1. POME: EFB Ratio: 1 ml: 0; 0.10; 0.15 and 0.20 gr [7]
2. Reactor temperature 35 ± 2°C [5, 8] and 55 ± 2°C [4]

2.2. Research procedures

Materials preparation
1. POME was obtained from bottom outlet Fat Pit of Sei Galuh Palm Oil Mill.
2. EFB was taken from Sei Rokan Palm Oil Mill, minced and dried in an oven for 6 hours with the temperature of 105°C. The dried EFB was sieved using 20 mesh filter (to obtain the average diameter of EFB powder ± 0.85 mm or below 1 mm)
3. Granular Sludge was obtained from UASB reactor treating textile waste in PT. Insansandang Internusa. The microbial consortia in granular sludge were *Micrococcus*, *sp*; *Nitrosomonas*, *sp*; *Nitrobacter*, *sp*; and *Methanobacter* sp.

Analysis of POME characteristics
Analysis of POME characteristics was held at the laboratory of Bina Marga Department in Riau Province.

Operation of EGSB reactor
The reactor was operated with variation in temperature 35 ± 2°C (mesophilic) and 55 ± 2°C (thermophilic), POME to EFB variation ratio 1 ml: 0; 0.10; 0.15 and 0.20 gr and 2 days HRT. The study was divided into 8 runs presented in table 1.

Table 1. Operational stage of EGSB reactor.

| Run  | Temperature (°C) | Co-digestion ratio (POME: EFB) |
|------|------------------|--------------------------------|
| 1st  |                  | 1: 0.00                        |
| 2nd  | 35 ± 2           | 1: 0.10                        |
| 3rd  |                  | 1: 0.15                        |
| 4th  |                  | 1: 0.20                        |
| 5th  |                  | 1: 0.00                        |
| 6th  |                  | 1: 0.10                        |
| 7th  | 55 ± 2           | 1: 0.15                        |
| 8th  |                  | 1: 0.20                        |

3. Results and discussion

Characterization of POME
POME used in this study was taken directly from Sei Galuh Palm Oil Mill’s Fat Pit outlet then analyzed in the Material Testing Lab of Dinas Bina Marga, Riau Province. This analysis was needed as a comparative data for influents’ COD analysis, especially for POME and EFB mixture. POME characterization analysis result can be seen in table 2.

Table 2. POME characteristics obtained from sei galuh palm oil mill.

| Parameters              | Value | Threshold*               |
|-------------------------|-------|--------------------------|
| pH                      | 4.58  | 6.0 – 9.0                |
| BOD₅ (mg/l)             | -     | 100                      |
| COD (mg/l)              | 55,000| 350                      |
| TSS (mg/l)              | -     | 250                      |
| Total Alkalinity (mg/l) | 1.220 | N/A                      |
| Volatile Fatty Acid (mg/l) | 180 | N/A                      |
| Total Nitrogen (mg/l)   | -     | 50                       |
| Max. Debit (m³/ton CPO) | -     | 2.5                      |

*Indonesia’s Ministry of Environment Regulation No. 5, 2014
Influent’s COD
The analysis of influent’s COD was used as the basis for calculation of EGSB reactor’s COD removal. The value was obtained from the influent’s COD analysis per run with three repetitions. The results presented in table 3.

Table 3. Influent’s COD analysis on every run.

| Run | Mesophilic | Thermophilic | POME: EFB | Sample 1 | Sample 2 | Sample 3 | Average |
|-----|------------|--------------|-----------|----------|----------|----------|---------|
| 1   | 5          | 1: 0.00      | 55,000    | 50,000   | 55,000   | 53,333   |
| 2   | 6          | 1: 0.10      | 60,000    | 57,500   | 60,000   | 59,167   |
| 3   | 7          | 1: 0.15      | 67,500    | 67,500   | 67,500   | 66,667   |
| 4   | 8          | 1: 0.20      | 77,500    | 77,500   | 87,500   | 83,333   |

3.1. COD removal
1st Run (T = 35 ± 2°C; Co-digestion ratio 1:0)
Compared to the early startup stage in day 8 to 12 (78.44 to 81.25%), the COD removal in first run decline, within the range of 48.44 – 67.19%. But the reactor still in a stable condition. The production of biogas generated in the first run was better compared to early steady state (day 8 to 12). The COD removal in the first run presented in figure 2.

![Figure 2](image1.png)

Figure 2. COD removal on 1st run.

2nd Run (T = 35 ± 2°C; Co-digestion ratio 1: 0.10)
The COD removal on the 2nd run was increased when compared to 1st run within the range of 61.97 – 78.87%. The influent’s COD increased due to the addition of EFB with co-digestion ratio 1:0.10. The average influents’ COD were 59,167 mg/l. The effluents’ COD on the 2nd run was better when compared to 1st run, i.e. within the range of 22,500 – 12,500 mg/l. From this data, it can be stated that the addition EFB as a co-substrate, increased the organic material settle-ability at the bottom of the reactor, so the effluents’ COD on the 2nd run was relatively low when compared to the previous run. During 6 days continuous operation on 2nd run, EGSB reactor exhibited good performance. The COD removal on the 2nd run is presented in figure 3.

3rd Run (T = 35 ± 2°C; Co-digestion ratio 1: 0.15)
The COD removal on the 3rd run was also increased when compared to 2nd run. The COD removal vary within the range of 70.00 to 81.25%. The average influents’ COD on the 3rd run was 66,667 mg/l. Compared to the previous run, the effluents’ COD was better, i.e. within the range of 20,000 – 12,500 mg/l. The Co-digestion ratio of 1: 0, 15 increased the organic material settle-ability. Thus effluents’ COD on 3rd run better than 2nd run. The COD removal on the 3rd run is presented in figure 4:
4th Run ($T = 35 \pm 2^\circ C$ ; Co-digestion ratio 1:0.20)
The highest COD removal during the operational stage; 88% was achieved in the 4th run on day 5 and 6. The COD removal on 4th run varies within 76-82%. Influent’s COD on this run were 83,333 mg/l. The effluents’ COD achieved on the 4th run was the best compared to 3 previous runs. The value vary within 10,000-20,000 mg/l. The effluents’ clarity were increased compared to the previous run. The COD removal on 4th run presented in figure 5:

5th Run ($T = 55 \pm 2^\circ C$ ; Co-digestion ratio 1:0)
On this 5th run, the EGSB reactor operated in Thermophilic condition (Temperature of 55 ± 2$^\circ$ C) and there is no addition of EFB as co-substrates. The influents’ COD value on 5th to 8th run was equal to the 1st to 4th run because the POME to EFB ratios was identical. The effluents’ COD were increased slightly compared to the Mesophilic condition. From the observations during the 5th run, thermophilic condition on EGSB reactor was more unfavorable for Methanogens bacteria in the granular sludge bed. The conversion of organic acid into biogas by Methanogens bacteria became obstructed. The effluents coming out of the reactor looked like a bit murkier compared to the effluents on 1st run. The COD removal at this stage varies within 48.44 – 62.50%. The COD removal on 5th run presented in figure 6.

6th Run ($T = 55 \pm 2^\circ C$ ; Co-digestion ratio 1:0.10)
Co-digestion ratios on 6th to 8th run were the same as on 2nd to 4th run. The difference was in the temperature conditions used. The condition of the reactor on 6th to 8th run was Thermophilic (Temperature 55 ± 2$^\circ$ C). From the observations made during the 6th run, it is known that the thermophilic condition causes negative effects in terms of biogas production. The organic acid conversion by Methanogens bacteria was limited, thus increased the VFA concentration in the reactor. The volume of biogas generated in this run was far below the 2nd run.
There was no major difference in terms of effluents’ COD value compared to the 5th run. The effluents’ COD on 6th run vary within 15,000-22,500 mg/l. On 2nd to 5th operational day, the effluents’ COD was stable at 20,000 mg/l.

The COD removal vary within 61.97 – 74.65% as presented in figure 7.

7th Run \((T = 55 \pm 2^\circ \text{C} ; \text{Co-digestion ratio} \ 1:0.15)\)

The EFB addition to the ratio of 1:0.15 on this run was not increase the biogas production said reactor. During the 7th run, it was observed that the thermophilic condition of the reactor help increased the substrate decomposition rate. More organic substrate converted to organic acid caused increased the VFA concentration and pH, hence the reactor became unstable.

The average influents’ COD on the 7th run was 66,667 mg/l, effluents’ COD increased slightly compared to the previous run, i.e., in the range of 17,500-25,000 mg/l. The COD removal vary within 62.50-73.75% as presented in figure 8.

8th Run \((T = 55 \pm 2^\circ \text{C} ; \text{Co-digestion ratio} \ 1:0.20)\)

The effluents’ COD on the 8th run was much higher compared to any other previous, i.e., in the range of 20,000 – 30,000 mg/l. The physical appearance of the effluents on the 8th run was pale yellow colored liquid with the strong sour smelling. The COD removal on this run was 64.00 – 76.00% as presented in figure 9.

3.2. Volatile fatty acid to total alkalinity ratios

The volatile fatty acids to total alkalinity ratios in the EGSB reactor reflects how high the value of organic acids which has been converted by bacterial fermentation of organic matter. When linked with the COD removal and biogas volume generated, this ratio indicates the equilibrium of organic materials/fatty acids/methane gas that is formed [9, 10].

EGSB reactor’s VFA/TA ratios performance-based detailed as follows:

1. Under 0.15; The reactor was stable, most of the organic material was successfully converted into fatty acids and Biomethane.
2. Between 0.15 to 0.20; reactor needs some attention and approaching the state of overloading.
3. Between 0.20 to 0.25; the reactor was on the verge of overload, there were limited bacteria present in the reactor that could convert the organic material to biogas.
4. Above 0.25; the reactor has been acidified, an organic material that goes largely converted into fatty acids, and only a fraction are converted into methane gas [9].

Details of VFA/TA ratios on every run in EGSB reactor presented in table 4.
The reactor was likely exhibited stable performance in mesophilic condition although it has received a fairly high organic load, whereas in the thermophilic condition reactor tend to be more acidic (high concentration of VFA).

3.3. Biogas volume

The addition of EFB as co-substrate with the ratio of 1:0.10 enhanced the biogas production in mesophilic. It can increase the production of biogas by 3.06% compared to a single substrate (POME). EGSB reactor was at stable condition during mesophilic operational temperature, although it had actually approached the overload condition. Inversely proportional to the mesophilic condition, the thermophilic condition with various POME to EFB ratios have no effect against the increase of biogas volume generated. The addition of co-substrate only increases the settle-ability of influents at the bottom of the EGSB reactor.

| Temperature | Run | POME: EFB ratios | VFA: TA ratios |
|-------------|-----|------------------|----------------|
| 35 ± 2°C (Mesophilic) | 1st | 1: 0.00 | Day 1 0.1477 | Day 2 0.1489 | Day 3 0.1515 | Day 4 0.1505 | Day 5 0.1545 | Day 6 0.1396 |
|  | 2nd | 1: 0.10 | 0.1538 | 0.1427 | 0.1419 | 0.1419 | 0.1566 | 0.1488 |
| 3rd | 1: 0.15 | 0.1663 | 0.1548 | 0.1442 | 0.1442 | 0.1492 | 0.1575 |
| 4th | 1: 0.20 | 0.1575 | 0.1457 | 0.1501 | 0.1501 | 0.1094 | 0.1281 |
| 55 ± 2°C (Thermophilic) | 5th | 1: 0.00 | 0.5758 | 0.5256 | 0.4647 | 0.4647 | 0.5700 | 0.6053 |
| 6th | 1: 0.10 | 0.5385 | 0.4498 | 0.6683 | 0.6683 | 0.5531 | 0.6386 |
| 7th | 1: 0.15 | 0.5122 | 0.5190 | 0.4794 | 0.4794 | 0.4184 | 0.4678 |
| 8th | 1: 0.20 | 0.5135 | 0.5395 | 0.5705 | 0.5705 | 0.5836 | 0.5977 |

Figure 10. Biogas volume on mesophilic condition.

Figure 11. Biogas volume on thermophilic condition.
Thermophilic condition

The biogas generated during thermophilic condition were less compared to the mesophilic, i.e., in the range of 150 – 350 ml. The various co-digestion ratio did not have any positive correlation in terms of biogas production by EGSB reactor. The biogas volume in thermophilic condition presented in figure 11.

3.4. Study comparison

POME and EFB co-digestion process in EGSB reactor at Mesophilic (temperature of 35 ± 2°C) and the ratio of 1:0.10 would enhance the biogas production. The study showed that the yield of Biomethane was 0.1359 - 0.1619 m³ CH₄/kg COD, slightly higher when compared to previous research by Yejian et al. (2008) (0.112 m³ CH₄/kg COD) [11] and Yejian et al. (2015) (0.108 m³ CH₄/kg COD) [8]. The higher Biomethane yield in this study was generated by the addition of EFB as co-substrate, which helps the bacterial consortia to grow rapidly and of biomass. Basically, the substrates decomposition and the microbial consortia in granular sludge as for their source of carbon-rich nutrients. The initial drying at the temperature of 110°C for 3 hours would help the bacterial consortia in doing EFB’s lignocellulose hydrolysis and acidogenesis [4]. Breaking the lignocellulose would enhance the carbon content of the substrate mixtures, hence increased the opportunities of acetates conversion into biomethane by bacteria consortia.

The Biogas volume achieved in thermophilic (temperature of 55 ± 2°C) with the same co-digestion ratio of 1: 0.10 were less compared to the mesophilic. The Biomethane yield was 0.0859 - 0.1358 m³ CH₄/kg COD. They were far below the Biomethane yield achieved on previous studies, i.e. [4]; 0.338 m³ CH₄/kg COD. O-Thong (2012) also used EFB as co-substrate with a ratio of 1: 6.8, in thermophilic (temperature of 55°C), HRT 45 days. O-Thong also has 2 (two) of POME biogas research in 2011 with UASB and EGSB reactor, HRT 5 days without using co-digestion processes [12]. The results of the study showed a lower biomethane production when compared to this research, i.e. 0.0053 m³ CH₄/kg COD for UASB reactor and 0.0036 m³ CH₄/kg COD for EGSB reactor.

Basically, the substrates decomposition rate were much higher in thermophilic conditions, because it helps the microbial consortia to grow rapidly [13]. Thus, the lignocellulose hydrolysis and acidogenesis were more likely to be done in this condition compared to the mesophilic [4]. So, it was lowered the reactor’s pH which was 4.52 to 4.72 in thermophilic and 6.13 to 6.81 in mesophilic. The low production of biomethane in thermophilic occurred due to the long chain fatty acids contained in undiluted POME. Long-chain fatty acids such as Palmitic acid (over 50 mg/g of dry weight) and oleic acid (above 200 mg/l) would inhibit the decomposition process by microbial consortia and Biomethane production in the reactor [4, 14, 15].

4. Conclusion

The biogas volumes achieved in mesophilic were much higher compared to the thermophilic condition. The largest biogas volume obtained at mesophilic (temperature of 35 ± 2°C), and POME to EFB ratio = 1: 0.10, was 7,400 ml for 6 days of operation (0.1359 – 0.1619 m³ CH₄/kg COD). The COD removal was 61.97 – 78.87%. The reactor operation was stable, as related to the ratio of VFA/TA 0.1418 – 0.1582. The Biogas content analysis showed that CH₄ generated was 46.10%; 26.70% of CO₂; 0.80% of O₂ and 1.119 ppm of H₂S. The biogas volume achieved in thermophilic (temperature of 55 ± 2°C) and POME to EFB ratio of 1: 0.10, was 1,350 ml for six days of operation (0.0859 – 0.1358 m³ CH₄/kg COD). The COD removal was 61.97 – 74.65%. The reactor was already unstable, and pH varies from 4.52 to 4.72. The VFA/TA ratios were also increased rapidly, i.e., 0.4498 – 0.6683 (> 0.25; reactor was acidified, most of the organic material were converted into fatty acids but only some fractions were converted into methane gas). The Biogas content analysis showed that CH₄ obtained was 41.25%; 29.80% of CO₂; 0.76% of O₂ and 1.126 ppm of H₂S.

References

[1] APHA (American Public Health Association) 2005 Standard Methods for the Examination of
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