Review on biogas from palm oil mill effluent (POME): Challenges and opportunities in Indonesia

A Rajani¹, Kusnadi¹, A Santosa¹, A Saepudin¹, S Gobikrishnan² and D Andriani¹,*

¹Research Center for Electrical Power and Mechatronics–Indonesian Institute of Sciences (LIPI), Komplek LIPI, Jl. Cisitu No. 21/154D, Bandung, 40135, Indonesia
²Department of Food Processing and Engineering, Karunya University, Karunya Nagar, Coimbatore, Tamil Nadu, 641114, India

*Corresponding author: dea1401@yahoo.com

Abstract. Palm oil mill effluent (POME) is a remarkably contaminating effluent that generated from three principle processes such as the sterilization, condensation, and hydrocyclone of palm oil in mills. The high biological oxygen demand (BOD), chemical oxygen demand (COD) and acidic pH of POME create an environmental issue if it is discharged into the aquatic and terrestrial ecosystem without treatment. However, by proper handling POME is also considered as a potential substrate for a renewable energy source. Biogas consisting mostly of methane and carbon dioxide has been produced using anaerobic digestion of POME. The process of biogas production involves the indigenous microbial community through hydrolysis, acidogenesis, acetogenesis, and methanogenesis. This study will elaborate on the potential of POME as a renewable energy source as well as the challenges and opportunities to develop biogas from POME in Indonesia. By proper handling and technology, from around (31 to 41) × 10⁶ t of palm oil products in Indonesia from the year 2015 to 2017 it is theoretically calculated that 150.93 MW, 173.37 MW, and 203.92 MW of power plant capacity can be generated, respectively.

Keywords: Anaerobic digestion, bioenergy, Indonesian palm oil, POME-to-electricity, renewable energy

1. Introduction

Indonesia is a country with about 242 × 10⁶ total populations, comprised of 33 provinces, 17 508 islands, and around 1 890 000 km² total area. Indonesia had a high growth rate which is about 1.26 % per year in 2017 [1] and predicted to have 285 × 10⁶ populations by 2025. The Gross Domestic Product (GDP) growth rate in Indonesia averaged at 5.0 % per annum from 2013 to 2016. This growth average will be stable at 5.0 % until 2021 based on the forecast of the Economist Intelligence Unit [2]. In line with the GDP growth rate, the energy and electricity demand in Indonesia has increased significantly. Indonesia’s energy demand will increase at 5 % to 10 % per year over the next 20 yr, meaning an additional 15 000 GW h will be needed each year [3]. Meanwhile, the national electrification ration in 2016 was 91.16 % with uneven distribution. The electrification ratio in Indonesia is set to increase to 97.4 % by 2019 and to 99.7 % by 2025 based on the 2017 to 2026 PLN Electricity Supply Business Plan [2]. Regarding these circumstances, further strategies such as the use of renewable energy are necessary for ensuring energy security, providing even distribution of...
electricity throughout the country, and also achieving greenhouse gas (GHG) emission reduction target of 26% by 2020 [4].

One of the potential ways to support the country’s transition to a low carbon economy and provide electricity is the utilization of natural resources available in Indonesia for a renewable energy source. Palm oil as one of the major commodities in Indonesia has been on the rise in the last years for their multiple uses such as food industry, biofuels, and cosmetics. The use of palm oil in mills to supply its demand generates a highly polluting residue called Palm Oil Mill Effluent (POME). POME is the liquid residue that produces mainly during three palm oil production process: the sterilization of bunches, after kernel separation from the shells in hydrocyclone, and after oil clarification [5, 6]. It is normally stored in open lagoons and emits significant volumes of methane (CH4) and carbon dioxide (CO2). For every ton of crude palm oil (CPO) produced, total emissions are between (5 to 25) t CO2 eq, of which, emissions from POME contribute 9% to 18% [3]. The use of methane from POME, however, could offer a great way for palm oil mills to reduce their environmental impact and to generate electricity from a renewable energy source (POME-to-electricity). Less than 10% of around 640 palm oil mills (POMs) in Indonesia treat their POME using biogas technology [3, 5].

This study approaches the employment of POME as renewable energy sources for methane production as well as the treatment of POME and optimization of biogas production through the diversification of digester. This paper also approaches the opportunities and challenges to develop biogas from POME in Indonesia.

2. Biogas production from POME
POME is the liquid waste generated from oil extraction process of Fresh Fruit Bunches (FFB) in POMs that contains a high concentration of organic molecules such as carbohydrates, proteins, fatty acids, lipids, nitrogenous compounds, and other minerals as can be seen in table 1 [7–9, 11–13]. This effluent is a thick brownish liquid with high biochemical oxygen demand (BOD) and chemical oxygen demand (COD) [8, 10]. Moreover, its high solids concentration and acidity cause it to be unsuitable for direct discharge to the aquatic and terrestrial ecosystem without treatment.

**Table 1.** General characteristics of POME.

| Parameters                               | Concentration range       |
|------------------------------------------|---------------------------|
| Temperature (°C)                         | 80 to 90                  |
| pH                                       | 3.4 to 5.2                |
| Oil and grease (mg L⁻¹)                  | 130 to 180 000            |
| Biochemical oxygen demand                | 10 250 to 43 750          |
| (BOD₃, incubated for 3 d, 30°C) (mg L⁻¹) |                           |
| Chemical oxygen demand (COD) (mg L⁻¹)    | 15 000 to 100 000         |
| Total solid (SS) (mg L⁻¹)                | 11 500 to 79 000          |
| Total suspended solid (TSS) (mg L⁻¹)     | 5 000 to 54 000           |
| Total volatile solid (TVS) (mg L⁻¹)      | 9 000 to 72 000           |
| Total nitrogen (TN) (mg L⁻¹)             | 180 to 1 400              |
| Ammoniacal nitrogen (mg L⁻¹)             | 4 to 80                   |
| Colour (ADMI)                            | > 500                     |
| Pottasium (mg L⁻¹)                       | 1 281 to 1 928            |
| Calcium (mg L⁻¹)                         | 276 to 405                |
| Magnesium (mg L⁻¹)                       | 254 to 344                |
| Phosphorus (mg L⁻¹)                      | 94 to 131                 |
| Manganese (mg L⁻¹)                       | 2.1 to 4.4                |
| Iron (mg L⁻¹)                            | 75 to 164                 |

continue on next page
Parameter & Concentration range  
--- & ---  
Zinc (mg L\(^{-1}\)) & 1.2 to 1.8  
Copper (mg L\(^{-1}\)) & 0.8 to 1.6  
Chromium (mg L\(^{-1}\)) & 0.05 to 0.43  
Cobalt (mg L\(^{-1}\)) & 0.04 to 0.06  
Cadmium (mg L\(^{-1}\)) & 0.01 to 0.02  

Palm oil is extracted from FFB via dry or wet milling processes. The wet process of palm oil milling is the most common in oil palm producing countries which are associated with environmental burden due to the voluminous discharge of the wastewater during milling process [7, 14, 15]. Ahmad et al. [7] and Wu et al. [8] estimated that from each ton of FFB, about 5 t to 7 t of water is required and about 50 % to 79 % end up as POME [8, 16, 17]. This implies that about 2.5 t to 3.75 t of POME will be generated per ton of FFB production [9].

The production of biogas from POME involves a multi stage of microbiological processes: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. These processes convert POME constituents that remain of carbohydrates, fatty acid, and proteins into CH\(_4\) and CO\(_2\) by the action group of the microorganism (figure 1) [6, 7, 18–20]. The efficiency of this process is highly affected by the consortium of microorganism and environmental factors, such as pH, temperature, nutrients, mixing condition, chemical equilibrium, pressure, hydraulic retention time, and also the presence of inhibitory materials [7, 11, 21, 22].

Biogas production from POME can be done either aerobic or anaerobic. The aerobic digester has a high microbial growth rate that leads to lower retention time during biogas production, while anaerobic treatment process is characterized by slow microbial growth and higher retention time compared to aerobic processes. However, the anaerobic method is considered more effective in terms of cost and conversion into useful product [10]. The biogas produced from POME is known to have a good potential for power generation using the gas engine. Biogas production from POME is ranged from (20 to 28) m\(^3\) of CH\(_4\) m\(^{-3}\) biogas [7, 23]. Basically, 28 m\(^3\) of biogas can be produced from 1 m\(^3\) of POME [6, 7]. About 1 m\(^3\) biogas is capable of generating about 1.8 kW h, which is equivalent to 25 % power generation efficiency [7, 23].

### 2.1. POME pretreatment

POME has high lipid content that might cause a problem during the anaerobic digestion due to the accumulation of long chain fatty acids (LCFAs). LCFAs are known as the metabolites of the lipids hydrolysis, and their accumulation will decrease the methane production [24, 25]. Pretreatment of POME is necessarily needed to overcome this problem, and some methods have been developed such as POME deoiling, POME sedimentation, POME pre-hydrolysis, and additional biological or inorganic additive. POME deoiling had resulted in a better methane yield due to lower LCFAs and protein content, and also lower portion of biofibers [24–26]. However, the next treatment is needed to manage the removed lipids. Sedimentation is another strategy to improve the anaerobic digestion of POME by removing the undigestable suspended solid fraction. However, this strategy needs special concern on digester/bioreactor design and operation condition otherwise the methane yield will not significantly increase [11]. POME pre-hydrolysis is believed to improve the biogas production effectively since the hydrolysis is the rate-limiting step in the anaerobic digestion process [24, 27]. The POME pre-hydrolysis method such as ozonation was reported greatly boosted the methane yield of POME by 925 % [24, 28] and reduces the toxicants such as LCFAs, and polyphenols. The addition of inorganic additives such as red mud- iron, calcium oxide-cement klin dust, and chitosan for POME pretreatment is purposed to improve biomass retention in the system [24, 29]. Meanwhile, the addition of microbial consortium as a biological additive is known to enhance the anaerobic digestion performance due to sufficient acclimatization and startup period, and also better of COD removal [11].
Figure 1. The process of biogas production from POME.

2.2. Bioreactors for biogas production from POME

Other than pretreatment, various strategies to improve methane production from POME have been observed such as bioreactor modification and co-digestion. The common types of anaerobic bioreactor for POME treatment are fluidized bed reactor (FBR), up-flow anaerobic sludge blanket (UASB) reactor, up-flow anaerobic sludge fixed-film (UASFF) reactor, modified anaerobic baffled bioreactor (MABB), anaerobic baffled bioreactor (ABR), continuous stirred tank reactor (CSTR), expanded granular sludge bed (EGSB) reactor, ultrasonicated membrane anaerobic system (UMAS), ultrasonic-assisted membrane anaerobic system (UAMAS) and membrane anaerobic system (MAS) [7, 30, 31]. Most of these bioreactors have demonstrated treatment efficiency and promising methane production in laboratory scale research [11, 24]. However, CSTR is known to be more acceptable for commercialized scale of POME treatment due to several advantages such as low investment and simple to construct, lower operating cost due to low electricity required, easy clean and maintenance, easy to control temperature, and provide more contact between wastewater and biomass [11, 24].

Meanwhile, the co-digestion is known as the most common strategy to improve the overall anaerobic digestion performance and biogas production by increase the process stability, balance the macronutrient (C and N) and micronutrient contents, promote synergistic effects of microorganisms
and dilute the inhibitors in the system [24, 32, 33]. The co-substrates that had been digested with POME are a lignocellulosic material such as oil palm empty fruit bunches (EFB) [12], sewage sludge [13], cow manure [14], and the combination of EFB and microalgae [15]. The sewage sludge and EFB will alter the C/N ratio within the digestion system [13] to finally the methane production.

3. Palm oil in Indonesia
Palm oil is one of the plantation commodities that have an important role in economic activities in Indonesia since Indonesia is the world's largest palm oil producer and exporter. The development of palm oil production (CPO) from 2011 to 2015 in Indonesia is increased by around 5.38 % to 8.42 % per year. In 2011 palm oil production amounted to $23.99 \times 10^6$ t, increased to $31.07 \times 10^6$ t in 2015 or an increase of 29.48 %. Based on data from Indonesian palm oil entrepreneurs (GAPKI) CPO production in the year 2017 had reached $38.17 \times 10^6$ t, and the palm kernel oil (PKO) was $3.05 \times 10^6$ t. Therefore, the overall palm oil production was $41.98 \times 10^6$ t. This amount has shown the increased production of 18 % compares to the production in 2016 which was $35.57 \times 10^6$ t. The largest palm oil production in 2015 came from Riau Province by $8.06 \times 10^6$ t or around 25.94 % of the total Indonesian production [16]. The palm oil production and plantation area in Indonesia from the year 2014 to 2017 can be seen in figure 2.

![Figure 2. Palm oil production and plantation area in Indonesia [38, 39].](image)

According to its business status, most of the oil palm plantations in 2015 were cultivated by large private plantations amounting to $5.98 \times 10^6$ ha (53.79 %), while smallholder plantations have $4.65 \times 10^6$ ha (41.88 %) and large state plantations only $0.73 \times 10^6$ ha (6.78 %), respectively. In 2016 oil palm plantations cultivated by large private plantations were estimated at $6.2 \times 10^6$ ha (50.56 %), while smallholder plantations $4.8 \times 10^6$ ha (40.91 %) and large state plantations only sought $0.75 \times 10^6$ ha (6.21 %). The palm oil plantation based on its business status from the year 2012 to 2016 is outlined in figure 3.
Meanwhile, the total palm oil exports in the last five years are ranged from 9.44 % to 16.06 % per year. However, in the year 2016, the total exports are decreased to about 13.95 %. In 2011, the total export volume reached $17.87 \times 10^6$ t with a total value of USD $19.37 \times 10^9$, increased to $24.33 \times 10^6$ t in 2016 with a total value of USD $16.27 \times 10^9$ [16]. The summary of volume and value of palm oil export in Indonesia can be seen in figure 4.
4. Potential and challenges of biogas from POME

POME could become one of the promising renewable energy resources in Indonesia if the POME treatments are proper and efficient. High organic contents in POME have promoted POME to be a good source to generate biogas (methane) via anaerobic digestion. This methane could be used more efficiently through capture and use for power generation (POME-to-electricity). However, only less than 10 % of around 640 POMs in Indonesia treat their POME using biogas technology; the real potential goes untapped. Based on the palm oil production in figure 2 and assumed that all POME from these CPO is treated anaerobically, it is expected that more than 800 000 t of methane could be produced as shown in table 2 [8, 40].

Table 2. Estimated biomethane production from POME based on CPO production in Indonesia.

| Parameter                          | Unit   | 2015          | 2016          | 2017          |
|------------------------------------|--------|---------------|---------------|---------------|
| CPO production/year                | T      | 31 070 000    | 35 570 000    | 41 980 000    |
| POME generated/year\(a\)          | m\(^3\) | 27 963 000    | 32 013 000    | 37 782 000    |
| COD loading\(b\)                  | mg L\(^{-1}\) | 1 537 965 000 | 1 766 715 000 | 2 078 010 000 |
| CH\(_4\) produced/year\(c\)      | t      | 346 042 125   | 397 510 875   | 467 552 250   |
| Electricity generated\(d\)        | MW h   | 1 207 440     | 1 386 960     | 1 631 382     |
| Power plant capacity (gas engine)\(e\) | MW     | 150.93        | 173.37        | 203.92        |

\(a\)Assume that 0.9 m\(^3\) POME generated per ton CPO produced (commonly 0.7 m\(^3\) to 1 m\(^3\)) [17]

\(b\)Typical COD level in POME is 55 000 mg L\(^{-1}\)

\(c\)Assume that digester efficiency is 90 % and theoretical methane conversion is 0.25 Nm\(^3\) CH\(_4\)/kg COD

\(d\)Assume that gas engine operating 8 000 h yr\(^{-1}\)

\(e\)Methane energy value is 35.7 MJ m\(^{-3}\) and assumes that the efficiency of the gas engine in converting energy value of methane to electrical energy is 38 %

Based on National Energy Policy, the target of renewable energy is 23 % of the national energy mix by 2025 which the bioenergy will share 10 %. Aside the use of bioenergy directly into the power generator set [41], one other strategy that will be conducted by the Indonesian government is the development of bioenergy power plant by using agricultural waste to provide electricity as well as to improve the environment; therefore the estimated power generation by POME is expected to be able to support the target of renewable energy in the national energy mix. Despite the high potential for renewable energy mitigation activities, some challenges have been faced in developing POME-to-electricity such as the unfamiliarity of palm oil industry with technologies used in methane capture, higher investment cost for biogas power plant, and regulatory challenges. The Government of Indonesia has already taken important steps to promote renewable energy, particularly bioenergy projects by reducing the diesel and fuel subsidies and defined targets for energy from biofuels [42]. The government also has launched the Ministerial Regulation number 27/2014 regarding Feed in Tariffs (FIT) for renewable energy from biomass and biogas as shown in table 3 [40].

Table 3. Feed-in-tariff for renewable energy from biomass and biogas.

| Region                        | Multiplication Factor (F) | Feed-in-tariff (IDR per kW h) | Medium voltage | Low voltage |
|-------------------------------|---------------------------|--------------------------------|----------------|-------------|
| Java                          | 1.00                      | 1 050.0                        | 1 400.0        |
| Sumatera                      | 1.15                      | 1 207.0                        | 1 610.0        |
| Sulawesi                      | 1.25                      | 1 312.5                        | 1 750.0        |
| Kalimantan                    | 1.30                      | 1 365.0                        | 1 820.0        |
| Bali, Bangka Belitung, Lombok | 1.50                      | 1 575.0                        | 2 100.0        |
| Riau, Papua, and other island | 1.60                      | 1 680.0                        | 2 240.0        |
The utilization of methane from POME also allows POMs to earn revenue by participating in clean development mechanism (CDM) program [8, 43]. By the end of 2012, there were 36 registered methane capture projects under the CDM in Indonesia. Amongst the projects, 10 have successfully obtained the certified emission reductions (CERs) and received the economic benefits from carbon financing under the CDM as shown in table 4 [17]. The profits from CER can be used to support the biogas plant operating cost [9]. The implementation of CDM is expected able to encourage the development of methane production from POME.

| POMs                         | Location         | Registration year | Reduction (t CO\textsubscript{2eq} yr\textsuperscript{-1}) |
|------------------------------|------------------|-------------------|----------------------------------------------------------|
| Milano Pinang Awam           | North Sumatera   | 2008              | 33 390                                                   |
| Victorindo Alam Lestari      | North Sumatera   | 2009              | 39 218                                                   |
| Tolan Tiga Indonesia (Perlabian) | North Sumatera   | 2009              | 31 757                                                   |
| Permata Hijau Sawit          | North Sumatera   | 2009              | 38 424                                                   |
| Tolan Tiga Innesia (Bukit Maradja) | North Sumatera   | 2009              | 10 094                                                   |
| Bakrie Pasaman               | West Sumatera    | 2009              | 21 980                                                   |
| Sumbertama Nusapertiwi       | Jambi            | 2010              | 15 743                                                   |
| Sisirau                      | Aceh             | 2009              | 16 470                                                   |
| Pinago Utama Sugihwaras     | South Sumatera   | 2010              | 54 312                                                   |
| Musim Mas Pangkalan Lesung   | Riau             | 2011              | 52 397                                                   |

5. Conclusion
Palm oil in Indonesia is the most significant agricultural products and is important for economic development, particularly in rural areas. However, POME as one of by product from palm oil can generate environmental problems due to the high content of BOD and COD. Capturing and converting methane to energy offers one way for POMs to reduce their environmental impact and to create renewable energy at the same time. By proper handling and technology, from around \((31 \text{ to } 41) \times 10^6\) t of palm oil products from the year 2015 to 2017 it is calculated 150.93 MW, 173.37 MW, and 203.92 MW of power plant capacity can be generated, respectively. Palm oil industry and POME-to-electricity in Indonesia are expected to be able to develop by the support from the government through out the regulation and also from the implementation of CDM projects.

Acknowledgment
The writers would like to thank all researchers in Research Centre for Electrical Power and Mechatronics, Indonesian Institute of Sciences.

References
[1] Statista 2018 *Indonesia: Total population from 2012 to 2022 (in million inhabitants)* [Online] from [https://www.statista.com/statistics/294100/total-population-of-indonesia/][Accessed on 30 October 2018]

[2] PWC 2017 *Power in Indonesia: Investment and Taxation Guide* [Online] from [https://www.pwc.com/id/en/pwc-publications/industries-publications/energy--utilities---mining-publications/power-indonesia-2017.html][ Accessed on 28 October 2018]

[3] Indonesia Climate Change Trust Fund (ICCTF), Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and GmbH 2011 *Palm oil mill effluent (POME) to Electricity, Green Economy and Locally-Appropriate Mitigation Actions in Indonesia (GE-LAMA-I)* [Online] from [http://www.gelamai.org/files/MediaPublication/Concept%20Paper%20Palm%20Oil%20Mill%20Effluent%20(POME)%20to%20Electricity.pdf][Accessed on 13 September 2018]
[4] Nachmany M, Fankhauser S, Townshend T, Collins M, Matthews A, Pavese C, Rietig K, Schleifer P, and Setzer J 2014 The GLOBE Climate Legislation Study [Online] from http://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2014/03/Globe2014.pdf [Accessed on 1 May 2018]

[5] Garritano A N, Faber M D O, De Sá L R V and Ferreira-Leitão V S 2018 Palm oil mill effluent (POME) as raw material for biohydrogen and methane production via dark fermentation Renew. Sustain. Energy Rev. 92 676–84 https://www.sciencedirect.com/science/article/pii/S1364032118302521?via%3Dihub

[6] Lam M K and Lee K T 2011 Renewable and sustainable bioenergies production from palm oil mill effluent (POME): Win–win strategies toward better environmental protection Biotechnol. Adv. 29(1) 124–41 http://linkinghub.elsevier.com/retrieve/pii/S0734975010001369

[7] Ohimain E I and Izah S C 2017 A review of biogas production from palm oil mill effluents using different configurations of bioreactors Renew. Sustain. Energy Rev. 70 242–53 https://linkinghub.elsevier.com/retrieve/pii/S1364032113630983

[8] Chin M J, Poh P E, Tey B T, Chan E S and Chin K L 2013 Biogas from palm oil mill effluent (POME): Opportunities and challenges from Malaysia’s perspective Renew. Sustain. Energy Rev. 26 717–26 https://linkinghub.elsevier.com/retrieve/pii/S1364032113003857

[9] Habib M A B, Yusoff F M, Phang S M, Ang K J, and Mohamed S 1997 Nutritional values of chironomid larvae grown in palm oil mill effluent and algal culture Aquaculture 158(1–2) 95–105 http://linkinghub.elsevier.com/retrieve/pii/S0044848697001762

[10] Poh P E, Yong W-J, and Chong M F 2010 Palm Oil Mill Effluent (POME) Characteristic in High Crop Season and the Applicability of High-Rate Anaerobic Bioreactors for the Treatment of POME Ind. Eng. Chem. Res. 49(22) 11732–40 http://pubs.acs.org/doi/abs/10.1021/ie101486w

[11] Ahmed Y, Yaakob Z, Akhtar P, and Sopian K 2015 Production of biogas and performance evaluation of existing treatment processes in palm oil mill effluent (POME) Renew. Sustain. Energy Rev. 42 1260–78 https://linkinghub.elsevier.com/retrieve/pii/S1364032114008983

[12] Wu T Y, Mohammad A W, Jahim J M, and Anuar N 2010 Pollution control technologies for the treatment of palm oil mill effluent (POME) through end-of-pipe processes J. Environ. Manage. 91(7) 1467–90 http://linkinghub.elsevier.com/retrieve/pii/S0301479710000368

[13] Bello M M, Nourouzi M M, Abdullah L C, Choong T S Y, Koay Y S, and Keshani S 2013 POME is treated for removal of color from biologically treated POME in fixed bed column: Applying wavelet neural network (WNN) J. Hazard. Mater. 262 106–13 https://linkinghub.elsevier.com/retrieve/pii/S0304389413004536

[14] Wu T Y, Mohammad A W, Jahim J M, and Anuar N 2009 A holistic approach to managing palm oil mill effluent (POME): Biotechnological advances in the sustainable reuse of POME Biotechnol. Adv. 27(1) 40–52 http://linkinghub.elsevier.com/retrieve/pii/S07349750800089X

[15] Ismail I, Hassan M A, Rahman N A A, and Soon C S 2010 Thermophilic biohydrogen production from palm oil mill effluent (POME) using suspended mixed culture Biomass and Bioenergy 34(1) 42–7 http://linkinghub.elsevier.com/retrieve/pii/S0961953409002001

[16] Ahmad A L, Ismail S, and Bhattia S 2003 Water recycling from palm oil mill effluent (POME) using membrane technology Desalination 157(1–3) 87–95 http://linkinghub.elsevier.com/retrieve/pii/S0011916403003874
[17] Chavalparit O, rulkens W H, mol A P J, and khaodhair S 2006 Options for environmental sustainability of the crude palm oil industry in thailand through enhancement of industrial ecosystems *Environ. Dev. Sustain.* **8**(2) 271–87
http://link.springer.com/10.1007/s10668-005-9018-z

[18] Ohimain E and Izah S 2014 Possible Contributions of Palm Oil Mill Effluents to Greenhouse Gas Emissions in Nigeria *Br. J. Appl. Sci. Technol.* **4**(33) 4705–20
http://www.sciencedomain.org/abstract.php?id=670&id=5&aid=6181

[19] Trisakti B, Manalu V, Taslim I, and Turmuzi M 2015 Acidogenesis of Palm Oil Mill Effluent to Produce Biogas: Effect of Hydraulic Retention Time and pH. *Procedia Soc. Behav. Sci.* **195** 2466–74
https://linkinghub.elsevier.com/retrieve/pii/S1877042815037726

[20] Mel M, Ihsan S I, Adesta E Y T 2010 Biogas energy potential in Riau Indonesia *Proc. of International Conference on Technology for New and Renewable Energy (ICT-NRE)* (Jakarta: Indonesian Institute of Science and Technology (ISTN))
https://pdfs.semanticscholar.org/656f/db3f533c414d62c90b4da142b1348f567378.pdf

[21] Guerrero L, Omil F, Méndez R, Lema J M 1999 Anaerobic hydrolysis and acidogenesis of wastewaters from food industries with high content of organic solids and protein *Water Res.* **33**(15) 3281–90
http://linkinghub.elsevier.com/retrieve/pii/S004313549900041X

[22] Karakashev D, Batstone D J, and Angelidaki I 2005 Influence of Environmental Conditions on Methanogenic Compositions in Anaerobic Biogas Reactors *Appl. Environ. Microbiol.* **71**(1) 331–8
http://aem.asm.org/cgi/doi/10.1128/AEM.71.1.331-338.2005

[23] Sridhar M K C and Oluwa O O A 2009 Palm Oil Industry Residues *Biotechnology for Agro-Industrial Residues Utilisation* (Dordrecht: Springer Netherlands) p 341–55
http://linkinghub.elsevier.com/retrieve/pii/S1364032111731403X

[24] Choong Y Y, Chou K W, and Norli I 2018 Strategies for improving biogas production of palm oil mill effluent (POME) anaerobic digestion: A critical review *Renew. Sustain. Energy Rev.* **82** 2993–3006
https://www.sciencedirect.com/science/article/pii/S1364032111731403X

[25] Rasit N, Idris A, Harun R, and Ghani W A W A K 2015 Effects of lipid inhibition on biogas production of anaerobic digestion from oily effluents and sludges: An overview *Renew. Sustain. Energy Rev.* **45** 351–8
http://linkinghub.elsevier.com/retrieve/pii/S1364032115000763

[26] Fang C, O-Thong S, Boe K, and Angelidaki I 2011 Comparison of UASB and EGSB reactors performance, for treatment of raw and deoiled palm oil mill effluent (POME) *J. Hazard. Mater.* **189**(1–2) 229–34
http://linkinghub.elsevier.com/retrieve/pii/S030438941100210X

[27] Climent M, Ferrer I, Baeza M del M, Artola A, Vázquez F, and Font X 2007 Effects of thermal and mechanical pretreatments of secondary sludge on biogas production under thermophilic conditions *Chem. Eng. J.* **133**(1–3) 335–42
http://linkinghub.elsevier.com/retrieve/pii/S1385894707001234

[28] Chaiiprapat S and Laklam T 2011 Enhancing digestion efficiency of POME in anaerobic sequencing batch reactor with ozonation pretreatment and cycle time reduction *Bioresour. Technol.* **102**(5) 4061–8
http://linkinghub.elsevier.com/retrieve/pii/S0960852410019632

[29] Ahmad A 2014 A novel application of red mud-iron on granulation and treatment of palm oil mill effluent using upflow anaerobic sludge blanket reactor *Environ. Technol.* **35**(21) 2718–26
http://www.tandfonline.com/doi/abs/10.1080/09593330.2014.919034
[30] Borja R, Banks C J, and Sánchez E 1996 Anaerobic treatment of palm oil mill effluent in a two-stage up-flow anaerobic sludge blanket (UASB) system *J. Biotechnol.* 45(2) 125–35 http://linkinghub.elsevier.com/retrieve/pii/0168165695001549

[31] Poh P E and Chong M F 2009 Development of anaerobic digestion methods for palm oil mill effluent (POME) treatment *Bioresour. Technol.* 100(1) 1–9 http://linkinghub.elsevier.com/retrieve/pii/S0960852408005427

[32] Hagos K, Zong J, Li D, Liu C, and Lu X 2017 Anaerobic co-digestion process for biogas production: Progress, challenges and perspectives *Renew. Sustain. Energy Rev.* 76 1485–96 https://linkinghub.elsevier.com/retrieve/pii/S1364032116309388

[33] Mata-Alvarez J, Dosta J, Romero-Gúiza M S, Fonoll X, Peces M, and Astals S 2014 A critical review on anaerobic co-digestion achievements between 2010 and 2013 *Renew. Sustain. Energy Rev.* 36 412–27 https://linkinghub.elsevier.com/retrieve/pii/S1364032114002664

[34] Kim S-H, Choi S-M, Ju H-J, and Jung J-Y 2013 Mesophilic co-digestion of palm oil mill effluent and empty fruit bunches *Environ. Technol.* 34(13‒14) 2163–70 http://www.tandfonline.com/doi/abs/10.1080/09593330.2013.826253

[35] Sivasankari R, Kumaran P, Normanbhay S, and Shamsuddin A H 2013 Preliminary experimental results of Sewage Sludge (SS) Co-digestion with Palm Oil Mill Effluent (POME) for Enhanced Biogas Production in Laboratory Scale Anaerobic Digester *IOP Conf Ser Earth Environ Sci* 16 1–4 https://iopscience.iop.org/article/10.1088/1755-1315/16/1/012009/meta

[36] Sidik U, Razali F, Alwi S, and Maigari F 2013 Biogas production through Co-digestion of palm oil mill effluent with cow manure *Niger. J. Basic. Appl. Sci.* 21(1) 79–84 http://www.ajol.info/index.php/njbas/article/view/89692

[37] Ahmad A, Shah S M U, Buang A, Othman M F, and Abdullah M A 2014 Evaluation of aerobic and anaerobic co-digestion of tetraselmis suecica and oil palm empty fruit bunches by response surface methodology *Adv. Mater. Res.* 925 243–7 https://www.scientific.net/AMR.925.243

[38] Badan Pusat Statistik 2017 *Statistik Kelapa Sawit Indonesia 2016* [2016 Indonesian Palm Oil Statistics] [Online] from https://www.bps.go.id/publication/2017/11/10/5c499b50899da29bb2a148e/statistik-kelapa-sawit-indonesia-2016.html [Accessed on 1 Mei 2018] [in Bahasa Indonesia]

[39] GAPKI 2018 *Refleksi Industri Kelapa Sawit 2017 dan Prospek 2018* [Reflections on the 2017 Palm Oil Industry and 2018 Prospects] [Online] from https://gapki.id/news/4140/refleksi-industri-kelapa-sawit-2017-dan-prospek-2018 Accessed on May 17, 2018 [in Bahasa Indonesia]

[40] Rahayu A S, Karsiwulan D, Yuwono H, Trisnavati I, Mulyasari S, Rahardjo S, Hokermin S, and Paramita V 2015 *Handbook POME-to-Biogas: Project Development in Indonesia* (United Stated: Winrock International) https://www.winrock.org/wp-content/uploads/2016/05/CIRCLE-Handbook-2nd-Edition-EN-25-Aug-2015-MASTER-rev02-final-new02-edited.pdf

[41] Wresta A, Saepudin A, Santosa A, Sudibyo H, Andriani D, and Kusnadi 2017 Efficiency analysis of spark ignition biogas genset for electricity power generation *JTEC* 9 67–70 http://journal.utem.edu.my/index.php/jtec/article/view/1837

[42] Syaifudin N, Nurkholis, Handika R, Setyobudi R H 2018 Formulating interest subsidy program to support the development of electricity generation from palm oil mill effluent (POME) biomass: An indonesian case study *MATEC Web Conf.* 164 1–9 https://doi.org/10.1051/matecconf/201816401033

[43] Clarke K R and Owens N J P 1983 A simple and versatile micro-computer program for the determination of “most probable number.” *J. Microbiol. Methods* 1(3) 133–7 http://linkinghub.elsevier.com/retrieve/pii/0167701283000313