Emissions of CH_4 and CO_2 from Wastewater of Palm Oil Mills: A Real Contribution to Increase the Greenhouse Gas and Its Potential as Renewable Energy Sources

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ABSTRACT

Palm oil mill effluent (POME) treatment in Indonesia is still predominant using an open pond system. This system has the weakness of the unknown and uncontrollable value of greenhouse gas (GHG) emissions into the atmosphere. This study estimated GHG emissions (CH_4 and CO_2) from anaerobic ponds and their potential as a renewable energy source and obtain GHG emission conversion coefficients for each kg of COD POME and ton of crude palm oil (CPO). Gas samples were collected using a closed static chamber. GHG sample concentration testing was done using Gas Chromatography with a flame ionization detector (FID) and thermal conductivity detector (TCD). The results showed that the emission rate of CH_4 and CO_2 in the anaerobic pond POME treatment was relatively high, 261.93 and 595.99 g/m^2/day, respectively, equivalent to 48.572 t CO_2-eq/day or 14,571.5 t CO_2-eq/year. CO_2 emissions were greater than two times CH_4 emissions, both spatially and temporally. There was a process of facultative biodegradation, aerobic and or anaerobic process according to the biotic-abiotic environment and the levels of organic components in the substrate. In anaerobic ponds, the optimal requirements for the biodegradation process tended to be unfulfilled, so the emission rate of CH_4 was less than CO_2. The GHG conversion coefficient was obtained, namely each kg of COD from POME emitted 6.266 kg CO_2-eq of GHG; for each m^3 of POME emitted by 0.163 t CO_2-eq of GHG; and 0.556 t CO_2-eq/t CPO. The maximum potential for POME to energy conversion was 1.045 MWe with a power capacity of 8,603 MWh/year.

1. INTRODUCTION

Palm oil-based agroindustry is an essential pillar of community development in Indonesia because it is the largest provider of employment and foreign exchange-earners from the non-oil and gas sector. In 2016, Indonesia produced 33.23 million tons of crude palm oil (CPO) (57% of world production), with 25.1 million tons for exports which generated a foreign exchange of USD 17.8 billion, with a workforce of 5.9 million people (11%) (Ministry of Agriculture, 2016; IPOA, 2017). As a result of high CPO production, a large amount of waste will be generated, including solid waste, liquid waste, and gas. Solid waste such as empty fruit bunches (EFB), fiber, and shells have been used for manufacturing processes and organic fertilizers in plantations. However, palm oils mill effluent (POME) is relatively untapped. Still, in its processing, it produces methane gas (CH_4) as a greenhouse gas (GHG) which causes global warming and climate change (Rahayu et al., 2015; El-Fadel and Massoud, 2001; Wu et al., 2010).

Every processing of one ton of fresh fruit bunches (FFB) produced 0.5-0.7 tons of POME (palm oil mill effluent) (Hassan et al., 2004); 0.75-0.90 m^3 POME (Morad et al., 2008) or every one ton of CPO produced 2.5-3.0 tons of POME (Wu et al., 2010). Furthermore, each ton of FFB produces 20 m^3 of biogas (Alkusma et al., 2016), or every one ton of POME was equivalent to 28 m^3 of biogas (Yacob et al., 2006; Lam and Lee, 2011). The results of research

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by Yacob et al. (2006), in Malaysia, found that one ton of POME would produce 12.36 kg of methane, similar to the report of 13.1 kg of methane by Pehnelt and Vietze (2013). In addition, one kg of chemical oxygen demand (COD) from POME, is equivalent to 0.238 kg of methane emissions. Other studies have found 6.54 kg of methane, equivalent to 137 kg of CO_2-eq (Schuchardt et al., 2008), and 6.67 kg of methane, equivalent to 163 kg of CO_2-eq (Suprihatin et al., 2012), emitted for each ton of fresh fruit bunches (FFB) processed.

The degradation of organic matter in POME in Indonesia is predominantly carried out conventionally with a ponding system and is still minimal in maintenance. This wastewater treatment system emits biogas as greenhouse gas (GHG), with the main composition of CH_4 and CO_2, into the atmosphere in unknown and uncontrolled quantities (Wu et al., 2010). Greenhouse gas (CH_4 and CO_2) accounts for more than 90% of all emissions from POME in palm oil mills (Rahayu et al., 2015; Hosseini and Wahid, 2015). The amount of biogas-methane emissions from wastewater treatment in palm oil mills is influenced by oil palm harvest season, the operational method of the palm oil mills (Yacob et al., 2006), POME organic matter content, type of wastewater treatment pond, work system for degradation of organic matter, the type and efficiency of the bioreactor (Ohimain and Izah, 2017), as well as the presence or absence of methane capture (Moriarty et al., 2014). Biogas-methane emissions would be proportional to the levels of organic matter in POME. Nutrient levels in organic matters are part of the nutrient cycle that occurs continuously in nature. Wastewater treatment through aerobic, facultative, and anaerobic processes would involve microorganisms and respiration-oxidation-reduction processes that produced CO_2 and or CH_4. Different compositions differed depending on the type and biodegradation process that occurs. Therefore, Indonesia, as the world's largest producer of CPO, reaching 40.5 million tons in 2018 (Ministry of Agriculture, 2018), with POME production of around 121.5 million cubic meters, will be a significant source of GHG emission contributors.

Globally, GHG from anthropogenic and natural sources includes CO_2 74%, CH_4 16%, N_2O 10%, and HFC, PFC, SF6, and CFC 1% (Tanaka, 2009). The dominant GHG emissions from POME processing are CH_4 and CO_2. In a study on GHG emissions, the value of GHG emissions was equated to CO_2 emissions based on their respective global warming potential (GWP) values. Apart from being a pollutant and GHG emitted into the atmosphere, biogas-methane is also a very potent renewable energy source. A palm oil mills (POM) with a capacity of 45 tons of FFB/hour could generate an electrical energy capacity of 1.25 MW (equivalent to 9,137 MWh/year) (Moriarty et al., 2014). However, few POM convert POME into energy (5%) (Lam et al., 2019; Taniwiryono et al., 2016).

In developing a strategy for reducing GHG emissions in palm oil mills, information on optimal performance and developing biogas-methane capture in POME processing is needed. For this reason, information on GHG emissions from anaerobic ponds in wastewater treatment plants (WWTP) is required. Especially in WWTP with multiple feeding systems based on direct measurements in the field, which has never been reported. Therefore, this research was conducted to estimate GHG emissions (CH_4 and CO_2) from anaerobic ponds based on direct measurements in the field and calculate their potential as a renewable energy source.

2. METHODOLOGY

2.1 Sriwijaya palm oil Indonesia mill

The palm oil mill of this study has a processing capacity of 30 tons of FFB/hour, located in Talang Kelapa District, Banyuasin Regency, South Sumatra Province (-2.826S, 104.732E). This factory belongs to the PT SPOI group of companies, processing FFB from the company itself and the plantations of the surrounding community. The writer conducted his research at the WWTP of the mill in an anaerobic pond (AP). The WWTP facility consists of seven ponds, namely three deoiling ponds, one cooling pond, and three anaerobic ponds (AP). The study was in anaerobic ponds I and II (AP2-AP1, which are functionally connected) with a depth of 6 meters and a total volume of 40,519 m^3. Wastewater flow path in AP2-AP1 combined pond: enters inlet AP2 to AP1 back to AP2 and finally at outlet AP2. Furthermore, the AP2 outlet to the AP3 inlet continues to the AP3 outlet (end of the WWTP) for land application.

2.2 Gas sampling and GHG concentration tests

The capture of biogas used closed static chambers, which were made of polypropylene (PP) material, was in the form of a cylinder with a size of 0.30 × 0.28 × 0.415 m (top diameter × bottom diameter × height), chamber's volume 0.02742 m^3 and a cross-sectional area of 0.07 m^2 (Figure 1). The containment volume became 25.44 liters when the application was above the anaerobic pond, with 3 cm submerged under the surface of the pond (effective height of the containment 0.385 m). The chamber was positioned at three locations, one each in the inlet, middle, and outlet of the anaerobic ponds (combined AP2-AP1) (Figure 2). The distance between chamber S1 to chamber S2 and chamber S1 to chamber S3 was 118 meters. The chamber placement was carried out proportionally and took into account the performance of the anaerobic pond.

(a) (b) (c)

Figure 1. Closed static chamber for capturing biogas (CH_4 and CO_2) on site, (a) inlet, (b) midle, and (c) outlet

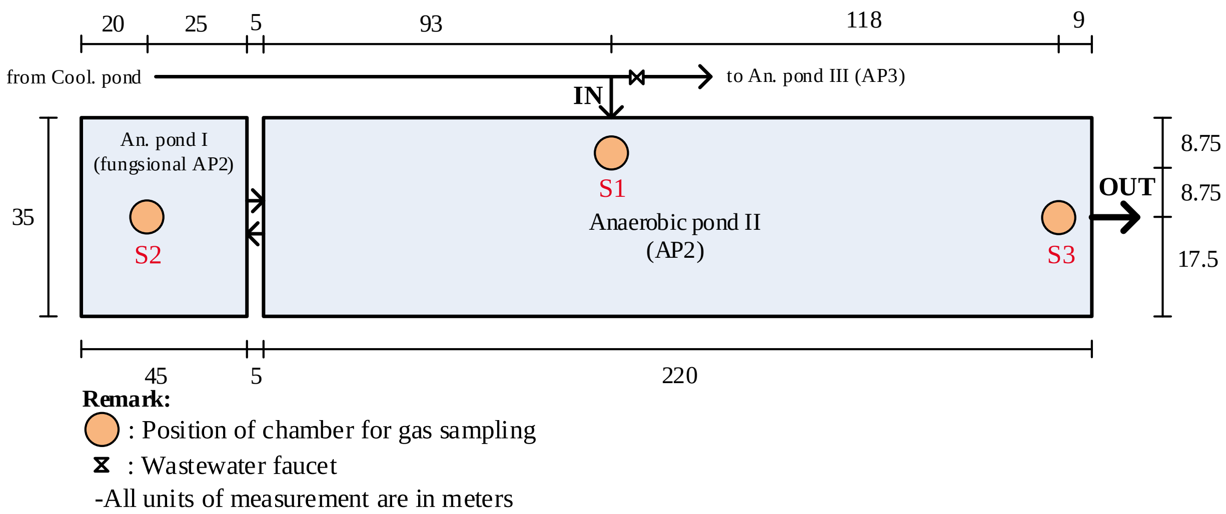

Figure 2. Placement of closed static chamber in an anaerobic pond

The chamber had a septum (rubber) and an air thermometer installed. For the homogeneity of the gas mixture in the chamber, it was equipped with a DC 6 Volt (1,500 rpm) electric fan with a size of 6×6 cm that was turned on when the sampling period was done. The septum was used to allow the insertion of syringes to take gas samples. The glass thermometer was used to measure the temperature of the chamber room air and was mounted tightly on the top of the chamber.

Biogas sampling with a syringe equipped with a faucet and a lever to pull it from the lid and push it into the 10 mL sample container (vial) bottle. Before using the vial, the tube had been made airtight (vacuum). Biogas sampling time intervals were 0, 10, 20, and 30 minutes (n=4). In the morning period (08.00), afternoon (12.00), and evening (18.00), as well as at three sampling locations in AP2-AP1 (inlet, middle, and pond outlet), 36 samples were obtained per day, carried out in three days (n=3) May 12 and 17, and June 23, 2019.

At each observation period, vials containing biogas samples were collected and stored in refrigerated containers and immediately sent to the laboratory for CH_4 and CO_2 gas concentration testing. Biogas samples were analyzed by using a Gas Chromatography (GC-Shimadzu 14A) equipped with a flame ionization detector (FID) for methane and thermal conductivity detector (TCD) for CO_2 gas analysis (Setyanto et al., 2014). The gas sample test was carried out in the Agricultural Environment Research Institute, Pati Regency, Central Java.

2.3 Monitoring the characteristics of POME and anaerobic pond wastewater

Wastewater sampling was carried out at three points: WWTP inlet (deoiling pond), around the AP2 inlet, and outlet. Each was carried out in palm oil mills operations in the morning (09.00) and evening (16.00). The results of the wastewater test are averaged so that each sampling point obtained one data per day. The test variables for wastewater characteristics are volatile solid (VS), COD, pH, ORP, POME temperature, and AP2 wastewater temperature. VS was with the Standard Methods for the Examination of Water and Wastewater (APHA, 1998) and COD variable with the colorimetric method using COD-Vario Photometer-System, Lovibond. Variable pH, ORP, temperature with a potentiometric method using Adwa AD-111 portable pH meter. AP2 wastewater temperature at a depth of 15 cm below the pond water's surface, with hourly measurements for 24 h/day using the HOBO-MX2203 temperature logger.

2.4 Data analysis

Methane and carbon dioxide emissions as the dominant compounds from greenhouse gases in POME processing are calculated according to the formula from IAEA (1992), Lantin et al. (1995), and Setyanto et al. (2014):

$$E = \frac{dc}{dt} \times \frac{Vch}{Ach} \times \frac{Wm}{Vm} \times \frac{273.2}{273.2+T} \quad (1)$$

Where; E is CH_4 or CO_2 emissions/flux (mg/m^2/min); dc/dt difference in CH_4 or CO_2 concentration per unit time (ppm/min) (as linear slope regression of time and CH_4 or CO_2 concentration, with R^2≥85%) (Paredes et al., 2015); Vch is containment volume (m^3); Ach is an area of containment (m^2); Wm is CH_4 or CO_2 molecular weight, 16.04.10^3 and 44.01.10^3 mg, respectively; Vm is molecular volume CH_4 or CO_2 (22.41.10^{-3} m^3); and T is average chamber air temperature during sampling (°C). CH_4 and CO_2 calculations are corrected with standard temperature and pressure (0°C and 1 atm).

The calculated value using equation (1) was used to obtain the value of methane emissions (mg/m^2/hour) according to the sampling period morning-afternoon-evening. To obtain all daytime data, periods of 8:00 to 18:00 and hourly intervals were carried out by interpolation (Chen et al., 2011; Khokhar dan Park, 2017). The "pchip" (cubic hermite) interpolation method was used. Calculation and data processing of the following interpolation process was with the Matlab R2017b program.

The total methane and carbon dioxide emission rates per sampling location per day were calculated by integrating the emission value per hour using the Simpson numerical method (Arif et al., 2015; Putro et al., 2019), as follows:

$$\int_a^b f(x)\,dx = \frac{b-a}{6}\left[f(a) + 4f\left(\frac{a+b}{2}\right) + f(b)\right] \quad (2)$$

Where; f(x) is the total emissions of CH_4 or CO_2 (mg/m^2/day); a is the initial hour of measurement of emissions and b is the final hour of measurement of emissions.

The potential energy generation capacity from POME conversion through anaerobic degradation was calculated using the following formula (IPCC, 2006; Rahayu et al., 2015):

$$\text{Power generation capacity} = CH_4 \text{ production} \times 35.7 \times 0.4 \times [1/(3.6 \times 24 \times 1000)] \quad (3)$$

$$\text{Power capacity} = \text{Power generation capacity} \times 8{,}760 \times 0.94 \quad (4)$$

$$CH_4 \text{ production} = \text{COD-loading} \times 0.2102 \quad (5)$$

$$\text{COD-loading} = \text{COD-removed} \times \text{POME production} \times 10^{-3} \quad (6)$$

Where; power generation capacity in MWe; CH_4 production in Nm^3/day; net calorific value (NCV) CH_4 35.7 MJ/Nm^3; engine efficiency 0.4 (Rahayu et al., 2015); conversion coefficient 1 kWh/3.6 MJ; power capacity in MWh/year; conversion coefficient hour/year 8,760; availability factor 0.94; COD-loading in kg/day; COD-removed in mg/L; POME production in m^3/day; CH_4 production in Nm^3/day; conversion coefficient Nm^3/kg COD-removed 0.2102 (Putro, 2021).

3. RESULTS AND DISCUSSION

3.1 Organic matter content and biodegradation of POME in the ponding system

Raw POME had an average COD level in the WWTP inlet, anaerobic pond II (AP2) inlet, and outlet, of 56,277, 32,608, and 6,541 mg/L, respectively (Table 1). It appeared that there had been a decrease in COD values since the WWTP inlet to the AP2 inlet and the inlet to the AP2 outlet; the mean values were

23,669 (42.06%), 26,067 mg/L (46.32%), respectively. The average COD removal in anaerobic ponds (AP2-AP1) was 26,067 mg/L (80.05%); this indicated the activity of the POME organic matter degradation by microorganisms and biogas (dominant composition CH_4 and CO_2) is produced in the WWTP system, especially in anaerobic ponds (Seadi et al., 2008; Lam and Lee, 2011; Choong et al., 2017).

The decrease in COD also occurred between the WWTP inlet (deoiling pond) to the AP2 inlet (23,669 mg/L). The value is almost the same as the COD removal from the AP2 inlet to an outlet (26,067 mg/L). The decrease in COD was due to the deoiling of the four initial WWTP ponds (deoiling ponds three and cooling pond one) to be returned to the fat-pit tank. In addition to oil-fat quoting, it is suspected that there has been aerobic degradation of POME in the four ponds. As a result of the above, there is a significant decrease in COD before POME reaches the AP2 inlet. At the beginning of the WWTP, this high organic matter degradation process is undoubtedly not expected if POME is processed to convert it into energy through an anaerobic bioreactor. The conversion of COD values is expected to occur in anaerobic bioreactors so that maximum biogas-methane is produced for its utilization as an energy source.

The mean value of VS inlet WWTP was 56,853±12,124 mg/L. The COD and VS value of fresh POME (influent) at the WWT inlet location was very high; this proved that the wastewater from processing oil palm fresh fruit bunches contained high organic matter levels. The high levels of organic components could also be indicated by other variables, namely: oil-fat, TS, and VS (Mahajoeno, 2008; Lam and Lee, 2011; Putro et al., 2019). The COD and VS variables in the previous anaerobic biodegradation study had a high enough correlation with the organic components of the substrate (solid and liquid waste), including POME, so that a conversion coefficient (factor) could be determined. The rapid detection of biogas-methane emissions from a substrate or waste was generally calculated using one or two of these variables in a conversion factor (Park and Craggs, 2007; Putro et al., 2019; Putro et al., 2020).

Table 1. AP2 inlet and outlet wastewater quality and organic loading (n=3)

Variable	Mean	Std. dev.	Interval
COD (raw effluent) (mg/L)	56,277	2,914	53,830-59,500
COD (inlet AP2) (mg/L)	32,608	1,882	30,900-34,625
COD (outlet AP2) (mg/L)	6,541	1,482	4,864-7,670
COD-removed (mg/L)[a]	26,067	873	25,210-26,955
COD-removed (%)[a]	80.05	3.65	77.85-84.26
POME inlet AP2 (m^3/day)	297.6	13.6	288.3-313.2
Organic loading rate (kg COD/m^3/day)	0.239	0.015	0.222-0.250
Organic loading (kg COD/day)	7,749.4	157.8	7581.9-7895.2

[a]POME degradation from the AP2-AP1 inlet to the AP2 outlet

An anaerobic process occurs at the bottom-middle of the pond, characterized by low redox potential (ORP) (negative; reduction) and DO close to zero to form biomethane. While in the middle-top (surface) of the pond, the aerobic process occurs with moderate ORP (zero to positive; oxidation) and a higher DO value (influenced by the interaction between POME and ambient air above the pond surface), resulting in a CO_2 emission rate>CH_4 (Putro et al., 2019; Nguyen et al., 2019; Deublein and Steinhauser, 2008; Yacob et al., 2006). Methane formation in anaerobic systems would go through a series of process steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, which involved microbes, each of which required the terms and conditions of the substrate (organic components) at specific optimum values (Drapcho et al., 2008; Seadi et al., 2008; Deublein and Steinhauser, 2008; Korres et al., 2013). The biogas-methane resulting from the biodegradation of POME was emitted into the ambient air, increasing the concentration of greenhouse gases in the atmosphere. This biogas-methane emission was influenced by wastewater, biotic and abiotic environmental factors (Drapcho et al., 2008; Seadi et al., 2008; Putro et al., 2019).

Apart from COD, another variable that could indicate a change in organic matter in POME was volatile solid (VS). This variable was a volatile particle that correlated with organic matter, which is converted to biogas-methane. Like the research Putro et al. (2019), methane emission was influenced by COD-R, VS-R, COD-R/N tot-R ratio, and ML-R/N tot-R ratio, with R^2 0.585 (R 0.765). So it means that together, these variables have 58.5% of the ability to determine methane emissions (R^2 or coefficient of determination), and other variables determine 42.5%. In the open pond system, POME treatment (lagoon/ponding system) with minimal maintenance, generally accumulating sludge at the pond's bottom would shorten the HRT and the organic matter biodegradation was not optimal. HRT correlated with the organic loading rate (OLR), had an inverse relationship, the higher the OLR, the shorter the HRT (Seadi et al., 2008; Choong et al., 2017; Ohimain and Izah, 2017). AP2 OLR value was 0.239 kg COD/m^3/day, or the average organic loading rate is 7,749.4 kg COD/day (Table 1). This OLR value was relatively small, characteristic of POME treatment in open pond systems (Choong et al., 2017). In the pond systems, generally high HRT (>100 days), low OLR (<1 kg COD/m^3/day), more waste ponds, high sludge accumulation, and require more land (Wu et al., 2010; Yacob et al., 2006). OLR that is too low causes the fermentation process (acidogenesis) to run slowly. On the other hand, if the OLR is too high, there will be an overload, and the substrate can inhibit the growth of microorganisms (Speece, 1996). HRT is related to the bioreactor (pond) volume, but HRT is inversely related to OLR. Therefore, it is necessary to optimize between these three variables to achieve maximum POME biodegradation performance.

The process of degradation of the organic matter in POME was strongly influenced by the characteristics of the organic matter and the type of bioreactor (ponding system) used. Open ponding systems had the lowest degradation performance compared to other types of bioreactors, but because they were easy and cheaper to operate, they were still widely used (>85%) (Wu et al., 2010; Ahmed et al., 2015). The use of the open ponding system WWTP has its disadvantages. In this system, biogas-methane is emitted directly into the atmosphere as GHG and is not environmentally friendly. Efforts to capture GHG can be carried out in this pond by building an airtight cover, including using a high-rate anaerobic lagoon system (HRAL) (Wall et al., 2000). HRAL and similar techniques can reduce GHG emissions in CPO production in palm oil mills by >70% (Prasetya et al., 2013; Rahayu et al., 2015) and obtain the benefits of biogas-methane as a renewable energy source from POME conversion.

3.2 Greenhouse gases emissions from POME processing

There had been GHG emissions into the atmosphere in POME processing with an open pond system (open lagoon with multiple feeding systems), in the form of gas methane and carbon dioxide. The mean CH_4 and CO_2 emissions from the combined anaerobic ponds AP2-AP1 were 261.93 and 595.99 g/m^2/day (10.91 and 24.83 g/m^2/hour), respectively, or 1,604.3 and 3,650.4 kg/day in the total effective area of the anaerobic pond 6,125 m^2 (degradation of wastewater by microorganisms was effective 5 m from anaerobic pond side) (Table 2; Figure 3). Methane emission in this study was lower than that of Yacob et al. (2006), in Malaysia, but higher than research of Mahajoeno (2008), in South Sumatra, that reported 759.7 and 179.2 g/m^2/day, respectively. The difference in methane emissions is caused by: the quality of oil palm fresh fruit bunches (FFB), differences in harvest seasons, plant operational systems and methods, wastewater treatment techniques, methane gas testing methods and equipment, and abiotic environmental factors (pond wastewater temperature, rainfall, air temperature) (Seadi et al., 2008; Drapcho et al., 2008; Putro et al., 2019).

Table 2. Emissions and GHG conversion coefficient values on biodegradation of POME

Variable	Unit	Mean
CH_4 emission rate	g/m^2/day	261.932±11.026
CH_4 emission[a]	kg/day	1,604.3±67.5
CO_2 emission rate	g/m^2/day	595.988±126.915
CO_2 emission[a]	kg/day	3,650.4±777.4
CH_4 emission (day) (equivalent)[b]	t CO_2-eq/day	44.921±1.891
CO_2 emission (day) (direct)[b]	t CO_2/day	3.650±0.777
GHG emission from POME (day)	t CO_2-eq/day	48.572±2.296
GHG emission from POME (year)[c]	t CO_2-eq/year	14,571.5
CH_4 emission proportion (GHG from POME)	%	92.48

Table 2. Emissions and GHG conversion coefficient values on biodegradation of POME (cont.)

Variable	Unit	Mean
Conversion coefficient of GHG:		
GHG vs. COD-POME	kg CO_2-eq/kg COD	6.266±0.193
GHG vs. POME volume	t CO_2-eq/m^3 POME	0.163±0.002
GHG vs. POME weight[d]	t CO_2-eq/t POME	0.184
GHG vs. FFB weight[e]	t CO_2-eq/t FFB	0.122
GHG vs. CPO weight[f]	t CO_2-eq/t CPO	0.556

[a]AP2 (220×35 m^2) and AP1 (45×35 m^2), effective area AP2-AP1 6,125 m^2 (effective ebullition process 66% AP2-AP1; factual activity in the field and according to Yacob et al., 2006)
[b]GWP CO_2 and CH_4 1 and 28, respectively (https://www.ipcc.ch/report/ar5/wg3/; Fifth Assessment Report; AR5, 2014)
[c]Assuming an average of 300 effective working days per year
[d]Density of POME 1,13 kg/L (Lam and Lee, 2011)
[e]0.75 m^3 POME/t FFB (Yuliasari et al., 2001; Morad et al., 2008)
[f]An average yield CPO 22% (field data)

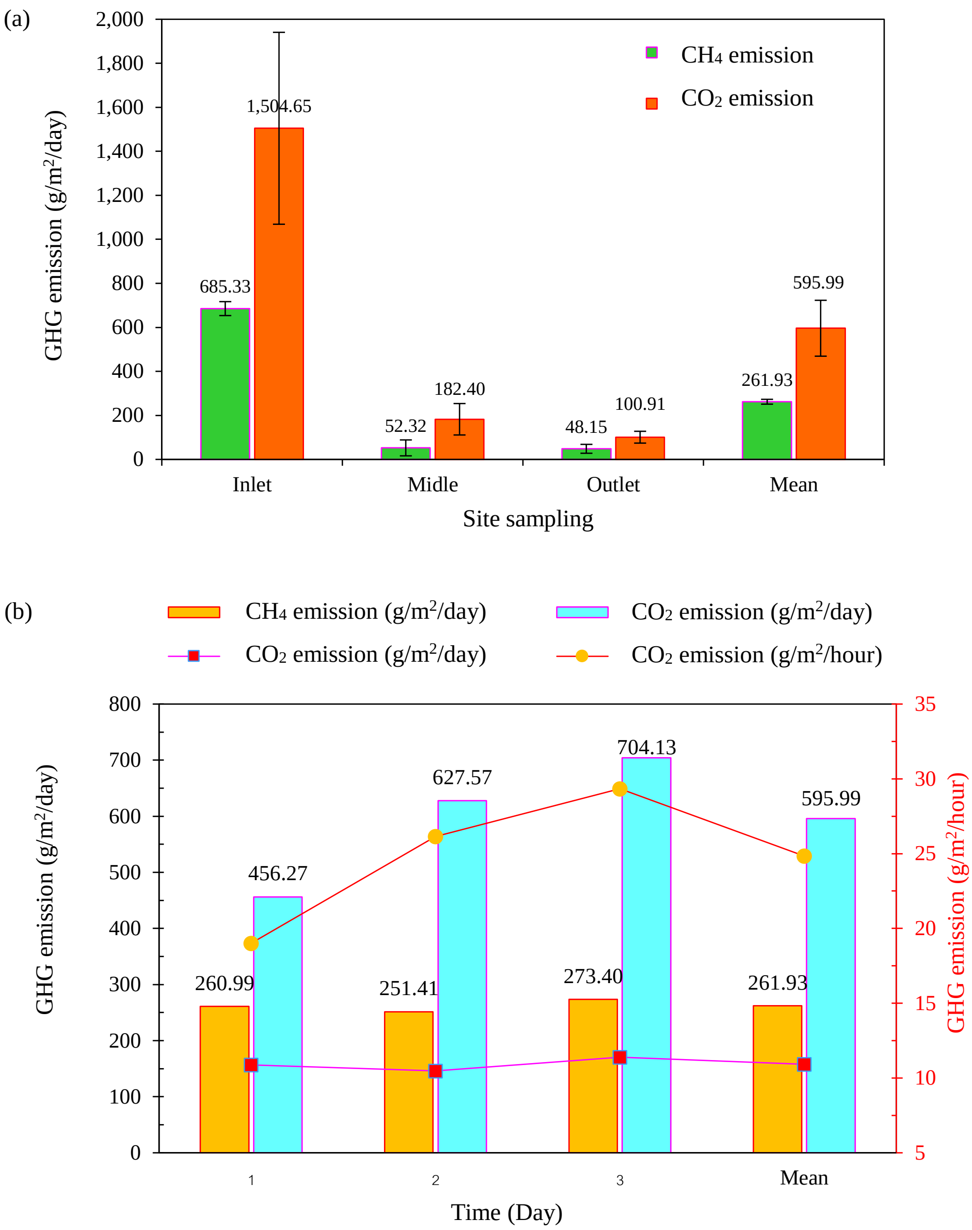

Figure 3. The dynamics of anaerobic pond GHG emissions based on, (a) sampling location and (b) sampling time

The highest CH_4 and CO_2 emissions occurred around the AP2 inlet, then around the middle AP2-AP1 location, and the lowest was around the AP2 outlet. The composition of CO_2 gas was more than two times the value of methane gas at each of these sampling locations (Figure 3(a)). It showed that the gradual and regular biodegradation of POME from inlet to outlet was proportionate to the gradual decrease in organic matter content from inlet to AP2-AP1 outlet. The dynamics of GHG emissions also occurred with an increasing trend from day 1 to day 3, which was caused by an increase in the amount of wastewater received by the anaerobic pond (288.3 to 313.2 m^3/day), although the level of COD degraded slightly decreased (26,955 to 25,210 mg/L). But the main thing is that CH_4 also follows the increase in CO_2 emission rates. This can be seen in various spatial (inlet-center-outlet locations) and temporal (days 1 to 3) conditions (Figure 3(a) and Figure 3(b)). This indicates that the biodegradation process occurs facultatively (aerobic and or anaerobic) under biotic-abiotic environments and substrate levels from various depths and locations in anaerobic ponds (AP2-AP1). In addition, the optimization requirements for anaerobic degradation processes tend not to be met, so that the emission rate of $CH_4<CO_2$ (Deublein and Steinhauser, 2008; Korres et al., 2013).

GHG emissions around the location of the highest AP2 inlet and influenced by the levels of COD variable. COD at the AP2 inlet was the highest compared to others (Table 1). The COD variable has a high correlation with GHG emissions, but this generally does not stand alone. The value of GHG emissions was also influenced by the role of other variables that have a moderate-high correlation with GHG emissions, such as volatile solids (VS), ORP, substrate temperature (waste pond water) (Putro et al., 2020; Putro, 2021). The decreasing value of GHG emissions from the inlet to outlet was in line with the reduction of the COD value. The decrease in GHG indicates that biodegradation of organic matter from POME has occurred in the anaerobic pond, resulting in the emission of biogas-methane into the atmosphere.

The optimum requirements for the hydrolysis and acidogenesis (fermentation) phases (temperature 25-35°C and pH 4.0-6.3) and the methanogenesis phase have been met (mesophilic temperature 30-40°C, pH 6.7-7.5, and Eh<-250 mV) at the AP2 inlet location (Table 3). These variables are the limiting variables for the rate of anaerobic biodegradation (Batstone, 2006; Putro, 2021). Several other conditions that explain this are: the optimum pH is achieved when the POME fed to the AP2 inlet mixes with the wastewater in the pond, the pH changes rapidly from 4.46 to 7.00 (optimum methanogenesis phase was achieved that is pH 6.7-7.5) (Putro, 2021; Deublein dan Steinhauser, 2008; Korres et al., 2013). Likewise, the optimum redox potential variable of the methanogenesis phase (Eh<-250 mV) was probably reached during the process from the bottom-center anaerobic pond. This was supported by the presence of gas bubbles during field observations, starting from the bottom-center of the pond zone without and or minimum oxygen (DO approaching 0 mg/L) towards the surface of the pond. Finally, biogas (CH_4 and CO_2) are released into the atmosphere (Nguyen, 2018). The phenomenon of active bubbles was very clearly visible around the inlet and was very active (high), especially in the morning to noon, compared to other locations (around the AP2 outlet and the middle of the AP1 pond), so this was an indicator that GHG emission rates occurred (CH_4 and CO_2) at that location (Mahajoeno, 2008; Yacob et al., 2006). The evidence above supports the arguments to that the location around the inlet had the highest GHG emissions compared to others.

Table 3. Value of pH, ORP, and temperature of anaerobic pond wastewater II (n=3)

Variable	Unit	Inlet		Outlet	
		Mean	Interval	Mean	Interval
pH	-	4.60±0.12	4.48-4.72	7.1±0.13	7.03-7.26
Eh	mV	147.2±6.5	141-154	(-18.2)±1.3	(-19.5)-(-17)
T_{POME}[a]	°C	44.3±1.2	43.0-45.3	31.6±0.7	30.8-32.1
T_{WW}[b]	°C	34.1±0.1	34.1-34.2	32.6±0.2	32.4-32.7

[a]Average POME temperature in the morning (09.00) and evening (16.00) sampling
[b]Average temperature of wastewater in AP2 for one day (24 hours)

The value obtained of GHG emissions, as CO_2 gas equivalents, from POME processing in palm oil mill was 48.572 t CO_2-eq/day, or 14,571.5 t CO_2-eq/year (Table 2). The value of GHG emissions (CH_4 and CO_2) in POME treatment in palm oil mills was different from previous studies, some are higher, and some are lower. However, from this study, the GHG emissions are almost the same as Suprihantin et al. (2012) (14,690.5 t CO_2-eq/year) (Table 4). The difference in GHG emissions is due to, among others: quality (variety and origin) of FFB, harvest season, FFB processing techniques, wastewater treatment systems, climatic factors (rainfall and air temperature), POME temperature, type of pond (bioreactor), levels of components organic matter of POME, and the amount of research data.

Table 4. GHG emission from palm oil mill effluent treatment

GHG emissions at 30 t FFB/hour ($t\ CO_2$-eq/year)	Reference
30,596[a]	Foong et al. (2021)
21,381.2[a]	Febijanto (2018)
26,091[b]	Moriarty et al. (2014)
10,670[a]	Sarono (2014)
14,690.5[a]	Suprihatin et al. (2012)
12,927	Febijanto (2010)
14,571.5	This study

[a]Calculated from POM 60 t FFB/hour
[b]Calculated from POM 45 t FFB/hour (GHG 39,136 t CO_2-eq/year)

From this research, it was also obtained that every kg of COD POME would emit 6.266 kg of CO_2-eq GHG, and every m^3 of POME would emit 0.163 t CO_2-eq of GHG; and 0.556 t CO_2-eq per ton of CPO produced, and 0.122 t CO_2-eq per ton of FFB processed, would be emitted (Table 2). These figures are new findings, and conversion factors (coefficients) helpful for a quick calculation of GHG emissions from POME in palm oil mills. This value was an initial estimate so that further and broader studies are needed at various mills with different operational conditions, climates, and sources (varieties and origins) of FFB. The conversion coefficient of 0.556 was almost the same as the results of the study of Rahayu et al. (2015) (0.51 t CO_2-eq/t CPO). This value was closely related to the yield of CPO, which was influenced by the efficiency of mill processing and the quality of processed FFB.

The methane emissions in the palm oil mill are the main part (92.48%) compared to CO_2 (7.5%) in GHG originating from POME processing in the WWTP (Table 2). Furthermore, GHG emissions resulting from POME processing constitute the largest share of GHG from palm oil mills (>90%) (Rahayu et al., 2015; Hosseini and Wahid, 2015). Therefore, controlling and reducing GHG emissions from POME must be essential for a palm oil mill. The utilization of methane from POME as a renewable energy source is an activity that needs to be done immediately for the palm oil industry, thus making the industry more environmentally friendly and sustainable. Several strategic efforts to control and reduce GHG from palm oil mills include the need for government regulations that encourage and require methane gas capture for conversion into energy and the active role of business actors in the palm oil sector. Another benefit obtained from the conversion of POME to energy is the certified emission reduction (CER) value in the clean development mechanism (CDM) scheme.

3.3 Potential for POME conversion to renewable energy

GHG emissions from POME biodegradation through anaerobic degradation would produce biogas as a renewable and sustainable energy source. Biogas has main contents of methane and carbon dioxide, respectively, of 45-80% and 20-55% (Coombs, 1991); 55-70% and 30-45% (Deublein and Steinhauser, 2008). With the optimum average POME production of 450 m^3/day, using a conversion coefficient of 0.2102 kg CH_4/kg COD (Putro, 2021), the efficiency of degradation of the organic components of WWTP is 85% (Rahayu et al., 2015), average COD of fresh POME was 56,277 mg/L (Table 1). The potential for maximum generating electricity from biogas power plants from palm oil mills with an installed capacity of 30 tons of FFB/hour was 1.045 MWe or 8,603 MWh/year (Table 5). This value was almost the same as the calculation in research by Rahayu et al. (2015) equal to 1.1 MWe.

The value of potential energy generation from POME conversion in palm oil mills varies. From the results of previous studies, POM installed capacities of 30, 45, 60, and 90 tons of FFB/hour, each of which has the potential to generate power of 0.53-1.10, 1.25-1.60, 0.74-2.10, 3.2 MWe (Rahayu et al., 2015; Febijanto, 2010; Moriarty et al., 2014; Taniwiryono et al., 2016). The optimum value for energy generation could be achieved through various efforts, including optimization of microbial performance for anaerobic biodegradation, high levels of substrate organic components, biogas purification (increasing methane levels by removing water vapor, hydrogen sulfide, and CO_2), using high-efficiency gas engines (>42%), choose a bioreactor technology with high performance (high COD removal, equivalent to high conversion of COD to methane) (>80-95%). In addition, there is a need for operational-maintenance management capabilities in balancing: OLR (substrate), HRT, bioreactor volume, and optimal organic matter content for maximum biodegradation performance. Other efforts to achieve biodegradation performance with maximum biogas-methane yield through a biotechnology approach include (1) co-digestion; (2) pre-treatment (through oil extraction, precipitation, and pre-hydrolysis); (3) addition of inorganic supplements; (4) addition of biological supplements; and (5) modification of bioreactors (Choong et al., 2017; Aziz et al., 2019).

Table 5. Potential energy generation capacity maximum of POME conversion to renewable energy

Measurement (estimation)	Unit	Potential
POME fed to AP2-AP1	m^3 POME/day	450[a]
COD-removed	mg/L	47,835[b]
Conversion coefficient (COD to CH_4)	kg CH_4/kg COD	0.2102[c]
COD loading	kg COD/day	21,526
CH_4 production (unit weight)[d]	kg CH_4/day	4,524
CH_4 production (unit volume)	m^3 CH_4/day	6,321
Energy value CH_4[e]; (1 kWh = 3,6 MJ)	MJ/m^3 CH_4	35.7
Engine gas efficiency[e]	%	40
Energy generation capacity (electricity)	MWe	1.045
Availability factor[e]	%	94
Power capacity (electricity) per year	MWh/year	8,603

[a]Potential of POME production per day (30 tons of FFB/hour × 20 hours × 0.75 m^3 POME/ton FFB) (Morad et al., 2008)
[b]COD-removed potential (optimization of WWTP); raw POME COD 56,277 mg/L and 85% COD-efficiency (Rahayu et al., 2015; 80-95%)
[c]Convertion coefficient COD-removed to CH_4, according to Putro (2021)
[d]CH_4 density 0.7157 kg/m^3 (16.04 g/22.41 L; at STP 0°C and 1 atm)
[e]According to Rahayu et al. (2015)

The development of POME conversion into bio-energy that could reduce its GHG through the various efforts above is an opportunity for future anaerobic digester technique research, with the application of effective-efficient and high-performance biotechnology. It is hoped that this can increase the value of energy output and achieve economic value. So that with an economical price, new and renewable energy (NRE) from POME conversion is competitive compared to other NRE sources (water, wind, solar, geothermal, ocean waves, and other biomass).

4. CONCLUSION

POME processing at the palm oil mill in anaerobic ponds emitted relatively high CH_4 (261.93 g/m^2/day) and CO_2 (595.99 g/m^2/day), equivalent to 48.572 t CO_2-eq/day or 14,571.5 t CO_2-eq/year. The average CO_2 emissions are greater than two times the average CH_4 emissions, both spatially (site) and temporally (time). There was a facultative, aerobic, and or anaerobic biodegradation process according to the interaction between the environment components of the biotic and abiotic and the organic content of the substrate. In the anaerobic pond, the optimum requirements for the anaerobic biodegradation process tended to be unfulfilled so that the emission rate of CO_2>CH_4. The GHG conversion coefficients were obtained for each kg of COD POME emitted 6.266 kg CO_2-eq, and each m^3 of POME emitted 0.163 t CO_2-eq and would be emitted 0.556 t CO_2-eq/t of CPO. The potential for conversion of POME into energy from a palm oil mill of 30 t FFB/hour was a maximum of 1,045 MWe and a power capacity of 8,603 MWh/year.

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REFERENCES

Ahmed Y, Yaakob Z, Akhtar P, Sopian K. Production of biogas and performance evaluation of existing treatment processes in palm oil mill effluent (POME). Renewable and Sustainable Energy Reviews 2015;42:1260-78.

Alkusma YM, Hermawan, Hadiyanto. Development of alternative energy potential by utilizing palm oil liquid waste as a new renewable energy source in East Kotawaringin Regency. Jurnal Ilmu Lingkungan 2016;14(2):96-102.

American Public Health Association (APHA). Standard Methods for the Examination of Water and Wastewater. Washington DC, USA: American Public Health Association, American Water Works Association, and Water Environment Federation; 1998.

Arif C, Setiawan BI, Widodo S, Rudiyanto, Hasanah NAI, Mizoguchi M. Development of artificial neural network models to estimate greenhouse gas emissions from rice fields with various water regimes. Jurnal Irigasi 2015;10(1):1-10.

Aziz MMA, Kassim KA, Elsergany M, Anuar S, Jorat ME, Yaacob H, et al. Recent advances on palm oil mill effluent (POME) pretreatment and anaerobic reactor for sustainable biogas production. Renewable and Sustainable Energy Reviews 2019;119:1-14.

Batstone DJ. Mathematical modelling of anaerobic reactors treating domestic wastewater: Rational criteria for model use. Reviews in Environmental Science and Biotechnology 2006;5:57-71.

Chen W, Wolf B, Zheng X, Yao Z, Butterbach-Bahl K, Brüggemann N, et al. Annual methane uptake by temperate semiarid steppes as regulated by stocking rates, aboveground plant biomass and topsoil air permeability. Global Change Biology 2011;17:2803-16.

Choong YY, Chou KW, Norli I. Strategies for improving biogas production of palm oil mill effluent (POME) anaerobic digestion: A critical review. Renewable and Sustainable Energy Reviews 2017;82:2993-3006.

Coombs J. The Present and Future of Anaerobic Digestion. New York, USA: Elsevier Science Publishing Co.Inc.; 1991.

Deublein D, Steinhauser A. Biogas from Waste and Renewable Resources an Introduction. Weinheim, Germany: Wiley-VCH Verlag GmbH and Co. KGaA; 2008.

Drapcho CM, Nhuan NP, Walker TH. Biofuels Engineering Proces Technology. USA: McGraw-Hill Companies Inc.; 2008.

El-Fadel M, Massoud M. Methane emissions from wastewater management. Environmental Pollution 2001;114(2):177-85.

Febijanto I. Potential for catching methane gas and its use as fuel for power generation at PTPN VI Jambi. Jurnal Ilmiah Teknologi Energi 2010;1(10):30-47.

Febijanto I. Optimization of methane gas use as energy resource in palm oil mill as an anticipated selling price of electricity based on the existing average cost of generation. Jurnal Teknologi Lingkungan 2018;19(1):49-60.

Foong SZY, Chong MF, Ng DKS. Strategies to promote biogas generation and utilisation from palm oil mill effluent. Process Integration and Optimization for Sustainability 2021;5: 175-91.

Hassan MA, Yacob S, Shirai Y. Treatment of palm oil wastewaters. In: Wang LK, Hung Y, Lo HH, Yapijakis C, editors. Handbook of Industrial and Hazardous Wastes Treatment. New York, USA: Marcel Dekker, Inc.; 2004. p. 719-36.

Hosseini SE, Wahid MA. Pollutant in palm oil production process. Journal of the Air and Waste Management Association 2015;65(7):773-81.

Indonesian Palm Oil Association (IPOA). Palm Oil Industry Reflection 2016 and Prospects 2017. Jakarta, Indonesia: Indonesian Palm Oil Association; 2017.

Intergovernmental Panel on Climate Change (IPCC). IPCC Guidelines for National Greenhouse Gas Inventories: Volume 1-5. Hayama, Japan: Institute for Global Environmental Strategies; 2006.

International Atomic Energy Agency (IAEA). Manual on Measurement of Methane and Nitrous Oxide Emissions from Agriculture. Vienna, Austria: Food and Agriculture Organization of The United Nations and International Atomic Energy Agency; 1992.

Khokhar NH, Park J. A simplified sampling procedure for the estimation of methane emission in rice fields. Environmental Monitoring and Assessment 2017;189:1-10.

Korres NE, O'Kiely P, Benzie JAH, West JS. Bioenergy Production by Anaerob Digester, Using Agricultural Biomass and Organic Waste. Maryland, USA: Taylor and Francis; 2013.

Lam MK, Lee KT. Renewable and sustainable bioenergies production from palm oil mill effluent (POME): Win-win strategies toward better environmental protection. Biotechnology Advances 2011;29:124-41.

Lam WY, Kulak M, Sim S, King H, Huijbregts MAJ, Chaplin-Kramer R. Greenhouse gas footprints of palm oil production in Indonesia over space and time. Science of the Total Environment 2019;688:827-37.

Lantin RS, Aduna JB, Javeliana AM. Methane Measurements in Rice Fields. Manila, Philippines: International Rice Research Institute; 1995.

Mahajoeno E. Development of Renewable Energy from Palm Oil Mill Wastewater [dissertation]. Bogor, Indonesia: Bogor Agricultural Institute; 2008.

Ministry of Agriculture. Statistics of Indonesian Estates 2015-2017 Palm Oil. Jakarta, Indonesia: Ministry of Agriculture; 2016.

Ministry of Agriculture. Tree Crop Estate Statistics of Indonesia 2017-2019 Palm Oil. Jakarta, Indonesia: Ministry of Agriculture; 2018.

Morad N, Choo SS, Hoo YC. Simplified life cycle assessment of crude palm oil: A case study at a palm oil mill. Proceedings of the International Conference on Environmental Research and Technology 2008 (ICERT 08); 2008 May 28-30; Parkroyal Hotel, Pulau Pinang: Malaysia; 2008.

Moriarty K, Elchinger M, Hill G, Katz J, Barnett J. Methane for Power Generation in Muaro Jambi: A Green Prosperity Model Project. Colorado, USA: National Renewable Energy Laboratory (NREL); 2014.

Nguyen D, Wu Z, Shrestha S, Lee PH, Raskin L, Khanal SK. Intermittent micro-aeration: New strategy to control volatile fatty acid accumulation in high organic loading anaerobic digestion. Water Research 2019;166:1-10.

Nguyen DM. Oxidation-Reduction Potential-Based Micro-Aeration Control System for Anaerobic Digestion [dissertation]. Honolulu, USA: University of Hawaii at Mānoa; 2018.

Ohimain EI, Izah SC. A review of biogas production from palm oil mill effluents using different configurations of bioreactors. Renewable and Sustainable Energy Reviews 2017;70:242-53.

Paredes MG, Güerecaa LP, Molinab LT, Noyolaa A. Methane emissions from stabilization ponds for municipal wastewater treatment in Mexico. Journal of Integrative Environmental Sciences 2015;12(SI):139-53.

Park JBK, Craggs RJ. Biogas production from anaerobik waste stabilisation ponds treating dairy and piggery wastewater in New Zealand. Water Science and Technology 2007; 55(11):257-64.

Pehnelt G, Vietze C. Recalculating GHG emissions saving of palm oil biodiesel. Environmental Monitoring and Assessment 2013;15:429-79.

Prasetya H, Arkeman Y, Hambali E. Role of methane capture for sustainable biodiesel production from palm oil: A life cycle assessment approach. International Journal on Advanced Science, Engineering and Information Technology 2013;3(5):17-20.

Putro LHS, Budianta D, Rohendi D, Rejo A. Biomethane emissions: Measurement in wastewater pond at palm oil mill by using TGS2611 methane gas sensor. Journal of Ecological Engineering 2019;20(6):25-35.

Putro LHS, Budianta D, Rohendi D, Rejo A. Modeling methane emission of wastewater anaerobic pond at palm oil mill using radial basis function neural network. International Journal on Advanced Science, Engineering and Information Technology 2020;10(1):260-8.

Putro LHS. Biomethane from Palm Oil Mill Effluent: An Overlooked Renewable Energy Sources. Depok, Indonesia: Rajawali Pers; 2021.

Rahayu AS, Karsiwulan D, Yuwono H, Paramita V. Guide Book for Converting POME into Biogas: Project Development in Indonesia. Jakarta, Indonesia: Winrock International; 2015.

Sarono. The Greenhouse Gas Reduction Strategy through Conversion of Palm Oil Mill Liquid Waste into Electrical Energy (Case Study in Lampung Province) [dissertation]. Bogor, Indonesia: Bogor Agricultural Institute; 2014.

Schuchardt F, Wulfert K, Darnoko, Herawan T. Effect of new palm oil mill processes on the EFB and POME utilization. Journal Oil Palm Research 2008;Special Issue:115-26.

Seadi TA, Rutz D, Prassl H, Köttner D, Finsterwalder D, Volk S, et al. Biogas Handbook. Esbjerg, Denmark: University of Southern Denmark; 2008.

Setyanto P, Wihardjaka A, Yulianingsih E, Agus F. Greenhouse gas emissions from drainage channels in Jabiren peatlands, Central Kalimantan. In: Wihardjaka, A, Maftu'ah E, editors. Proceedings of the National Seminar: Sustainable Management of Degraded Peatlands for GHG Emission Mitigation and Economic Value Enhancement; 2014 Aug 18-19; Jakarta: Indonesia; 2014.

Speece RE. Anaerobic Biotechnology for Industrial Wastewaters. Tennessee, USA: Archae Press; 1996.

Suprihatin, Sa'id EG, Suparno O, Sarono. Palm oil mill wastewater potential as an alternative energy sources. Prosiding Seminar Nasional PERTETA; 2012 Nov 30 - Dec 2; Malang: Indonesia; 2012 (in Indonesian).

Tanaka N. Energy Sector Methane Recovery and Use: The Importance of Policy. Paris, France: International Energy Agency (IEA); 2009.

Taniwiryono D, Siswanto, Herman. Policy and Financial Analysis for Development of Biogas Power Plant in Palm Oil Mills "Towards Low Carbon Development in Oil Palm Sector". Jakarta, Indonesia: Coordinating Ministry for Economic Affairs; 2016.

Wall G, Hammond B, Donlon P, Johnson ND, Smith JC. Commissioning and operation of high rate anaerobic lagoon (HRAL) reactors. Proceedings of the 63rd Annual Water Industry Engineers and Operators Conference; 2000 Sep 6-7; Brauer College, Warrnambool: Australia; 2000.

Wu TY, Mohammad AW, Jahim JMd, Anuar N. Pollution control technologies for the treatment of palm oil mill effluent (POME) through end-of-pipe processes. Journal of Environment Management 2010;91:1467-90.

Yacob S, Hassan MA, Shirai Y, Wakisaka M, Subash S. Baseline study of methane emission from anaerobic ponds of palm oil mill effluent treatment. Science of the Total Environment 2006;366:187-96.

Yuliasari R, Darnoko, Wulfred K, Gindulis W. Oil palm wastewater treatment using fixed bed anaerobic reactor down-flow type. Warta Pusat Penelitian Kelapa Sawit 2001;9:75-81.