

Biogas Production Using Continuous Stirred Tank Reactor (CSTR) from Palm Oil Mill Effluent (POME) Utilizing Mesophilic Bacteria

Suratni Afrianti^{1,2*}, Edwina Zainal³

¹Faculty of Agricultural Technology, Universitas Prima Indonesia, North Sumatra, Medan, 20118, Indonesia

²Agro Sustainable Center, Universitas Prima Indonesia, North Sumatra, Medan, 20118, Indonesia

³Department of Civil Engineering, Universitas Bung Hatta, West Sumatra, Padang, 25133, Indonesia

*Corresponding author e-mail: suratniafrianti@unprimdn.ac.id

Abstract

Energy is essential for human life, yet dependence on fossil fuels and other non-renewable resources contributes to global energy crises and environmental degradation. Biogas is an environmentally friendly alternative that has the potential to partially replace fossil fuels. Palm Oil Mill Effluent (POME), which contains high concentrations of biodegradable organic matter, is a promising substrate for biogas production through anaerobic fermentation. This study aims to evaluate the potential of Palm Oil Mill Effluent (POME) as a substrate for biogas production using a Continuous Stirred Tank Reactor (CSTR) under mesophilic conditions (35–37°C). The experiment was conducted for 30 days with at a laboratory scale (10 L reactor volume). Feedstock characterization (COD, TSS, TS, VS, and pH) confirmed that POME has high organic content and slightly acidic conditions, supporting its suitability for anaerobic digestion. The results show that anaerobic fermentation of POME produced biogas with an average methane (CH₄) concentration of 66–71%, indicating stable digestion performance and relatively high efficiency. These methane levels indicate stable digestion performance and relatively high process efficiency. Overall, the findings confirm that POME is a promising feedstock for biogas production and can contribute to renewable, environmentally friendly energy supply.

Keywords

Biodigester, Fermentor, Biogas, Methane, Anaerobic, Mesophilic

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1. INTRODUCTION

Energy is one of the essential needs for humans to carry out various activities in daily life (Zhang et al., 2018). However, the world's energy supply is highly dependent on energy sourced from non-renewable natural resources, leading to a crisis in fossil fuel energy and environmental degradation. The global energy crisis has shifted attention to alternative, non-fossil energy sources or energy derived from renewable natural resources.

One of the non-fossil energy sources is biogas (Chen et al., 2017), which serves as an environmentally friendly alternative to replace fossil fuels. Biogas is produced through the degradation of organic materials by anaerobic bacteria in an oxygen-free environment (Kainthola et al., 2019). One of the raw materials suitable for biogas production is Palm Oil Mill Effluent (POME).

Currently, the management of POME is commonly done using open waste pond technology with anaerobic, facultative, and aerobic pond processes. For every ton of Crude

Palm Oil (CPO), approximately 2.9-3.5 m³ of POME is produced. POME contains a significant amount of organic carbon compounds such as chemical oxygen demand (COD) exceeding 40 g/L and nitrogen content around 0.2 to 0.5 g/L as ammonia nitrogen and total nitrogen (Liew et al., 2021).

The temperature of fresh POME ranges between 80-90°C, with its composition consisting of 95-96% water, 0.6-0.7% oil, and 4-5% total solids, including 2-4% suspended solids, and an acidic pH of 4-5 (Jumadi et al., 2024). POME can be managed both aerobically and anaerobically. Anaerobic treatment is more advantageous for POME management because it can remove more inorganic materials, with available nutrients being limited, and it contains biodegradable constituents with a BOD/COD ratio of 0.5. This indicates that POME can be easily processed biologically. Both POME and empty fruit bunches (EFB) can be utilized for biogas production using anaerobic digestion technology.

Anaerobic digestion is an alternative energy source that

is affordable and environmentally friendly. Anaerobic digestion is defined as the breakdown of organic compounds without the use of oxygen, which produces biogas, with the biogas composition typically consisting of 60% methane (CH_4), 35% carbon dioxide (CO_2), and 5% ammonia (NH_3) (Scamardellaa et al., 2019). Anaerobic digestion can be operated at psychrophilic ($<20^\circ\text{C}$), mesophilic ($30\text{--}40^\circ\text{C}$), or thermophilic ($43\text{--}55^\circ\text{C}$) temperatures (Chow et al., 2020). According to Begum et al. (2020), methane production and total methane yield are more efficient at thermophilic temperatures compared to mesophilic conditions.

Previous studies on the utilization of POME as a raw material for biogas production were conducted by Isa et al. (2020) using operational temperatures of 25°C and 45°C . Research by Hoo et al. (2017) found that POME could replace fossil fuels by 40% - 67%. Hoo et al. (2017) achieved methane production of 74%. Trisakti et al. (2017) conducted a study using varying Hydraulic Retention Times (HRT) of 100, 40, 6, and 4 hours, using a Continuous Stirred Reactor (CSTR), resulting in organic content degradation, specifically Volatile Solid (VS) decomposition and COD removal, with values of 51.56 ± 8.30 and 79.82 ± 6.03 , respectively. Biogas production in the mesophilic range was 31.77 ± 3.46 L/kgVS. Trisakti et al. (2017) produced biogas using a polyvinylidene fluoride (PVDF) ultrafiltration membrane bioreactor. Additionally, research Trisakti et al. (2017) found that the pH remained stable during the process at 7. The alkalinity profile from previous studies indicates that POME has significant potential as a raw material for biogas production.

Previous studies on the utilization of Palm Oil Mill Effluent (POME) as a substrate for biogas production have been conducted by Isa et al. (2020) at operational temperatures of 25°C and 45°C . Hoo et al. (2017) reported that POME has the potential to replace fossil fuels by 40–67% with methane production reaching 74%. Meanwhile, Irvan et al. (2017) investigated various Hydraulic Retention Times (HRT) using a Continuous Stirred Tank Reactor (CSTR), showing significant COD and VS removal as well as stable pH and alkalinity. These findings indicate that POME has considerable potential as a feedstock for biogas production. However, most previous studies have been limited to batch experiments or non-systematic conditions, with few focusing on mesophilic CSTR operation, limited systematic comparison of methane yields, and little consideration of scale-up potential.

However, despite these promising results, most previous studies have been limited to batch experiments or non-systematic conditions, with few focusing specifically on mesophilic CSTR operation, limited systematic comparison of methane yields, and little consideration of scale-up potential. Therefore, this study focuses on investigating the anaerobic digestion of POME using a mesophilic CSTR under controlled operating conditions. The research includes characterization of POME feedstock, analyzing parameters

such as COD, TS, TSS, VS, VSS, protein content, volatile fatty acids (including acetic acid, propionic acid, and butyric acid), and pH. Methane concentration, methane yield, COD/VS removal efficiency, and biogas production rate are measured as the main performance indicators. This approach is expected to provide a more comprehensive understanding of POME's potential for biogas production and contribute to the development of scalable renewable energy solutions.

2. EXPERIMENTAL SECTION

2.1 Materials

The materials used in this study include starter bacteria. POME was obtained from a palm oil mill.

2.2 Equipment

The equipment used in this study includes several main instruments and analytical tools that support the biogas production process. The primary equipment is the CSTR (Continuous Stirred Tank Reactor) shown in Figure 2, which is used for continuous anaerobic fermentation, with temperature and pH controllers to maintain optimal conditions for microbial activity. The stirrer in the reactor ensures that the mixture remains homogeneous throughout the fermentation process. For analysis, a 25 mL buret was used for titration, which helps in measuring parameters such as alkalinity and chemical concentration in the reactor. An analytical balance was used to weigh materials with high precision, such as pH stabilizing chemicals and POME samples. An oven was used to dry samples and measure Total Solids (TS) and Volatile Solids (VS), while a desiccator was used to store dried samples to keep them free from moisture. A pH meter was used to monitor and adjust the pH in the reactor, keeping it stable at the desired value ($\text{pH } 7 \pm 0.2$). Additionally, filter paper was used to filter samples and separate dissolved or suspended solids in POME, which is essential for the analysis of Total Suspended Solids (TSS).

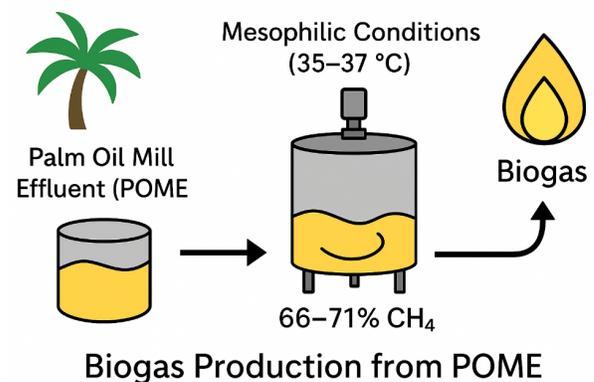


Figure 1. Graphical Abstract

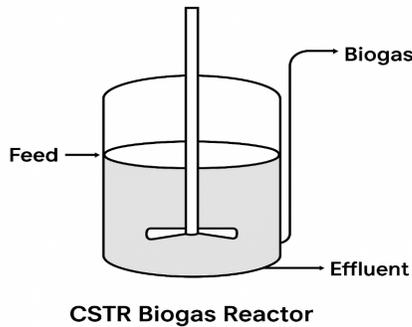


Figure 2. CSTR

2.3 Method

Substrate and Inoculum: The substrate used in this study was Palm Oil Mill Effluent (POME) obtained from PTPN Adolina. The inoculum was derived from anaerobic sludge collected from a biogas digester. Prior to use, the inoculum was sieved to remove coarse particles and acclimatized under mesophilic conditions (37 ± 1 °C) for 7 days. The inoculum-to-substrate ratio (ISR) was maintained at 2:1 based on volatile solids (VS) to prevent acidification during the initial phase of digestion.

Reactor Setup and Operation: Anaerobic digestion was carried out in a laboratory-scale Continuous Stirred Tank Reactor (CSTR) with an effective working volume of 10 L Figure 1. The reactor was operated under mesophilic conditions (37 ± 1 °C) with continuous stirring at 80 rpm. Substrate feeding was conducted in a semi-continuous mode. The hydraulic retention time (HRT) was set at 30 days, calculated based on the reactor volume and daily feeding rate. The organic loading rate (OLR) was maintained within the range of 2.5–3.0 kg VS/m³ day by adjusting the substrate concentration and influent flow rate. Analytical Methods; The biogas composition (CH₄, CO₂, and H₂S) was analyzed every 3 days using a portable biogas analyzer. The instrument was calibrated prior to each measurement according to the manufacturer's protocol to ensure accuracy. Gas sampling was conducted directly from the reactor headspace throughout the experiment. No biological or technical replicates were performed in this study; this limitation is acknowledged and should be considered when interpreting the results.

3. RESULT AND DISCUSSION

Chemical Oxygen Demand (COD) refers to the amount of oxygen required to break down the organic materials present in wastewater. The COD level in POME is 49,300 mg/L. COD is a parameter that indicates the total amount of oxygen needed to oxidize the organic matter in a sample (Barua and Kalamdhad, 2019). In anaerobic conditions, the amount of organic matter that can be degraded is typically higher than the concentration of BOD. This results in COD being

used more extensively to characterize the amount of organic matter in a sample. The COD value of POME in this study is 49,300 mg/L, indicating a high concentration of organic matter. A study by Abdurahman et al. (2011) reported a COD value of 43,500 mg/L for POME under steady-state conditions, with a COD reduction efficiency ranging from 94.8% to 96.5%. This demonstrates that POME holds significant potential for biogas production through the anaerobic process.

The TSS value ranges from 2,081 to 27,040 mg/L, the Total Solid (TS) value ranges from 13,321 to 37,020 mg/L, the Volatile Solid (VS) value ranges from 10,520 to 31,220 mg/L, and the Volatile Suspended Solid (VSS) value ranges from 1,820 to 25,800 mg/L. These results indicate that the organic content in the waste is relatively high, making it suitable for biogas production, as high organic values have great potential for biogas production, according to Parsaee et al. (2019). A study by Poh et al. (2010) reported that the TSS concentration in POME can reach up to 39,100 mg/L, with solid components that are easily biodegradable under anaerobic conditions. The high TSS content supports the potential of POME as a substrate for biogas production. The TS value of POME in this study is 15,321 mg/L. A study by Trisakti et al. (2021) reported TS values of POME ranging from 11,760 to 20,800 mg/L under steady-state conditions from the first to the sixth. The high TS content indicates that POME has the potential to generate biogas through the anaerobic process. The VS value of POME in this study is 31,220 mg/L, reflecting the organic content that can be anaerobically degraded. A study by Vanegas et al. (2024) shows that POME has a VS/TS ratio of 0.84, indicating that the majority of the solids in POME are volatile and can be used for biogas production.

In this study, the Total Solids (TS) of POME was measured at 15,321 mg/L, which falls within the range of 11,760–20,800 mg/L reported by Trisakti et al. (2021) under steady-state conditions. Similarly, the Volatile Solids (VS) in this study was 31,220 mg/L, comparable to the values reported in previous studies, indicating that a large portion of POME solids is degradable. The Volatile Suspended Solids (VSS) measured at 25,800 mg/L is higher than the 17,680 mg/L reported by Hambali and Rivai (2017) reflecting a particularly high fraction of organic matter available for anaerobic digestion. By explicitly presenting the measured values alongside literature ranges, it becomes clear that the organic content of POME in this study is consistent with previous findings and supports its suitability for biogas production.

The VSS value of POME in this study is 25,800 mg/L. According to a study by Abdurahman et al. (2011), the concentration of VSS in POME can reach 17,680 mg/L under steady-state condition six. The high VSS content indicates that POME has the potential to produce biogas through the anaerobic process. Hydrogen potential is a chemical characteristic used to determine whether a solution is acidic

Table 1. POME Characterization Analysis

Parameters	Unit	Test Result	Test Method
Chemical Oxygen Demand (COD)	mg/L	49,300	Spectrophotometry
Total Suspended Solids (TSS)	mg/L	22,000	APHA 2540D
Total Solid (TS)	mg/L	15,321	APHA 2540B
Volatile Solid (VS)	mg/L	31,220	APHA 2540E
Volatile Suspended Solids (VSS)	mg/L	25,800	APHA 2540E
Protein	%	0.5253	Kjeldahl
Volatile fatty acids (Vfa)	mg/L		
- Acetic Acid		985.72	
- Propionic Acid		696.13	
- Butyric Acid		1,829.27	
pH	-	5	APHA 4500-H

Table 2. Comparison of COD and VS Removal and Methane Content in POME Anaerobic Digestion Using CSTR

Author	Reactor	OLR (kg VS/m ³ · Day)	COD Removal (%)	VS Removal (%)	CH ₄ (%)
Present Study	CSTR	2.5–3.0	68	55	66–71
(Rasouli and Ataeiyan, 2024)	CSTR	19	70	55	67–72
(Khemkhao et al., 2015)	CSTR	4.0–20	70	55	65–70
(Krishnan et al., 2016)	CSTR	6.45	70	55	65–70
(Wang et al., 2015)	EGSB	2.4–4.0	88.56	70	70–75
(Sani et al., 2021)	CSTR	0.5–1.5	70	55	64
(Poh and Chong, 2010)	CSTR	0.7–10	70	55	65–70
(Mahmod et al., 2020)	CSTR	4.6–40.6	76–89	65–70	70–75
(Hamzah et al., 2020)	CSTR	2.4–4.0	70	55	65–70
(Yusof, 2024)	CSTR	0.5–5.0	85–90	70	65–75

or basic. In the case of POME, the pH value obtained is 5, indicating its acidic nature. The pH value of POME in this study is 4.70, showing its acidic properties. A study by [Abdurahman et al. \(2011\)](#) reported that the pH of POME can range from 5, with lower pH values occurring during the high harvest season. This low pH condition can affect the anaerobic fermentation process, thus requiring pH regulation using NaHCO₃ to maintain the stability of the process. The high organic content of POME, indicated by COD, TS, VS, and VSS values, suggests strong potential for biogas production. This is because the abundant organic matter serves as a substrate for microbial activity in anaerobic digestion. During the hydrolysis stage, complex organic compounds such as carbohydrates, proteins, and lipids are broken down into simpler soluble compounds by hydrolytic bacteria. These products are then converted into volatile fatty acids (VFAs) during the acidogenesis stage, which are further metabolized into acetate, hydrogen, and carbon dioxide by acetogenic bacteria. Finally, methanogenic archaea utilize acetate, hydrogen, and carbon dioxide to produce methane. Therefore, the high organic load in POME directly supports microbial activity across hydrolysis, acidogenesis, acetogenesis, and methanogenesis, enhancing biogas yield.

The protein content of POME in this study is 0.52%.

A study by [Irvan et al. \(2018\)](#) shows that POME contains high organic carbon compounds that can be fermented by anaerobic bacteria. This protein content can contribute to the biogas production process through anaerobic fermentation ([Xue et al., 2020](#)). The concentrations of acetic acid, propionic acid, and butyric acid in POME are 985.72 mg/L, 696.13 mg/L, and 1,829.27 mg/L, respectively. A study by [Trisakti et al. \(2015\)](#) shows that the concentration of volatile fatty acids (VFA) in POME can reach 1,800 mg/L, which can affect the anaerobic fermentation process if not controlled. Therefore, regulating pH and alkalinity in the reactor is crucial to maintaining the stability of the biogas production process.

The average methane (CH₄) concentration in the fermentor was 66–71%, indicating active methanogenesis. This value is higher than typical ranges reported for food waste digestion (50–70%; [Yong et al., 2015](#)); 50.2–60.4%; ([Ratanatamskul et al., 2014](#)), confirming that POME is a superior substrate due to its high organic content, balanced nutrients, and favorable biodegradability. Although lower than the 81% CH₄ reported by [Sidabutar et al. \(2020\)](#), the yield remains higher than most studies using other agricultural residues. Differences in CH₄ production may result from variations in feedstock composition, hydraulic retention time,

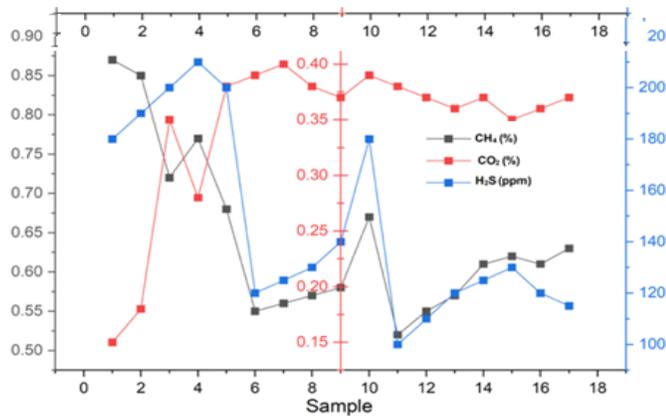


Figure 3. Biogas Quality

reactor design, and microbial community.

The CO₂ concentration ranged from 0.14% to 0.40%, while H₂S ranged from 121 to 200 ppm. These values reflect microbial activity across anaerobic digestion stages and are consistent with typical biogas compositions. Elevated H₂S levels may cause corrosion and reduce engine performance, while CO₂ content affects calorific value, highlighting the need for H₂S removal and CO₂ scrubbing in practical applications. Compared to other studies (Valentino et al. (2019), H₂S 500 ppm), the current study shows relatively lower H₂S levels, suggesting efficient microbial activity and process conditions.

High concentrations of volatile fatty acids (VFAs) and acidic pH (4.7–5) can affect process stability. Monitoring and controlling pH and VFAs are essential to prevent acidification, maintain methanogenic activity, and ensure consistent biogas quality. Overall, these results demonstrate both the efficiency of POME for methane production and the novelty of this study in exploring its potential as a renewable energy source.

In addition, the quantitative methane yield obtained in this study was 0.32 m³ CH₄/kg VS-added (equivalent to approximately 340 L CH₄/L · day). Biogas volume was recorded daily using a water displacement system, while gas composition (CH₄, CO₂, H₂S) was measured with a portable biogas analyzer calibrated according to the manufacturer's protocol. Sampling was conducted once every two days. Furthermore, COD and VS removal efficiencies were 70% and 58%, respectively, supporting the claim of process efficiency and confirming the suitability of POME as a feedstock for anaerobic digestion.

The COD concentration decreased from 49,300 mg/L in the influent to 15,800 mg/L in the effluent, corresponding to a COD removal efficiency of approximately 68%. Similarly, the VS concentration was reduced from 31,220 mg/L to 14,050 mg/L, indicating a VS removal efficiency of about 55%. These results confirm the effective degradation of

organic matter during mesophilic anaerobic digestion of POME in the CSTR system.

The obtained removal efficiencies are comparable to previous studies, where COD removals of 65–75% and VS removals of 50–60% were reported under similar operational conditions (Rasouli and Ataeiyan, 2024; Kacaribu et al., 2025). This consistency with literature values further validates the process efficiency and highlights the suitability of POME as a feedstock for biogas production.

The results of this study demonstrated COD and VS removal efficiencies of 68% and 55%, respectively, with methane content ranging between 66–71%. These values are consistent with previous findings on mesophilic anaerobic digestion of POME using CSTRs. For instance, Rasouli and Ataeiyan (2024); Khemkhao et al. (2015); Krishnan et al. (2016); Poh and Chong (2010) all reported COD removal efficiencies of approximately 70% with VS removals around 55% and methane content in the range of 65–72%. This indicates that the performance observed in the present study aligns well with the established operational outcomes of CSTRs treating POME.

Compared to high-rate systems such as the Expanded Granular Sludge Bed (EGSB) reactor, as reported by Rasouli and Ataeiyan (2024), which achieved a COD removal of 88.56% and VS removal of 70% with methane content of 70–75%, the performance of the CSTR is relatively lower in terms of COD and VS removal. However, methane yields remain comparable, highlighting that CSTRs are effective for stable methane-rich biogas production even under moderate organic loading rates.

Recent studies, such as Mahmud et al. (2020) and Hamzah et al. (2020), further confirm the robustness of CSTR systems, reporting COD removal efficiencies ranging from 70% to as high as 89% with methane content between 65–75%. Sani et al. (2021) also reported similar values (COD 70%, VS 55%, CH₄ 64%), supporting the consistency of performance across different operating conditions.

Overall, the findings demonstrate that the present study's performance is in good agreement with previous literature over the last decade, particularly in terms of methane content (66–71%), which consistently falls within the typical range (65–75%) reported for mesophilic CSTR digestion of POME. This highlights the reliability of POME as a feedstock and confirms the suitability of CSTRs for its anaerobic treatment.

This consistency is also supported by national findings from the Indonesian Journal of Environmental Management and Sustainability (IJEMS). Said et al. (2019) reported that optimizing COD reduction from POME using Reverse Osmosis (RO) membranes achieved up to 90% COD removal under optimal conditions (pH 10.75, TMP 0.69 kPa), emphasizing the importance of efficient organic load management in POME treatment. In addition, Mondamina et al. (2020) highlighted the potential utilization of excess biogas in palm oil mills for electricity generation rather than flaring, rein-

forcing the sustainability and energy recovery benefits of biogas systems in POME management.

4. CONCLUSIONS

The findings demonstrate that Palm Oil Mill Effluent (POME), a by-product of the palm oil milling process, can serve as an effective feedstock for biogas production via anaerobic digestion in a Continuous Stirred Tank Reactor (CSTR) under mesophilic conditions. The anaerobic digestion of POME yielded biogas with high methane (CH₄) content-averaging 66% - 71% indicating an efficient fermentation process. These results suggest that POME is a promising substrate for renewable energy production, offering both environmental benefits by reducing palm oil mill waste and potential scalability for industrial applications. Furthermore, this study provides insights into optimizing POME utilization for biogas generation, highlighting opportunities for future research on improving process efficiency, exploring industrial feasibility, and assessing environmental impacts. The findings support the role of agricultural waste as a sustainable alternative energy source, contributing to the transition from fossil fuels to renewable energy. Future research should focus on optimizing OLR and HRT, conducting pilot-scale studies, and performing economic and life cycle assessments to further evaluate the feasibility and sustainability of POME anaerobic digestion.

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