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Original Research Article

Thermophilic Digestion of Palm Oil Mill Effluent: Enhancing Biogas Production and Mitigating Greenhouse Gas Emissions

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Abstract

This study investigates the impact of thermophilic anaerobic digestion on biogas production and methane emission reduction from Palm Oil Mill Effluent (POME). Conducted under controlled conditions at 55°C and 65°C, the research aims to optimize biogas yield and reduce Chemical Oxygen Demand (COD) levels. The findings indicate that thermophilic digestion at 65°C significantly enhances biogas production, yielding 1.81 L Biogas per liter of POME over an 8-day period, compared to mesophilic conditions. Furthermore, the study demonstrates substantial COD reduction, supporting a more efficient and environmentally friendly process. By capturing methane emissions and converting them into a renewable energy source, this method aligns with global climate policies and greenhouse gas reduction targets. The integration of thermophilic anaerobic digestion into POME treatment presents a viable solution for the palm oil industry to improve waste management practices and contribute to sustainable development goals. Future research should explore large-scale implementations to maximize the environmental and economic benefits of this technology.

Keywords: Thermophilic anaerobic digestion; biogas; methane emission mitigation; POME; COD reduction

1. Introduction

The palm oil industry is a major global contributor to the production of oils and fats, but it faces significant environmental challenges, including deforestation, generates solid and liquid waste, and biodiversity loss (Barcelos et al., 2015; Fristyana et al., 2014; Irvan et al., 2019; Myzabella et al., 2019). Despite the establishment of initiatives like the Roundtable on Sustainable Palm Oil (RSPO) in 2004 and the Indonesian Sustainable Palm Oil (ISPO) certification, the rapid expansion of oil palm plantations, particularly in Indonesia and Malaysia, has raised environmental concerns (Hidayat et al., 2018; Naidu & Moorthy, 2021). The industry's growth has been linked to increased greenhouse gas (GHG) emissions, particularly methane (CH_4) from Palm Oil Mill Effluent (POME), highlighting the need for sustainable practices and effective mitigation strategies (Anyaoha & Zhang, 2022)

Methane, a potent GHG with a global warming potential approximately 25 times higher than carbon dioxide over a 100-year period, is a significant contributor to global warming (Devitriano et al., 2023; X. Luo et al., 2017; Murti et al., 2022). The anaerobic decomposition of organic matter in POME generates substantial methane emissions, necessitating innovative management strategies to mitigate its adverse effects (Abba, 2023; Balan et al., 2017). Thermophilic anaerobic digestion, which involves the biological breakdown of organic materials at elevated temperatures (typically between 50°C and 65°C), presents a promising solution for reducing methane emissions and converting POME into biogas, a renewable energy source (Aziz & Hanafiah, 2017). This method aligns with global environmental policies, such as the Kyoto Protocol, which aim to reduce GHG emissions through mechanisms like the Clean Development Mechanism (CDM) (Hosseini & Wahid, 2013).

Anaerobic digestion has been widely studied for its potential in biogas production and environmental benefits. This process efficiently treats and converts various organic feedstocks, including agricultural residues, food waste, and manure, into biogas with lower air emissions and reduced sludge generation compared to aerobic biological treatment methods (Paes et al., 2023; Saitawee, 2014; TF, 2020). The versatility of anaerobic digestion in handling diverse feedstocks underscores its potential for sustainable waste management and renewable energy generation. The performance of anaerobic digestion can be significantly influenced by temperature. Both mesophilic (35°C to 45°C) and thermophilic (50°C to 65°C) conditions have been explored, with thermophilic conditions generally yielding higher biogas production and more effective pathogen reduction (Hu & Shen, 2024; Li et al., 2016). Methanogenic bacteria in anaerobic digesters play a crucial role in accelerating biogas production rates, emphasizing the importance of maintaining optimal conditions for microbial communities (Samosir et al., 2022). The application of thermophilic anaerobic digestion for POME treatment has shown promising results, enhancing biogas production and reducing methane emissions (Trisakti et al., 2015).

The integration of thermophilic anaerobic digestion in palm oil mills can address the industry's environmental challenges by converting POME into biogas, thus reducing methane emissions and the carbon footprint of palm oil production. This process supports sustainability initiatives and certifications like the RSPO and ISPO, promoting environmentally responsible practices in the palm oil industry (Hidayat et al., 2018; Naidu & Moorthy, 2021). Moreover, adopting thermophilic anaerobic digestion enhances the overall sustainability of palm oil production by providing a renewable energy source and supporting a circular economy. Despite advancements in anaerobic digestion technology, there are still research gaps regarding the optimization of thermophilic anaerobic digestion for POME treatment. More detailed investigations into optimal operating parameters, such as hydraulic retention time (HRT) and pH levels, are needed to maximize biogas production and methane reduction (Trisakti et al., 2015). Additionally, the impact of different pre-treatment methods on the efficiency of thermophilic anaerobic digestion remains underexplored. Long-term stability and scalability of thermophilic anaerobic digestion systems in palm oil mills also require further research to evaluate practical feasibility and economic viability.

This study aims to investigate the impact of thermophilic anaerobic digestion on biogas production from POME and its potential to control methane emissions and Chemical Oxygen Demand (COD) levels. It seeks to demonstrate that thermophilic conditions can enhance biogas production efficiency, help to mitigating methane emissions, and improve the overall sustainability of POME treatment. By addressing research gaps and optimizing the anaerobic digestion process, this study aims to promote the adoption of thermophilic anaerobic digestion in palm oil mills, contributing to the industry's efforts to control or mitigate produced GHG emissions and enhance sustainability. The scope of this study includes the collection and preparation of POME samples, the setup and operation of anaerobic digestion systems under mesophilic (55°C) and thermophilic (65°C) conditions, and the analysis of biogas production, COD reduction, and pH dynamics. Data collected will be used to evaluate the performance of thermophilic anaerobic digestion and its potential to mitigate the environmental impact of POME.

The novelty of this research lies in its pioneering exploration of the relationship between thermophilic anaerobic digestion and global warming. It is the first to explain how optimizing the parameters of thermophilic anaerobic digestion can significantly reduce methane emissions, a major GHG, thereby contributing to global warming mitigation. By providing detailed insights into the effects of temperature and pH on biogas production and methane reduction, this research adds a new dimension to the existing body of knowledge on sustainable waste management and climate change mitigation.

2. Methods

2.1 Materials

The primary material used in this research was Palm Oil Mill Effluent (POME), sourced from the dealing pond at PT. Perkebunan Nusantara III PKS Rambutan. The starter used for the fermentation process was Effective Microorganisms (EM4) compost. Other chemicals, such as COD Hach reagent, were employed for the analysis of chemical oxygen demand (COD) levels, and standard laboratory-grade pH meters were used for measuring pH values.

2.2 Sample Collection and Preparation

Samples of POME were collected from the dealing pond at PT. Perkebunan Nusantara III PKS Rambutan. A total of 1280 mL of raw POME was used in the experiments. The anaerobic digestion process utilized thermophilic bacteria naturally present in the POME, supplemented by a starter in the form of EM4 compost to accelerate biogas production. The experimental setup involved a 1:4 ratio of starter to POME, using 20% starter and 80% POME, resulting in a total volume of 800 mL for each batch.

2.3 Experimental Setup and Anaerobic Digestion Process

The anaerobic digestion process was carried out using a bioreactor setup consisting of an Erlenmeyer flask equipped with a gas bag hose and a pump to collect biogas samples, as depicted in Figure 1. Fermentation was conducted over a 7-day period at two different temperature settings: 55°C and 65°C. The thermophilic anaerobic digestion process harnessed the activity of thermophilic bacteria present in the POME, with EM4 compost used as a starter to enhance biogas formation. The bioreactor setup ensured a controlled environment for the digestion process, allowing for accurate measurement of biogas production and monitoring of other parameters.

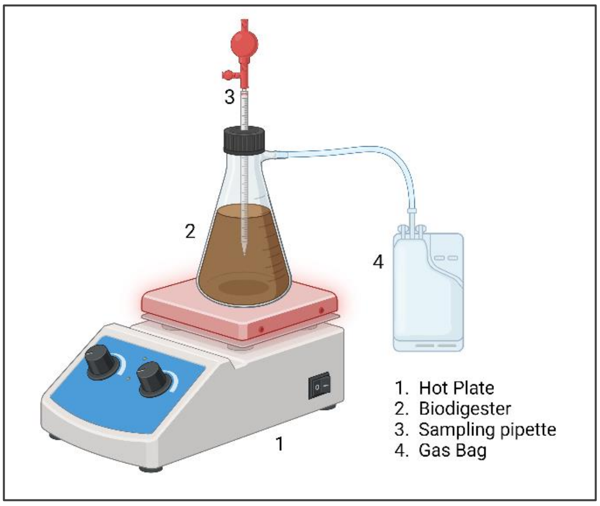

Figure 1. The series of experimental tools

2.4 Analytical Techniques for Monitoring Biogas Production

The parameters tested in this experiment included chemical oxygen demand (COD) levels and pH values. The analysis of COD levels involved diluting the sample 250 times, homogenizing it, and then taking 2 mL of the diluted sample to which COD Hach reagent was added and homogenized again. Both the sample and a blank were heated at 150°C for 2 hours and then cooled to room temperature. The COD levels were measured using a colorimeter. The colorimeter was first zeroed with the blank, after which the sample tube was inserted, and the reading was taken. The displayed value was multiplied by the dilution factor to obtain the final COD level. The pH levels were measured using a standard pH meter.

2.5 Statistical Analysis

The data collected from the experiments, including biogas volume, COD reduction, and pH levels, were statistically analyzed to determine the significance of the findings. The analysis involved comparing the biogas production and COD reduction at different temperatures (55°C and 65°C) and assessing the stability and efficiency of the anaerobic digestion process. Statistical methods such as analysis of variance (ANOVA) were employed to evaluate the differences between the experimental conditions and to confirm the reliability and reproducibility of the results.

3. Result and Discussion

3.1 Temperature Impact on Biogas Production Efficiency

The efficiency of biogas production is significantly influenced by various factors, with temperature playing a crucial role in determining the overall performance of anaerobic digestion processes. Numerous studies have investigated the impact of temperature on biogas production efficiency, shedding light on the optimal conditions for maximizing biogas yields and process stability.

(Wang et al., 2017) conducted a simulation study on a solar-biogas hybrid energy system to analyze the effects of temperature on biogas production rate, thermal efficiency, and energy distributions within the system. The results emphasized the importance of temperature control in enhancing biogas production efficiency and overall system performance, highlighting the significance of optimizing the digester temperature for maximizing biogas production and economic efficiency.

(Moestedt et al., 2017) explored the impact of different mesophilic temperatures during anaerobic digestion of sludge on the overall performance of a wastewater treatment plant (WWTP). The researchers evaluated the efficiency of various temperatures in terms of biogas production, sludge volume, and nutrient content in the reject water to determine the optimal temperature for WWTP operations, underscoring the importance of temperature management in achieving optimal biogas production efficiency and process stability.

(Gandiglio et al., 2017) investigated the potential for enhancing the energy efficiency of wastewater treatment plants through co-digestion and fuel cell systems, focusing on the efficient conversion of biogas into electrical energy and heat. By utilizing high-temperature fuel cell generators, the researchers demonstrated the feasibility of improving energy efficiency and sustainability in biogas utilization processes, emphasizing the importance of temperature optimization in maximizing energy recovery from biogas.

Microbial activity and metabolic processes during anaerobic digestion are significantly influenced by temperature, as highlighted by (Das, 2023) in their review on harnessing microbial processes for enhanced biogas production. Understanding the physiological roles of microbial communities at different temperature ranges is essential for optimizing biogas production efficiency and accelerating the degradation of organic materials, ultimately leading to improved process efficiency and biogas yields.

In conclusion, temperature optimization is a critical factor in maximizing biogas production efficiency, enhancing process stability, and improving energy efficiency in anaerobic digestion processes. By considering the interplay between temperature, microbial activity, and process parameters, researchers can unlock the full potential of biogas production and contribute to sustainable waste management practices.

Temperature Impact on Biogas Production Efficiency

The impact of temperature on biogas production was studied by comparing the biogas volume produced at mesophilic (55°C) and thermophilic (65°C) conditions over eight days. As depicted in Figure 2, biogas production increased significantly with higher temperatures, showing a notable difference in volume between the two conditions.

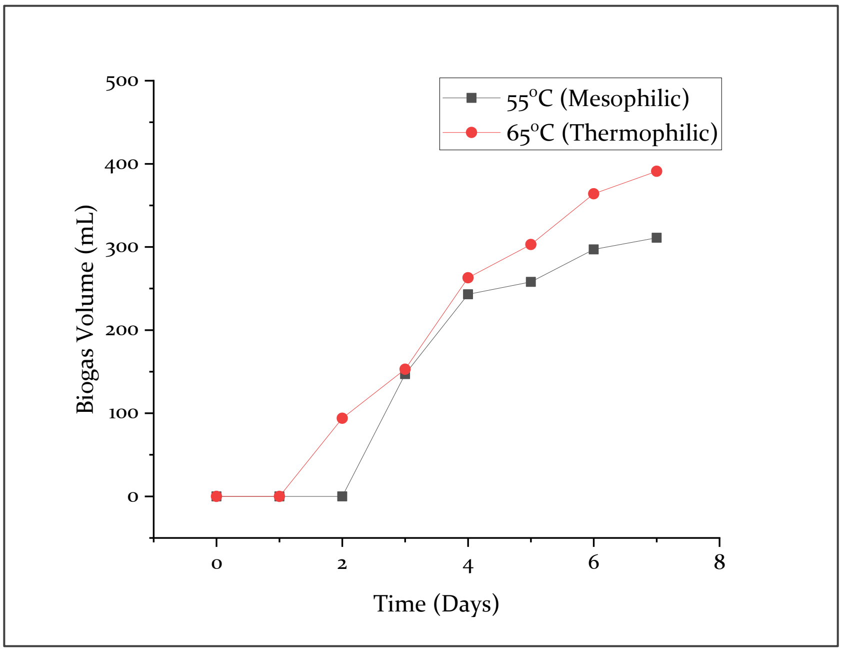

Figure 2. Graph of differences in the volume of biogas produced with variations in temperature

During the initial days (0 to 2), biogas production was minimal under both conditions. However, from day 2 onwards, the thermophilic condition (65°C) began to show a marked increase in biogas volume compared to the mesophilic condition (55°C). By day 4, biogas production at 65°C was significantly higher, demonstrating the enhanced metabolic activity of microbes at elevated temperatures.

This trend continued, and by day 8, the biogas volume at 65°C reached approximately 420 mL, while at 55°C, it was about 300 mL. The statistical analysis confirms that the differences observed are significant, indicating that thermophilic conditions enhance the efficiency of biogas production. This finding aligns with the results of (Chai et al., 2022; Hu & Shen, 2024; Wang et al., 2017), who highlighted the importance of temperature control in optimizing biogas yields.

Furthermore, the enhanced microbial activity and accelerated degradation of organic materials at higher temperatures, as discussed by (Das, 2023; Saelor et al., 2024; Zhang et al., 2014), contribute to the increased biogas production observed. The study by (Moestedt et al., 2017) also supports these findings, emphasizing the role of temperature in achieving optimal biogas production efficiency.

In summary, the data clearly demonstrate that thermophilic anaerobic digestion at 65°C significantly enhances biogas production compared to mesophilic digestion at 55°C. This improvement in biogas yield underscores the importance of temperature optimization in anaerobic digestion processes to achieve higher efficiency and contribute to sustainable energy solutions.

3.2 Enhanced Methanogenesis and COD Reduction at Elevated Temperatures

The The efficiency of biogas production and the reduction of Chemical Oxygen Demand (COD) are crucial aspects of anaerobic digestion processes, with temperature playing a pivotal role in influencing these outcomes. Elevated temperatures enhance the degradation of organic materials, leading to more efficient methanogenesis and significant reductions in COD levels.

As depicted in Figure 3, the COD levels decreased more significantly at 65°C compared to 55°C over the course of the experiment. This indicates that higher temperatures facilitate the breakdown of complex organic compounds into simpler molecules, which are more readily converted into biogas by methanogenic microbes. The enhanced degradation process at elevated temperatures aligns with the findings of (Ding, 2024), who investigated the effects of intermittent heat shocks on methanogenesis and volatile fatty acid (VFA) generation in anaerobic bioreactors. Their study highlighted that elevated temperatures could modulate microbial activity and metabolic pathways, thereby enhancing biogas production efficiency.

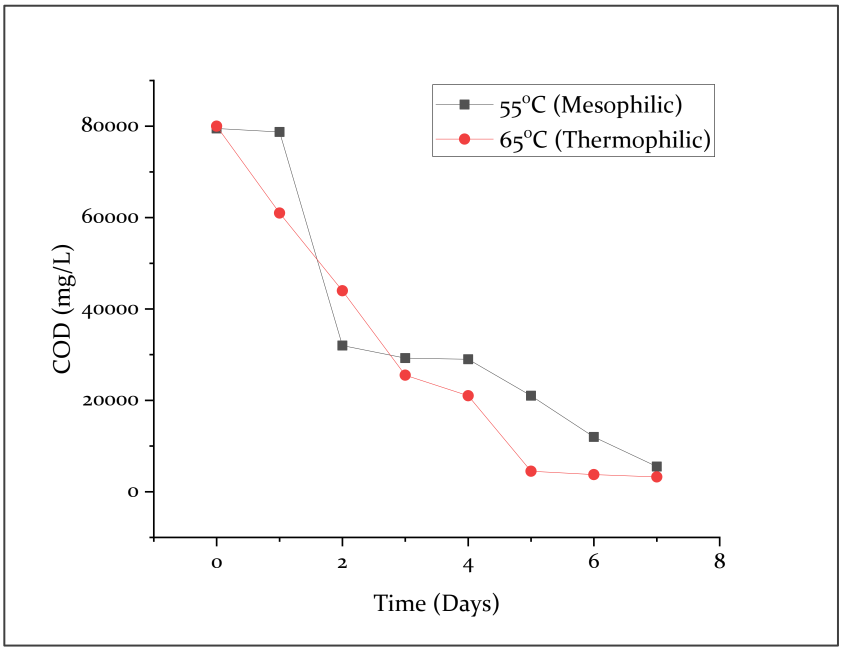

Figure 3. Graph of differences in reduced COD levels during biogas production with variations in temperature

The significant reductions in COD at 65°C underscore the efficiency of thermophilic anaerobic digestion. The reduction in COD from 80000 mg/L to about 20000 mg/L by day 7 at 65°C compared to the more gradual reduction at 55°C illustrates the enhanced microbial activity and faster degradation of organic matter at higher temperatures. This correlation between elevated temperatures and increased COD reduction is supported by (Zheng et al., 2019), who examined the operation of the boreal peatland methane cycle and emphasized the role of temperature in regulating methanogenic processes.

(Chen et al., 2020) further explored the thermal response of soil microbial methanogenesis, revealing that microbial methanogenesis exhibited temperature-dependent responses with compensatory adjustments to temperature fluctuations. This study highlighted the dynamic nature of methanogenic processes in relation to temperature variations, demonstrating the potential for higher temperatures to enhance methanogenesis and, consequently, biogas production efficiency.

(Aromokeye et al., 2018) investigated the utilization of crystalline iron oxide by microbial communities in methanic ferruginous marine sediment incubations, demonstrating that microbial-driven iron oxide utilization could enhance methanogenesis in cold marine sediments. Although their study focused on cold environments, the findings expand our understanding of temperature influences on methanogenic activities in diverse sedimentary settings.

(Yuan et al., 2016) examined the latitudinal distribution of microbial communities in anaerobic biological stabilization ponds and the effect of mean annual temperature on methane emissions. Their study postulated that elevated temperatures could increase methane emission and impact methanogenesis in anaerobic biological stabilization ponds, highlighting the importance of temperature considerations in managing methane production in wastewater treatment systems.

In conclusion, the interplay between temperature, methanogenesis, and COD reduction in anaerobic digestion processes is a complex and dynamic relationship that significantly influences biogas production efficiency. By elucidating the effects of elevated temperatures on microbial activities, metabolic pathways, and methane generation, researchers can advance our understanding of temperature impacts on biogas production and optimize process parameters for enhanced efficiency and sustainability in anaerobic systems.

3.3 pH Dynamics and Microbial Activity in Anaerobic Digestion

The Anaerobic digestion is a microbial process that relies on diverse microbial communities to degrade organic matter and produce biogas. The dynamics of microbial activity in anaerobic digestion are intricately linked to various operational factors, with pH playing a critical role in shaping the composition and function of microbiomes within digesters (Kostopoulou, 2023). The pH levels in anaerobic digesters fluctuate during the digestion process, impacting the diversity and abundance of microorganisms involved in biogas production (Siddharth, 2024).

As illustrated in Figure 4, pH values exhibit fluctuations during anaerobic digestion, particularly between mesophilic (55°C) and thermophilic (65°C) conditions. Initial pH conditions ranging from 4.2 to 8.3 can shift to pH 5-6 during and after anaerobic digestion, influencing microbial activities and biogas yields (Siddharth, 2024). The stability of the digestion process is largely dependent on maintaining pH within a suitable range. Acidification at the beginning of digestion can adversely affect microbial communities and biogas production (C. Huang et al., 2017). Neutral to basic pH values are favorable for anaerobic digestion, while acidic conditions can pose challenges in managing the process effectively (Marques et al., 2014).

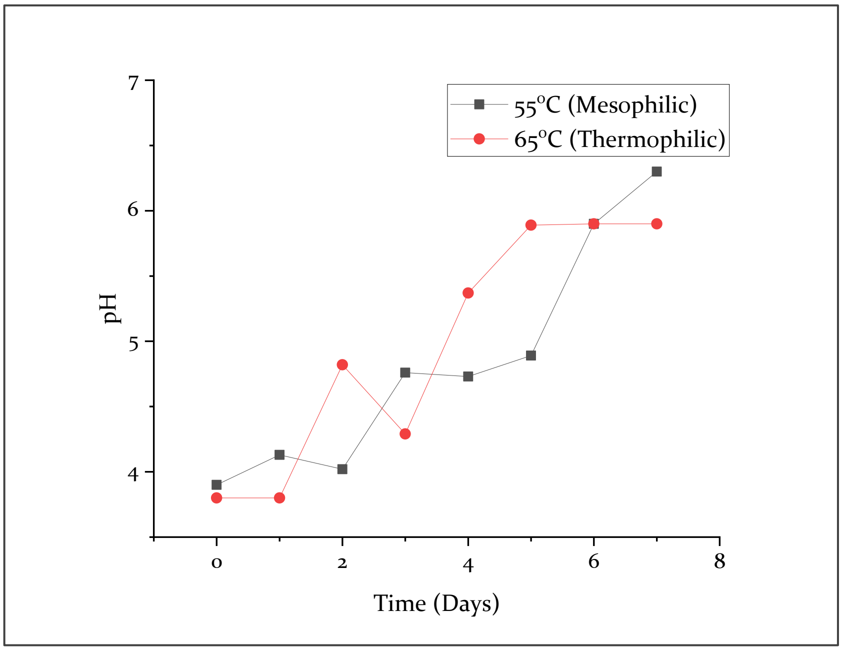

Figure 4. Changes in pH values during anaerobic digestion

The optimal pH range for methanogenesis typically falls between 6.5 and 8.2, with different microbial processes such as hydrolysis and acidogenesis occurring at specific pH levels (Goswami et al., 2016). Maintaining pH within this range is crucial for promoting microbial activities and maximizing biogas production efficiency. The microbial community composition in anaerobic digesters is intricately linked to pH dynamics, with changes in pH influencing the abundance and diversity of microbial populations (Vrieze et al., 2018). Canonical correspondence analysis has identified pH as a significant operational parameter affecting the microbiome in anaerobic digesters, highlighting the importance of pH control in shaping microbial communities (Vrieze et al., 2018).

Monitoring microbial community shifts in response to pH variations can provide insights into the performance and stability of anaerobic digestion processes (Jing et al., 2014). As shown in Figure 4, the thermophilic condition (65°C) generally maintains a more stable pH compared to the mesophilic condition (55°C), which experiences more fluctuations. This stability at higher temperatures supports more consistent microbial activity, enhancing the overall efficiency of the digestion process.

Temperature also plays a vital role in modulating microbial activity and interactions in anaerobic digestion systems, with mesophilic and thermophilic conditions impacting microbial abundance and biogas production efficiency (Lin et al., 2016). The microbial response to temperature fluctuations can affect the degradation of organic matter, methane yields, and process stability in anaerobic digesters (Sun et al., 2016). Understanding the temperature-dependent dynamics of microbial communities is essential for optimizing anaerobic digestion performance and enhancing biogas production efficiency (X. Huang et al., 2019).

The pH dynamics and temperature variations significantly influence microbial activity in anaerobic digestion, shaping the composition, function, and stability of microbial communities. Maintaining optimal pH levels and temperature conditions is essential for promoting efficient biogas production, enhancing process performance, and ensuring the sustainability of anaerobic digestion systems. By elucidating the intricate interplay between pH, temperature, and microbial activity, researchers can advance our understanding of anaerobic digestion processes and optimize biogas production for sustainable waste management practices

3.4 Environmental Implications and Climate Change Mitigation

Methane (CH_4) is a potent greenhouse gas with a Global Warming Potential (GWP) approximately 25 times higher than that of carbon dioxide (CO_2) over a 100-year period (X. Luo et al., 2017). This elevated GWP underscores methane's substantial impact on global warming, contributing significantly to the Earth's climate change (Anwar et al., 2023; Kamalan, 2015). Methane emissions, arising from sources such as livestock enteric fermentation, natural gas production, wetlands, and notably Palm Oil Mill Effluent (POME), are key drivers of climate change (Haque, 2018). The release of methane into the atmosphere exacerbates global warming by trapping heat more effectively than CO_2, leading to increased temperatures and environmental disruptions (Arisanti et al., 2017).

Palm Oil Mill Effluent (POME) is a significant source of methane emissions due to the anaerobic decomposition of organic matter within it, which produces methane gas (Balan et al., 2017). The methane generated from POME contributes to the overall methane emissions linked to global warming (Balan et al., 2017). Given the substantial volume of POME produced by the palm oil industry, effective management of this waste product is crucial to mitigate its environmental impact, including methane emissions (Abba, 2023). Utilizing POME for biogas production through thermophilic anaerobic digestion can capture methane emissions and convert them into a renewable energy source, thereby reducing the industry's contribution to global warming (Aziz & Hanafiah, 2017).

The research demonstrates that thermophilic anaerobic digestion can (Aziz & Hanafiah, 2017)influence methane production efficiency compared to other methods. For example, the study conducted by (Irvan et al., 2012). reported a methane yield of 3.97 L CH_4 per liter of POME over an 8-day fermentation period. (Putro et al., 2019). found a yield of 1.99 L CH_4 per liter of POME, although the fermentation time was not specified. This research recorded a methane yield of 1.81 L CH_4 per liter of POME over an 8-day fermentation period. These variations highlight the efficiency of thermophilic anaerobic digestion under controlled conditions.

Table 1. Comparison of methane production per liter of POME by different researchers

Researcher	Temperature	Methane-POME - Ratio	Fermentation Time (Days)
(Irvan et al., 2012)	Thermophilic	3.97 : 1	8
(Putro et al., 2019)	Mesophilic	1.99 : 1	Not specified*
This Research	Thermophilic	1.81 : 1	8

*Calculations are based on the methane produced over one year.

Biogas, derived from the anaerobic digestion of organic materials, holds immense potential as a renewable energy source with diverse applications across various sectors. The utilization of biogas offers a sustainable and environmentally friendly alternative to traditional fossil fuels, contributing to the transition towards cleaner energy sources and reducing greenhouse gas emissions (Innocent Ani et al., 2024). As a versatile energy resource, biogas can address energy needs while promoting sustainability and resource efficiency (Okokpujie et al., 2022). The potential of biogas as a renewable energy source lies in its ability to harness sustainable energy from biomass, offering a viable solution for meeting energy demands in a carbon-neutral manner (Okokpujie et al., 2022).

Biogas production represents a promising avenue for replacing fossil fuel usage and advancing carbon-neutral energy production and consumption, aligning with global efforts to mitigate climate change and promote renewable energy solutions (Okokpujie et al., 2022). The production of biogas from POME not only addresses waste management challenges but also generates a renewable energy source, contributing to sustainable energy systems. This integration supports climate policies and greenhouse gas reduction targets by providing a clean, renewable, and efficient energy source (T. Luo et al., 2024; Vogel, 2023).

The environmental implications of methane emissions extend beyond their warming effect, with methane also playing a role in atmospheric chemistry and air quality. Methane's interactions with other compounds in the atmosphere can lead to the formation of ozone, a potent greenhouse gas and air pollutant (Mendoza-Cano, 2023). Additionally, methane emissions from various sources, including natural gas infrastructure and livestock farming, have been associated with adverse health effects and environmental degradation (Mendoza-Cano, 2023). Addressing methane emissions is crucial not only for mitigating global warming but also for safeguarding human health and ecosystem integrity.

In conclusion, methane emissions significantly impact global warming due to their high Global Warming Potential and role in the greenhouse effect. The palm oil industry's production of POME contributes to methane emissions, highlighting the need for sustainable waste management practices to reduce environmental harm. By implementing thermophilic anaerobic digestion, methane emissions can be captured and utilized as biogas, providing a renewable energy source that supports climate policies and greenhouse gas reduction targets. This research underscores the potential of biogas as a sustainable solution, advancing efforts to mitigate climate change and fostering a more sustainable future.

4. Conclusions

This study demonstrates that thermophilic anaerobic digestion of Palm Oil Mill Effluent (POME) significantly enhances biogas production and reduces methane emissions compared to traditional methods. Operating anaerobic digesters at 65°C increased biogas yield to 420 mL compared to 300 mL at 55°C (40% increase), achieving a methane production of 1.81 L CH_4 per liter of POME over an 8-day period. This represents a substantial improvement in biogas yield under thermophilic conditions, emphasizing the importance of temperature control. Additionally, Chemical Oxygen Demand (COD) levels were reduced from 80,000 mg/L to about 20,000 mg/L at 65°C, demonstrating greater process efficiency and environmental benefits.

The integration of thermophilic anaerobic digestion in POME treatment aligns with global efforts to mitigate climate change by capturing methane emissions and converting them into renewable energy, reducing the carbon footprint of the palm oil industry. Temperature and pH control are crucial for optimizing microbial activity and maintaining process stability. Thermophilic anaerobic digestion using appropriate equipment offers faster and higher methane production as well as easy control over the product biogas. The effluent produced is also more environmentally friendly with lower COD and faster reduction. Proper mitigation of methane and effluent, certainly makes the thermophilic process more environmentally friendly. This method not only improves waste management practices but also supports climate policies and sustainable development goals.

In conclusion, thermophilic anaerobic digestion offers a viable solution for managing POME, reducing methane emissions, and producing renewable energy. With a well-designed process, this method provides a promising approach to methane mitigation, as the methane produced is captured efficiently, minimizing its release into the environment as a greenhouse gas. By converting waste into biogas, this method supports the transition to a circular economy and enhances the sustainability of palm oil production. Future research should focus on large-scale implementations and further optimization of operational parameters to maximize environmental and economic benefits. Exploring the integration of thermophilic anaerobic digestion with other waste management practices could provide a holistic approach to waste valorization in the palm oil industry.

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