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Analysis of Retention Time on COD, pH, and Biogas Volume from Three Different Palm Oil Mills

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Abstract: *This study examines how retention time affects the effectiveness of anaerobic digestion in the treatment of Palm Oil Mill Effluent (POME). The study focuses on variations in Chemical Oxygen Demand (COD), pH levels, and biogas production using wastewater sourced from three palm oil processing facilities: Pagar Merbau POM, Adolina POM, and Cinta Raja POM retention Time. Anaerobic digestion was conducted for various retention periods of 0, 15, 30, 45, and 60 days. Evaluations were conducted to assess the reduction of organic contaminants, stabilization of pH levels, and the amount of biogas produced during the fermentation phase. The results showed that COD generally decreased with increasing retention time, although temporary increases were observed at days 30 and 60, while pH levels gradually moved towards a more stable state. Biogas production increased and peaked at 45 days, but no biogas production was observed at 60 days. These results indicate that retention time is crucial in influencing the effectiveness of anaerobic treatment methods. A retention period of 45 days offers the best conditions for the reduction of organic pollutants and for optimizing biogas production from POME.*

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INTRODUCTION

The rapid growth of the palm oil industry has significantly increased the volume of wastewater generated during processing activities. This condition raises serious environmental concerns, particularly due to the high organic content found in Palm Oil Mill Effluent (POME). Globally, palm oil is considered one of the most extensively produced and consumed vegetable oils, with approximately 70–90% of its trade being utilized in the food industry (Tandra et al., 2022). In addition to its applications in food, cosmetics, household products, and renewable energy, palm oil processing also generates significant quantities of liquid waste.

One of the main by-products of palm oil processing is Palm Oil Mill Effluent (POME), which originates from the wastewater discharged during the sterilization and clarification stages (Low et al., 2021). The production of POME is substantial, reaching approximately 70% of the total processing output. On average, processing one ton of Fresh Fruit Bunches (FFB) can produce around 700 L (0.7 m^3) of POME (Trisakti et al., 2024). POME is typically characterized by high organic content and complex suspended materials, making it a challenging wastewater to treatFor instance (Kan et al., 2024). In some cases, COD levels in POME can reach up to 50,000 mg/L, indicating a very high organic pollution load (Kamyab et al., 2018). Without proper treatment, such wastewater has the potential to significantly degrade environmental quality, particularly in aquatic ecosystems.

To control environmental impacts, the Indonesian government has established regulations regarding wastewater discharge standards. Based on the Minister of Environment Regulation No. 5 of 2014, the allowable COD limit for palm oil mill effluent is 350 mg/L before being released into the

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environment. However, maintaining sustainable river ecosystems requires not only compliance with discharge standards but also integrated management approaches, including advanced treatment technologies and comprehensive environmental planning (Kartikasari et al., 2024). Increasing anthropogenic pressures, driven by rapid industrial and economic development, continue to threaten river systems by deteriorating water quality and reducing ecological resilience (Wulandari & Diep, 2026).

One of the most widely applied methods for treating POME is the anaerobic digestion process. This approach is effective in reducing organic pollutant concentrations while simultaneously generating biogas, which can be utilized as a renewable energy source (Imam et al., 2025). The anaerobic conversion of POME not only minimizes environmental pollution but also enhances the value of waste through energy recovery (W. S. Winanti et al., 2019). Typically, the biogas produced consists mainly of methane (CH_4) ranging from 50–75% and carbon dioxide (CO_2) between 25–45% (Yan et al., 2025).

The efficiency of the anaerobic digestion process is strongly influenced by several operational parameters, one of which is retention time. Retention time refers to the duration in which the substrate remains in the reactor, allowing microorganisms to degrade complex organic compounds into simpler substances and ultimately produce methane as the main component of biogas (Ramadhani et al., 2021). Insufficient retention time may result in incomplete degradation, whereas excessively long retention time can reduce process efficiency.

In addition to biogas production, anaerobic treatment also contributes to reducing organic pollutant levels, particularly COD, and affects pH variations during the fermentation process (Hafiz et al., 2024). Therefore, parameters such as COD, pH, and biogas volume are commonly used as key indicators to evaluate the performance of the treatment system. Previous studies have reported that anaerobic digestion of POME is capable of reducing COD levels by more than 90% while producing biogas with high methane content (Sodri & Septriana, 2022). Furthermore, a near-neutral pH condition is known to support microbial activity, thereby enhancing biogas production efficiency (Arianingsih et al., 2021).

Previous research has indicated that Hydraulic Retention Time (HRT) is a key factor influencing the anaerobic digestion performance of POME and biomethane production. For instance, ((Ramadhani et al., 2021) evaluated the impact of varying HRT on biomethane production from POME using a two-stage anaerobic reactor equipped with a fluidized bed. However, POME characteristics are not always consistent across palm oil mills. (M. A. B. Mohd Yusof et al., 2023) demonstrated that differences in operational processes and equipment at various palm oil mills can lead to variations in POME characteristics—such as COD and pH—which, in turn, can affect anaerobic treatment potential and biogas production. In contrast to those studies, this research utilizes POME from three different palm oil mills—Pagar Merbau, Adolina, and Cinta Raja—and examines changes in COD, pH, and biogas volume under various conditions.

Based on these considerations, this study aims to determine the effect of retention time on the anaerobic digestion performance of POME from three different palm oil mills, namely PKS Pagar Merbau, PKS Adolina, and PKS Cinta Raja. The study specifically evaluates changes in Chemical Oxygen Demand (COD), pH, and biogas volume at retention times of 0, 15, 30, 45, and 60 days. Furthermore, this study aims to compare the response of POME from the three palm oil mills under the same retention time conditions and to identify the retention time that provides the most favorable

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treatment performance based on COD reduction, pH stabilization, and biogas production. The results are expected to provide a basis for determining an appropriate retention time for improving the efficiency of anaerobic POME treatment and biogas production.

RESEARCH METHOD

This study applied a quantitative experimental approach to evaluate the changes in Chemical Oxygen Demand (COD), pH, and biogas production during the anaerobic biogasification process of Palm Oil Mill Effluent (POME). The wastewater samples used in this research were collected from three different palm oil mills, namely PKS Pagar Merbau, PKS Adolina, and PKS Cinta Raja.

The biogasification process was carried out in a closed anaerobic system using a modified 19 L water gallon as the digester. Each reactor was filled with 14 L of POME and supplemented with an Effective Microorganism 4 (EM4) culture that had undergone a prior inoculation process. The inoculation was prepared by dissolving 37.5 mL of EM4 into 750 mL of distilled water, followed by a 5-day incubation period before being introduced into the reactor. After loading, all reactors were tightly sealed to ensure anaerobic conditions were maintained throughout the fermentation process. The system was operated at room temperature, ranging between 25–27°C, following the procedure described by Hafiz & Purwanto (2024).

The experiment was conducted under different retention times of 0, 15, 30, 45, and 60 days. Observations were performed at each retention interval to monitor changes in wastewater characteristics and the amount of biogas produced.

The parameters analyzed in this study included COD, pH, and biogas volume. COD measurements were conducted using the closed reflux method based on SNI 6989.2:2019, employing the Regen COD HR instrument. The pH values were measured using a calibrated pH meter prior to each measurement. Meanwhile, biogas volume was determined using the water displacement method and recorded in milliliters (mL).

The experimental design consisted of 15 observation combinations derived from three POME sources (PKS Pagar Merbau, PKS Adolina, and PKS Cinta Raja) and five retention time treatments (0, 15, 30, 45, and 60 days). Thus, each POME source was observed at five different retention times, resulting in a total of 15 experimental observation units. The collected data were analyzed descriptively and statistically using SPSS. Analysis of Variance (ANOVA) was applied to determine whether retention time and POME source significantly affected COD, pH, and biogas volume. Multiple linear regression analysis was subsequently used to evaluate the simultaneous relationship between retention time and POME source as independent variables and COD, pH, and biogas volume as dependent variables. Statistical significance was evaluated at a 5% significance level ($p < 0.05$).

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RESULTS AND DISCUSSION

Effect of Retention Time on COD

Table 1. Changes in COD of Palm Oil Mill Effluent under Different Retention Times

Retention Time (Days)	Pagar Merbau (mg/L)	Adolina (mg/L)	Cinta Raja (mg/L)
0	55664	62328	79184
15	27040	20683	24173
30	41552	37524	43460
45	17600	15000	19200
60	20600	16000	32600

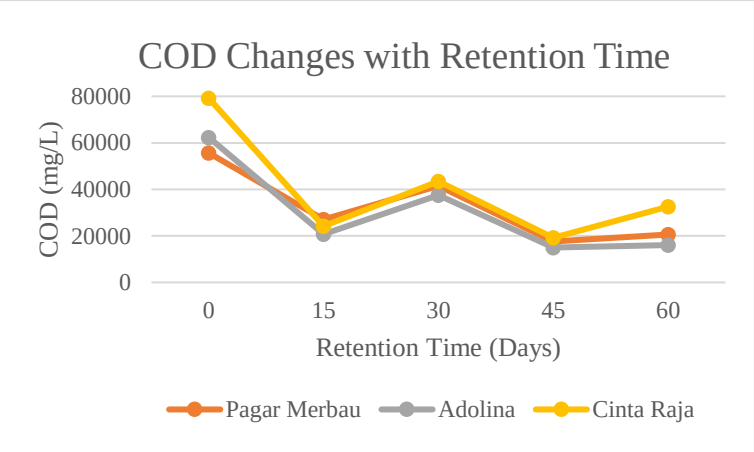

Figure 1. Changes in COD with Retention Time

COD reduction rate can be used to evaluate the effectiveness of the anaerobic digestion process in treating POME (Kamyab et al., 2018). As shown in Table 1 and Figure 1, the COD values of the three POME samples exhibit significant variations as the retention time increases.

On day 0, prior to anaerobic treatment, the Chemical Oxygen Demand (COD) values of POME obtained from PKS Pagar Merbau, PKS Adolina, and PKS Cinta Raja were 55,664 mg/L, 62,328 mg/L, and 79,184 mg/L, respectively, indicating a considerable organic load in the untreated samples. A significant reduction in COD was observed at day 15, suggesting that anaerobic microorganisms had begun actively degrading organic compounds.

However, an increase in COD values was observed at day 30. This condition may occur due to the hydrolysis of complex organic compounds into simpler forms that remain measurable as COD. A comparable pattern has also been observed in previous studies, where intermediate products temporarily increase COD levels during the degradation process (Ramadhani et al., 2021).

The increase in COD observed at day 30 should not necessarily be interpreted as a failure of the anaerobic digestion process. During anaerobic digestion, complex organic compounds undergo hydrolysis and acidogenesis before being converted into substrates that can be utilized by methanogenic microorganisms. The accumulation of soluble organic intermediates during these stages can temporarily increase the amount of oxidizable organic matter detected as COD. This condition may explain the increase in COD observed at day 30 in all three POME sources, despite the substantial

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reduction recorded at day 15. The different COD values among the three POME sources at this stage also indicate that the rate of organic matter conversion was not identical for each substrate.

A further decrease in COD was recorded at day 45, where the lowest values were obtained across all samples. This result suggests that the system had entered a more efficient operational phase, with microorganisms operating at maximum efficiency in converting organic matter into biogas (Rajani et al., 2019).

At day 60, COD values increased again, particularly in PKS Cinta Raja. This increase may indicate that the anaerobic digestion system had passed its most active degradation phase. At longer retention times, readily biodegradable organic substrates may have been substantially consumed, while partially degraded organic compounds and intermediate products could remain in the reactor. Consequently, the rate of microbial degradation may have decreased, resulting in the persistence or accumulation of measurable organic compounds and a subsequent increase in COD (Sodri & Septriana, 2022). This condition is also supported by the absence of biogas production at day 60, suggesting that the remaining organic compounds were no longer efficiently converted into biogas. Therefore, the increase in COD at day 60 should not necessarily be interpreted as an increase in the original organic load, but rather as an indication that the system had exceeded its optimal retention period.

The results clearly show that changes in retention time affect the reduction of organic content in POME. The optimal retention time was identified as 45 days, which provided the most effective reduction in organic pollutant concentration.

Effect of Retention Time on pH

Table 2. Changes in pH of Palm Oil Mill Effluent under Different Retention Times

Retention Time (Days)	Pagar Merbau	Adolina	Cinta Raja
0	4.09	3.80	4.20
15	4.26	4.00	4.33
30	4.26	4.20	4.33
45	4.33	4.37	4.31
60	5.61	5.68	4.94

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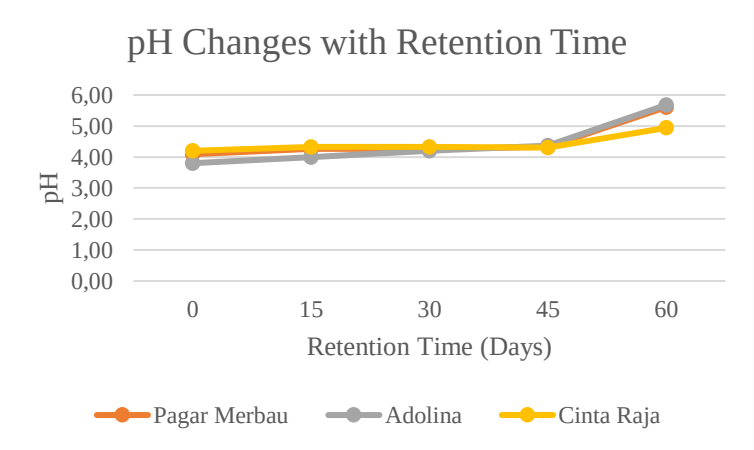

Figure 2. Changes in pH with Retention Time

pH plays an important role in controlling microbial activity during the anaerobic process, as it directly affects the activity of microorganisms responsible for biogas production. Changes in pH during fermentation indicate the shift between acid formation and methane production in the system.

As shown in Table 2 and Figure 2, the pH values of the three POME samples gradually increased with increasing retention time. At the initial condition (day 0), the pH values for PKS Pagar Merbau, PKS Adolina, and PKS Cinta Raja were 4.09, 3.80, and 4.20, respectively. These values indicate that the POME was in an acidic condition at the beginning of the process due to the presence of organic acids (Mohammad et al., 2021).

At day 15 and day 30, the pH values showed a slight increase, indicating the beginning of the stabilization phase. During this stage, acidogenic bacteria produce organic acids, while methanogenic microorganisms begin to adapt to the system. This condition contributes to the gradual increase in pH values and reflects the transition between acidogenic and methanogenic phases.

A more significant increase in pH was observed at day 45, where the values approached near-neutral conditions. This result shows the predominance of methanogenic activity, which promoted the biodegradation of organic acids into methane and carbon dioxide. As a result, the system reached a more stable condition that supports optimal biogas production. This observation is consistent with previous research demonstrating that pH adjustment can influence anaerobic digestion performance and methane production from POME, emphasizing the importance of maintaining suitable pH conditions for methanogenic activity (Singkhala et al., 2021). The increase in pH observed at day 45 is in agreement with previous studies that reported improved anaerobic digestion performance under more stable pH conditions (Ramadhani et al., 2021) reported that longer retention times promoted microbial adaptation and process stability, resulting in enhanced biomethane production. This finding is consistent with previous studies that reported that appropriate retention time and stable operating conditions improve the performance of anaerobic digestion in POME treatment (Dominic & Baidurah, 2022).

On day 60, the pH values continued to increase, reaching 5.61 for PKS Pagar Merbau, 5.68 for PKS Adolina, and 4.94 for PKS Cinta Raja. Although the pH values increased, they remained below the optimal neutral range, suggesting a decline in microbial efficiency. This condition may be associated with the accumulation of intermediate compounds or reduced activity of methanogenic microorganisms.

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Overall, the results indicate that retention time significantly influences pH changes in POME during anaerobic digestion. The most stable pH condition was observed at day 45, indicating that this retention time provides a more favorable environment for microbial activity and biogas production.

Effect of Retention Time on Biogas Volume

Table 3. Biogas Volume of Palm Oil Mill Effluent under Different Retention Times

Retention Time (Days)	Pagar Merbau (mL)	Adolina (mL)	Cinta Raja (mL)
0	0	0	0
15	1300	0	900
30	700	1450	550
45	2600	3100	2300
60	0	0	0

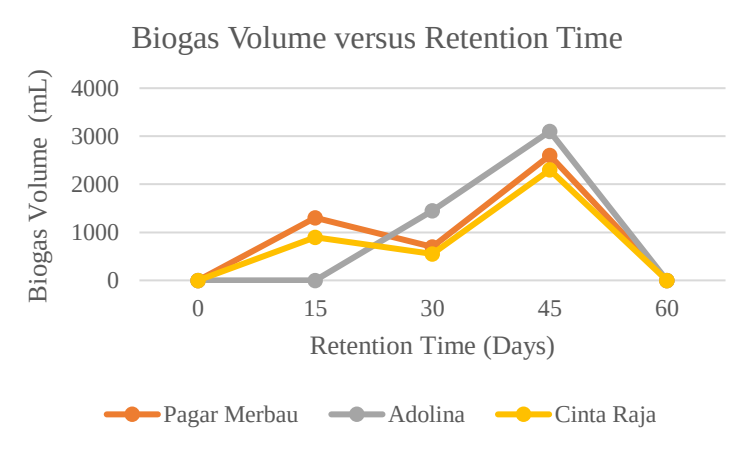

Figure 3. Changes in Biogas Volume with Retention Time

Biogas production indicates how effectively the anaerobic process performs in treating POME. The amount of biogas produced represents the level of microbial activity during the anaerobic process, particularly methanogenic microorganisms, in converting organic matter into methane (Hafiz et al., 2024).

As shown in Table 3 and Figure 3, the biogas volume from the three POME samples increased with increasing retention time up to a certain point, followed by a significant decline. At the initial condition (day 0), no biogas production was observed in all samples, indicating that microbial activity had not yet developed.

At day 15, biogas production began to occur, with volumes of 1300 mL for PKS Pagar Merbau, 0 mL for PKS Adolina, and 900 mL for PKS Cinta Raja. This result shows that anaerobic microorganisms had started adapting to the system, although their activity was still relatively low.

A substantial increase in biogas production was observed on day 30, with PKS Adolina achieving a maximum volume of 1,450 mL. This trend indicates an acceleration of microbial activity, particularly during the transition between the acidogenic and methanogenic phases of anaerobic digestion.

The highest biogas production was recorded at day 45, with volumes of 2600 mL for PKS Pagar Merbau, 3100 mL for PKS Adolina, and 2300 mL for PKS Cinta Raja. This observation indicates that

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the anaerobic digestion system had reached an optimal condition in which methanogenic microorganisms exhibited high metabolic activity, resulting in the conversion of organic matter into methane.

The observed trend is consistent with previous studies showing that retention time plays an important role in anaerobic digestion performance and can influence biogas production under different operating conditions (Suksaroj et al., 2023). Previous studies have shown that optimal methane production is achieved when microbial activity reaches a stable phase under suitable retention time conditions (Ramadhani et al., 2021).

At day 60, no biogas production was observed in all samples. This decline may be attributed to the depletion of biodegradable organic substrates and reduced microbial activity, indicating that the system had surpassed its optimal phase.

The absence of biogas production at day 60 in all three POME sources suggests that the anaerobic system had entered a post-optimal phase. Biogas production depends on the availability of biodegradable organic substrates and the activity of methanogenic microorganisms. After prolonged retention, a considerable portion of the readily degradable organic matter may have been consumed during the earlier stages of digestion. As a result, the remaining substrate may have been less biodegradable or may have consisted of intermediate compounds that were not efficiently converted into methane. In addition, the increase in COD observed at day 60 supports the possibility that organic compounds remained in the reactor but were not effectively converted into biogas. Therefore, the absence of biogas at day 60 does not indicate that organic matter was completely absent, but rather suggests that the microbial conversion of the remaining organic matter into biogas had become substantially less effective.

Overall, the results demonstrate that retention time significantly influences biogas production from POME. A retention time of 45 days provides the highest biogas yield, indicating that this condition is optimal for maximizing methane production.

Differences Among POME Sources

The results also demonstrate differences in the response of POME obtained from PKS Pagar Merbau, PKS Adolina, and PKS Cinta Raja under the same retention time conditions. The initial COD concentration was highest in POME from PKS Cinta Raja (79,184 mg/L), followed by PKS Adolina (62,328 mg/L) and PKS Pagar Merbau (55,664 mg/L). These differences indicate that the organic characteristics of POME were not identical among the three mills. Previous research has shown that differences in palm oil mill processing operations and equipment can result in variations in POME characteristics, including COD and pH, which may subsequently influence anaerobic digestion performance and biogas production (M. A. B. Mohd Yusof et al., 2023).

Differences were also observed in biogas production. At a retention time of 45 days, PKS Adolina produced the highest biogas volume of 3,100 mL, followed by PKS Pagar Merbau with 2,600 mL and PKS Cinta Raja with 2,300 mL. Interestingly, POME from PKS Cinta Raja, which had the highest initial COD concentration, did not produce the highest biogas volume. This finding indicates that initial COD concentration alone does not determine biogas production. The biodegradability and composition of organic matter, together with microbial activity and adaptation during anaerobic digestion, may also influence biogas formation. Therefore, differences in POME characteristics among palm oil mills should

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be considered when evaluating anaerobic digestion performance and determining suitable retention time conditions.

Statistical Analysis

One-Way Analysis of Variance (ANOVA)

To statistically evaluate the effects of retention time on the measured parameters, one-way analysis of variance (ANOVA) was performed for COD, pH, and biogas volume. The statistical analysis was performed using SPSS, with a significance level of 5% (α = 0.05).

Table 4. Summary of One-Way ANOVA Results

Parameter	F-value	df	p-value	Interpretation
COD	23.853	4, 10	<0.001	Significant
pH	18.518	4, 10	<0.001	Significant
Biogas volume	21.275	4, 10	<0.001	Significant

Note: One-way ANOVA was conducted at a significance level of 5% (α = 0.05)

The one-way ANOVA results demonstrated that retention time significantly affected all measured parameters, including COD, pH, and biogas volume ($p < 0.001$). The F-values for COD, pH, and biogas volume were 23.853, 18.518, and 21.275, respectively. These results indicate that the observed variations in COD concentration, pH, and biogas production across the five retention time conditions were statistically significant. Therefore, the ANOVA results provide statistical support for the observed changes in the measured parameters throughout the anaerobic digestion process.

Multiple Linear Regression Analysis

To further examine the relationship between the measured parameters and biogas production, a multiple linear regression analysis was performed using biogas volume as the dependent variable and retention time, COD, and pH as independent variables. The analysis was conducted to determine the combined contribution of these variables to variations in biogas production and to identify the individual predictors that significantly influenced biogas volume. The results of the regression analysis are presented in Table 5.

Table 5. Multiple Linear Regression Analysis for Biogas Volume

Predictor	B	β	t	p-value
COD	-0.022	-0.398	-1.471	0.169
pH	-1953.096	-0.992	-3.204	0.008
Retention time	37.041	0.762	1.958	0.076

Model summary: $R = 0.783$; $R^2 = 0.613$; Adjusted $R^2 = 0.507$; $F(3,11) = 5.796$; $p = 0.013$.
Note: The dependent variable was biogas volume (mL). Statistical significance was evaluated at α = 0.05.

The multiple linear regression model was statistically significant ($F(3,11) = 5.796$, $p = 0.013$), with an R^2 value of 0.613 and an adjusted R^2 of 0.507. This indicates that retention time, COD, and pH

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jointly explained 61.3% of the variation in biogas volume. Among the individual predictors, Among the individual predictors, pH showed a significant negative relationship with biogas volume (β = −0.992, p = 0.008). In contrast, COD (β = −0.398, p = 0.169) and retention time (β = 0.762, p = 0.076) did not show statistically significant individual effects at the 5% significance level. These results indicate that pH was the only predictor that showed a statistically significant individual relationship with biogas volume, while the overall regression model significantly explained variations in biogas production.

CONCLUSION

The results of this study indicate that retention time is a critical factor affecting the efficiency of anaerobic digestion in the processing of palm oil mill effluent. Different retention periods significantly influenced major process parameters, including COD, pH, and biogas production.

COD decreased significantly with increasing retention time, indicating effective degradation of organic matter by anaerobic microorganisms. The lowest COD values were observed at a retention time of 45 days, suggesting optimal treatment performance. Similarly, the pH values gradually increased from acidic conditions toward near-neutral levels, indicating improved system stability and favorable conditions for microbial activity.

Biogas production also showed a strong dependence on retention time, with the highest volume recorded at 45 days. This indicates that microbial activity, particularly that of methanogenic microorganisms, was at its peak under this condition. However, a decline in performance was observed at 60 days, as indicated by the increase in COD and the absence of biogas production, suggesting that the system had surpassed its optimal operating condition.

Overall, a retention time of 45 days is identified as the optimal condition for the anaerobic treatment of POME, providing the most effective reduction in COD, stable pH conditions, and maximum biogas production. These findings can serve as a reference for optimizing biogas production and improving wastewater treatment efficiency in palm oil processing industries.

This study has several limitations that should be considered when interpreting the results. The experiment was conducted using POME from only three palm oil mills and was evaluated under a limited range of retention times, while other factors that may influence anaerobic digestion performance, such as organic composition, nutrient availability, microbial community dynamics, and biogas composition, were not extensively investigated. Future research should therefore involve a larger number of POME sources, broader operating conditions, and additional physicochemical and microbiological parameters to provide a more comprehensive understanding of the factors affecting anaerobic digestion performance. Further studies at pilot or larger scales are also recommended to evaluate the applicability of the findings under practical palm oil mill conditions.

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