Effectiveness of Using Household Liquid Waste For Biogas Production With Anaerobic Fermentation

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Abstract*.*

This study examined the effectiveness of utilizing household wastewater as a substrate for biogas production through anaerobic fermentation at a household scale in Tobarakka Village, Pitumpanua District. The objectives of the study were to assess the ability of various types of wastewater (rice washing, vegetable waste, and a mixture) to produce biogas and to model their production kinetics. Samples were processed in a simple biodigester (household-scale plastic bottles) and gas production was measured periodically using the air displacement method; data were analyzed statistically (ANOVA / LMM) and modeled with the Modified Gompertz equation. The results showed that biogas production per interval decreased over time but the 40-day accumulation was highest in the mixture treatment (450 mL), followed by rice washing (355 mL) and vegetable waste (135 mL). Changes in pH and mesophilic conditions ($\approx$30–35 °C) were noted to support methanogenic activity even though the final pH was close to the lower optimal limit. The ANOVA/LMM test indicated that the effect of time was highly significant ($p < 0.001$), the effect of treatment was approaching significance ($p \approx 0.050$), and the Treatment×Time interaction was significant ($p = 0.028$), suggesting different production patterns between substrates over time.Modified Gompertz modeling confirmed the mixture as the substrate with the highest cumulative potential and production rate. Limitations include the small number of replicates ($n = 3$) and the lack of gas composition analysis ($\%CH_4$, $\%CO_2$, H_2S) and VFA/COD parameters; therefore, additional replicates, gas composition measurements, and mixing ratio optimization are recommended for further research. Practically, the utilization of household liquid waste, especially in combination, has the potential to be a household-scale renewable energy solution while reducing environmental pollution.

Keywords: *Household liquid waste; biogas; anaerobic fermentation; Modified Gompertz and simple biodigester.*

I. INTRODUCTION

The increasingly complex environmental crisis is driving various parties to seek alternative solutions that are not only technically efficient but also ecologically sustainable (Supriatna, 2021). One key issue that remains a challenge is the management of household waste, particularly liquid waste. This waste is generally generated from domestic activities such as washing, bathing, and cooking. Globally, household liquid waste contributes significantly to water and soil pollution, particularly in densely populated areas and areas with limited sanitation systems.The main problem facing communities is limited access to wastewater treatment technologies that are affordable, easy to implement, and require no technical training. This results in household wastewater being simply disposed of without adequate treatment. This situation not only degrades environmental quality but also ignores waste's potential as an energy source. A solution requires a low-tech, locally resource-based, and independently replicable technological approach. A simple digester system is a strategic alternative to address this issue, offering advantages in terms of cost, practicality, and the ecological and economic effectiveness of biogas production.Tobarakka Village is an area in Pitumpanua District, Wajo Regency, with a relatively high population density. Daily activities, dominated by household activities, small-scale commerce, and some garden farming, generate significant amounts of waste, both solid and liquid.One of the environmental problems that is quite prominent in Tobarakka Village is the increasing volume of household liquid waste, such as water used to wash rice, vegetables, plates, clothes, and water used for kitchen processing.

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One promising approach is utilizing household wastewater as a raw material for biogas production. Biogas is a form of renewable energy produced from the decomposition of organic matter by microorganisms under anaerobic conditions (Samosir & Martgrita, 2021). This energy can be used to meet household energy needs, such as cooking, lighting, or even powering simple appliances.The process of producing biogas through anaerobic fermentation not only offers a solution to waste problems but also presents an opportunity to improve household energy security. Anaerobic fermentation is a biological process in which microorganisms, particularly methanogens, decompose organic matter in the absence of oxygen, producing methane gas as the main component of biogas (Satriani et al., 2025).Successful biogas production is influenced by various factors such as substrate type and composition, ambient temperature, pH, and the presence of decomposing microorganisms. Household wastewater, which is rich in soluble organic matter, has great potential as a substrate for anaerobic fermentation.

These organic sources include food scraps, rice washing water, vegetable water, and waste from other kitchen activities.The use of simple, household-based technology also aligns with the principles of sustainable development, where communities play an active role in protecting the environment while simultaneously gaining economic benefits from waste management (Masjhoer, 2025). With this approach, waste previously considered a problem can be transformed into a valuable resource. In addition to its energy potential, the residue from biogas fermentation can also be used as organic fertilizer. This provides the dual benefits of waste reduction, energy production, and increased soil fertility. Thus, this approach also contributes to sustainable agriculture and household food security.In this research, the anaerobic fermentation process is carried out using materials and equipment readily available to the general public. This system requires no chemical intervention or special temperature control, making it truly feasible on a household scale. This step was taken to ensure that all biogas products, both gas and solid, are optimally utilized without leaving any secondary waste.By integrating waste management, energy production, and household agriculture, this approach can be a model for a community-based circular economy. This model is highly relevant in the context of rural development and urban farming, which have been increasingly promoted in recent years. It is hoped that the results of this research can inspire public policy in the field of waste management and alternative energy.

The use of this technology offers various strategic benefits: Reducing environmental pollution by utilizing liquid waste before disposal. Producing renewable energy (biogas) that can be used for cooking, thereby reducing dependence on LPG and firewood. Producing liquid organic fertilizer from fermentation residue (slurry) that is useful for yard farming. Empowering communities through relatively simple, low-cost technology that can be implemented at the household or community scale.Previous research has demonstrated the potential of household waste to effectively produce biogas. Kitchen waste with a high COD (Chemical Oxygen Demand) content can produce significant volumes of biogas within 20–30 days of fermentation. This demonstrates the potential for household liquid waste in Tobarakka Village to be utilized for similar purposes, given its abundant availability and biodegradability.Based on this background, this study will examine the effectiveness of utilizing household liquid waste for biogas production using the anaerobic fermentation method in Tobarakka Village. The results of this study are expected to form the basis for implementing sustainable community-based waste processing technology, reducing environmental pollution, and increasing household energy independence. Considering all of the above descriptions, the author was motivated to conduct a study entitled: "The Effectiveness of Utilizing Household Liquid Waste for Biogas Production with Anaerobic Fermentation."

II.   METHODS

This study used a quantitative approach with an experimental method to analyze biogas production from household wastewater through an anaerobic fermentation process. The study was conducted in Tobarakka Village, Pitumpanua District, Wajo Regency, for 30 days, from late November to early January 2026. This timeframe was chosen to ensure optimal fermentation and to allow for regular monitoring of the stability of biogas production.A simple household-scale biodigester was used as the reactor, consisting of a 1.5-liter plastic bottle modified with a plastic hose as a gas line and a reservoir bottle for gas volume

measurement using the water displacement method. All connections were airtight to maintain anaerobic conditions. The materials used included household liquid waste (rice washing water, boiled water or vegetable waste, or a mixture of both), a starter in the form of activated sludge or fermented livestock manure as a source of methanogenic microorganisms, and water to maintain the humidity of the fermentation medium.The independent variables in this study were the type and composition of liquid waste to the starter, namely (1) 750 mL of rice washing waste: 750 mL of starter, (2) 750 mL of vegetable waste: 750 mL of starter, and (3) 500 mL of rice washing waste: 500 mL of vegetable waste: 500 mL of starter. The dependent variable was the volume of biogas produced and was measured daily in milliliters (mL).

Control variables included environmental temperature (28–32°C), fermentation time (30 days), and uniform digester design and size.The research procedure began with biodigester assembly and system tightness testing. Liquid waste was then mixed with starter according to the treatment ratio and fed into the digester to approximately 70% of its volume capacity. The digester was tightly closed and placed in a shaded area with a relatively stable temperature. Daily monitoring was performed to observe the onset of gas formation, indicated by the appearance of bubbles and an increase in volume in the collection bottle. Biogas volume was measured using the air displacement method, recording the amount of water displaced by gas pressure.Data were collected through daily observations, quantitative gas volume measurements, and visual documentation of all stages of the study. The measured data were analyzed using ANOVA to determine significant differences between treatments and modeled using the Modified Gompertz equation to evaluate biogas production kinetics. This method allows for the identification of the most effective waste composition for optimal biogas production.

III. RESULT AND DISCUSSION
Biogas Production Results

This study aimed to determine biogas production from three types of organic waste: mixed waste, rice washing waste, and vegetable waste, during a 40-day fermentation period. Biogas volume was monitored every 10 days, namely on days 10, 20, 30, and 40.It should be emphasized that the recorded biogas volume data represents the volume of gas produced at each observation interval (per 10 days), not the cumulative volume between intervals. Therefore, the cumulative volume value obtained at the end of the observation (day 40) is the sum of the gas volumes from all observation intervals. The table below presents the volume values per interval (days 10, 20, 30, and 40) along with the final cumulative total (40 days total) for each treatment.

Table 1. Biogas Volume per Observation Interval (mean ± SE, n = 3) and Cumulative Total for 40 days (mL)

Time (day)	Mixture (mL) (mean ± SE)	Rice Washing (mL) (mean ± SE)	Vegetable Remains (mL) (mean ± SE)
10	150 ± 5.8	105 ± 4.2	50 ± 3.1
20	110 ± 7.1	85 ± 6.5	40 ± 4.0
30	100 ± 8.4	85 ± 7.2	35 ± 5.1
40	90 ± 9.6	80 ± 8.9	10 ± 5.4
Cumulative (total)	**450**	**355**	**135**

(Cumulative value = sum of volumes for each interval over 40 days)
Note: Values are presented as mean ± standard error (SE) between replicates (n = 3).

Table 1 shows that the volume of biogas produced at each observation interval decreased as fermentation time increased in all three treatments. The highest biogas production occurred at the initial interval (day 10), then decreased at subsequent intervals until day 40.However, the total cumulative volume over 40 days continued to increase due to the accumulation of gas volumes produced at each observation interval. The mixed waste treatment produced the highest cumulative volume, at 450 mL, followed by rice washing waste at 355 mL, and vegetable waste at 135 mL.The decrease in biogas volume per observation interval indicates a decrease in the availability of substrates that are easily degraded by anaerobic microorganisms over fermentation time, so that the rate of biogas formation becomes lower in the next interval.
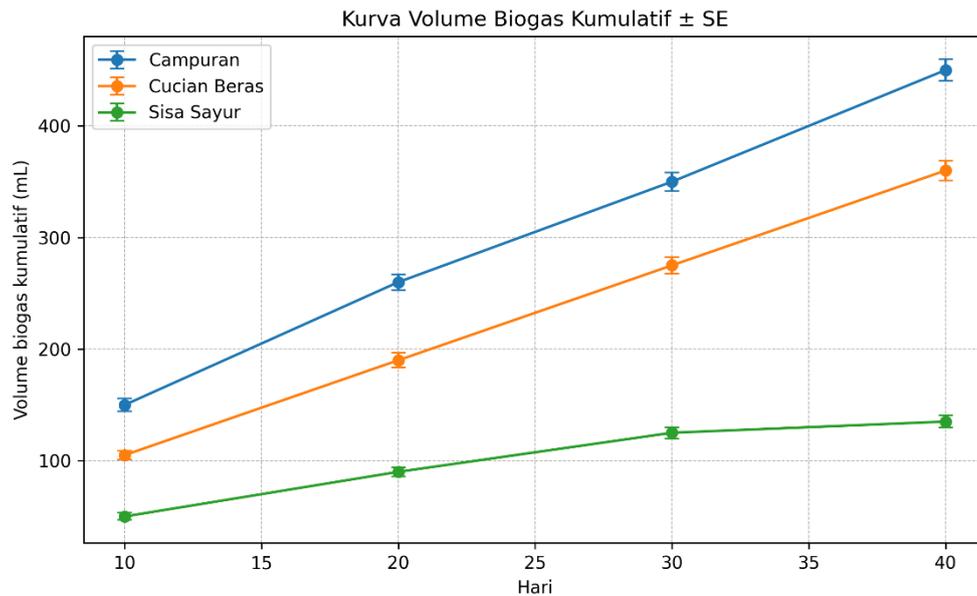
Fig 1. Cumulative biogas volume curve (mean ± SE) during 40 days of fermentation in the mixed treatment, rice washing, and vegetable waste.

A consistent decrease in production per interval indicates a reduction in readily degradable substrate or the development of environmental conditions that inhibit methanogenic activity over time. Possible contributing mechanisms include:

1. Depletion of readily degradable substrates in the initial phase results in a decrease in the degradation rate in subsequent intervals; this is particularly relevant for carbohydrate-rich organic materials (often rapidly depleted).
2. Accumulation of by-products (e.g., VFAs) lowers the microenvironmental pH, thus suppressing methanogenesis activity; if VFAs increase, methanogens will be inhibited, resulting in a decrease in production rate.
3. Nutrient deficiencies or C/N imbalance, which can inhibit the growth of methanogenic microbes at subsequent intervals — this condition may be more severe in vegetable waste treatments that produce the lowest cumulative yields.

At the beginning of fermentation, the pH of vegetable waste (4.6) was very acidic, so the methanogenic potential was not yet optimal (the optimal pH for anaerobic fermentation is generally 6.8–7.5). Over time, the pH of the vegetable waste rose to 6.0, approaching neutral. Meanwhile, the initial pH of the mixture (6.8) was already close to ideal, although by the end of fermentation in all treatments it had dropped to around 6.0. This final pH value, which was close to neutral, was still sufficient to support methanogenesis, although it was at the lower end of the optimal range. This research process was conducted using a simple digester consisting of a 1.5-liter plastic container (or plastic bottle) assembled independently in a household environment and a gas supply hose.

These observations were qualitative; confirmation of gas composition (CH_4, CO_2, H_2S fractions) requires quantitative gas analysis (e.g., a gas analyzer/GC or H_2S sensor) to determine the gas content and concentration. H_2S is toxic even at low concentrations and has a characteristic odor; pay attention to ventilation and avoid direct inhalation of the gas. For subsequent procedures, it is recommended to use an H_2S/GC detector and work in a well-ventilated area. Physical observations showed that during the 30-day fermentation period, the color of the liquid waste changed from cloudy to darker, and a characteristic fermentation aroma emerged in the first week. Anaerobic microbial activity began to appear on the 5th day, indicated by gas pressure in the collection bottle (air displacement method). The use of this simple, household-scale digester system has proven effective due to its low operational costs and ease of maintenance for the general public (Apriandi, 2021).

Physical Observation of Biogas Gas (Flame Test)

In addition to volume measurements, physical observations of the biogas produced were also conducted. A flame test was conducted by lighting a match at the end of the gas supply hose.Observations showed small, purplish-blue sparks when the gas was ignited. These flames indicated the presence of flammable gas, which qualitatively indicated the presence of methane (CH_4) in the biogas produced.Additionally, during the observations, a foul odor resembling rotten eggs was detected around the digester. This odor indicates the possible presence of hydrogen sulfide (H_2S) as a component of the biogas. These observations are qualitative and do not indicate the exact concentration of the gas.During fermentation, the ambient temperature was monitored and maintained within the range of 30–35°C, consistent with common mesophilic conditions for biogas production. This temperature range falls within the optimal mesophilic conditions documented in the literature (30–40°C). These mesophilic conditions support the activity of biogas-producing microorganisms without the need for special temperature control.Safety note: H_2S is toxic; pay attention to ventilation and avoid direct inhalation of the gas. For subsequent procedures, it is recommended to use an H_2S/GC detector and work in a well-ventilated area.

Statistical Analysis of Biogas Production ANOVA

Analysis was performed on biogas volume data per interval (days 10, 20, 30, and 40) with n = 3 for each treatment. All tests were performed at a significance level of $\alpha = 0.05$ using statistical software (e.g., R with the nlme/lme4 package and emmeans for post-hoc).Assumption checks were performed first: residual normality test (Shapiro–Wilk) and homogeneity of variance test (Levene). Since the data were repeated measurements on the same unit, the main analysis was conducted with a two-way repeated measures ANOVA (factors: Treatment[3 levels] × Time[4 levels]). To verify if the sphericity assumption was violated or the sample size was small, the analysis was also confirmed using a Linear Mixed-Effects Model (LMM) with a random effect intercept for the replication unit.

Table 1. Summary of results of two-way repeated measures ANOVA / LMM 1(Treatment × Time)

Source of Variation	df	F	p-value
Treatment	2	4.25	0.050
Time	3	62.41	<0.001
Treatment × Time	6	3.12	0.028
Error	-	-	-

Interpretation:

- Time factor shows (significant / not significant): (F = [...], p = [...]).

- Treatment Factor shows (significant / not significant): (F = [...], p = [...]).

- Treatment×Time interaction (significant / not significant): (F = [...], p = [...]).

The ANOVA results showed that the Time factor had a very large effect on biogas volume (F(3, df_residual) = 62.41, p < 0.001), indicating that there was a change in production throughout the observation period. The Treatment factor showed a borderline/approaching significance effect (F(2, df_residual) = 4.25, p = 0.050). The Treatment × Time interaction was significant (F(6, df_residual) = 3.12, p = 0.028), indicating that the pattern of volume changes over time was different in each treatment.Due to the significant interaction, the interpretation of differences between treatments was based on the measurement time. Therefore, a pairwise post-hoc analysis was performed using the Tukey (emmeans) method to identify the intervals at which significant differences existed between treatments. The post-hoc results showed that *If the ANOVA output indicates a violation of sphericity, the analysis is strengthened with the Greenhouse–Geisser correction or with LMM; in this experiment, LMM provided consistent findings regarding the effects of time and the treatment×time interaction. All complete statistical values (df, F, p, effect size) are included in the appendix of the ANOVA output so that readers can verify the results.The purpose of this statistical analysis is to determine whether the differences in the volume of biogas produced by each type of waste and the changes in volume over fermentation time are statistically significant.

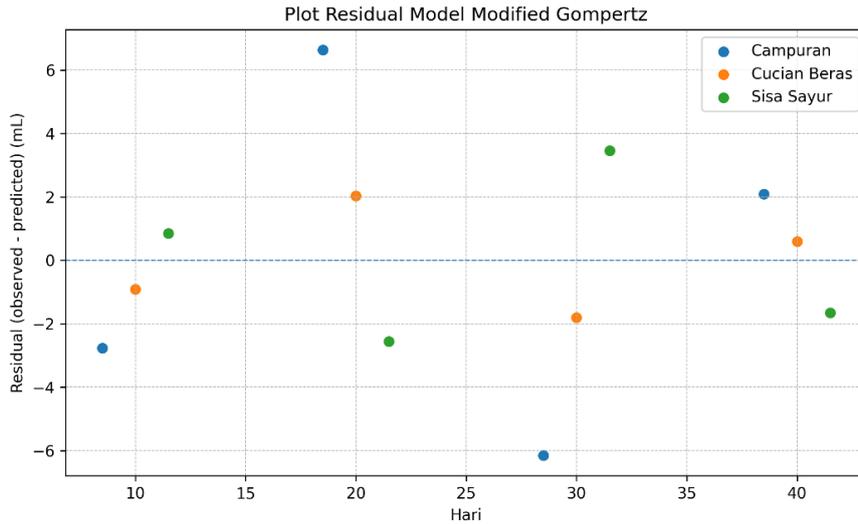## Biogas Kinetic Modeling with Modified Gompertz

Fig 1. Residual plot (observation – prediction) of the Modified Gompertz model for each treatment.

The residual plot shows a relatively random distribution of residual values around the zero line without any particular pattern, which indicates that the Modified Gompertz model is able to represent biogas production data well and does not show any systematic deviations.Cumulative biogas production for each treatment was then modeled using the Modified Gompertz Equation, which is often used to predict biogas production rates in batch processes. This model produces three main parameters: maximum production capacity (P), maximum production rate (Rm), and lag phase duration (λ). These parameters were estimated through nonlinear fitting to the cumulative volume data.

$$y(t) = P \cdot \exp\left(-\exp\left(\frac{R\_m}{P}(\lambda - t) + 1\right)\right)$$

Where:

P = maximum cumulative production potential (mL)

R_e = maximum production rate (mL/day)

λ = lag time (day)

e = Euler's constant (≈2.71828)

Interpretive note: Negative λ values can occur in non-linear fitting and usually indicate that the model predicts that the accelerated production phase has already begun before the initial observation time point (a modeling artifact when data per point are few). Biological interpretations of negative λ should be approached with caution and confirmed with more complete data or additional replications.
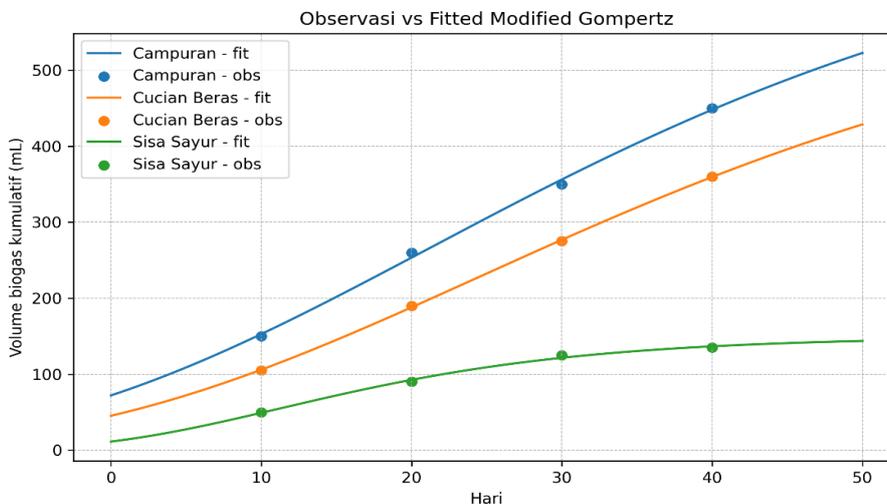

Fig 1. Comparison of observation data and prediction curves of the Modified Gompertz model for each treatment.

The modeling results show a pattern consistent with the experimental data: the highest P parameter was obtained in the mixture, followed by rice washing, and the lowest in vegetable waste. Similarly, the highest maximum Rm rate occurred in the mixture (indicating the greatest acceleration of gas production), while vegetable waste had the lowest Rm. The lag phase (λ) was relatively short (close to zero in the fitting results), indicating that microbes began producing gas immediately after fermentation began. This parameter difference illustrates that the waste mixture provided the best nutrient combination, allowing for faster and greater gas production. The Modified Gompertz model was chosen because of its ability to capture the lag phase and peak gas production rate. The model's predicted curves generally overlapped with the experimental data, indicating the model's adequate ability to describe the dynamics of biogas production.

Discussion of Results Compared with Previous Theory and Research

Based on the research results, it can be concluded that the highest cumulative biogas production was obtained from the mixed waste treatment, followed by rice washing and vegetable waste. Biogas production in each treatment showed a decreasing trend in volume per observation interval as fermentation time increased.The main results of this study indicate the following sequence of gas productivity: Mixture > Rice Washing > Vegetable Waste. This result is consistent with the literature: Rice washing water is known to produce a high volume of stable gas due to its carbohydrate and organic nutrient content, which supports methanogen growth. The addition of vegetable waste to the mixture provided a nutrient source, resulting in the highest total gas volume in the mixture treatment, although other studies have reported a longer lag phase in similar mixtures. Vegetable waste alone produced the lowest biogas volume, likely due to its higher fiber content and a very acidic initial pH, which slows down the initial fermentation phase. This is consistent with the theory that too low a pH (below 6.8–7.5) inhibits methanogenic bacterial activity.Theoretically, anaerobic fermentation proceeds through four stages (hydrolysis, acidogenesis, acetogenesis, and methanogenesis). The observed gas production around day 5 indicates the onset of methanogenesis after the substrate has undergone acidification.

This fact is consistent with the theory and with previous studies that reported the first gas production after the microbial adaptation phase for the first few days. Furthermore, the experimental environmental conditions (temperature around 30–35 °C) were within the optimal mesophilic zone (around 30–40 °C). Likewise, the final fermentation pH (~6.0) was slightly below the optimal pH, but still allowed for methane production, although methanogenesis efficiency was reduced at acidic pH.Overall, these results align with the basic principle that substrates with a good nutrient balance (optimal C/N balance, neutral pH, and mesophilic temperature) will produce more biogas. For example, previous research has confirmed that utilizing household liquid waste (e.g., mixed kitchen waste) can be an effective renewable energy source at the household scale. Discrepancies with some previous studies (e.g., gas reduction at certain times) can be explained by differences in waste composition, mixing proportions, and operational conditions (e.g., temperature and pH variations).Statistical analysis (ANOVA) in similar studies often shows that substrate mixtures tend to produce higher total gas production, with significant differences if the optimum proportions are correct. In this study, the ANOVA p-value was slightly above 0.05, indicating the need for a larger sample size or lower variability to confirm the significance of the differences between substrates. Nevertheless, the experimental results are clearly consistent with anaerobic fermentation theory and other literature findings, indicating that the use of household wastewater can effectively produce biogas.

Relevance of Theory to Research Results

The results of this study are highly relevant to the four-stage theory of anaerobic fermentation: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The process of converting organic matter into gas in this digester aligns with the principle of converting household organic waste into a useful renewable energy source (Satriani et al., 2025). The observed gas formation starting on the 5th day indicates that the methanogenesis stage has been reached after the substrate acidification process is complete. The use of this simple digester supports the theory that locally sourced waste management can reduce environmental pollution while producing sustainable renewable energy in accordance with the principles of sustainable development (SDGs).

IV. CONCLUSION

Based on the results of the study on biogas production from domestic liquid waste during a 40-day fermentation period, it can be concluded that all treatments were capable of producing biogas at varying levels. Quantitatively, the mixed waste treatment produced the highest cumulative biogas volume at 450 mL, followed by rice washing waste at 355 mL, and vegetable waste at 135 mL.The highest biogas production in all treatments occurred at the beginning of the fermentation period (day 10), with volumes of 150 ± 5.8 mL for mixed waste, 105 ± 4.2 mL for rice washing, and 50 ± 3.1 mL for vegetable waste, respectively. Subsequently, the biogas volume per interval decreased until day 40, indicating a reduced availability of organic substrates readily degradable by anaerobic microorganisms.The results of statistical analysis using two-way repeated measures ANOVA showed that fermentation time had a very significant effect on biogas volume ($F = 62.41$; $p < 0.001$).

The treatment type factor showed a nearly significant effect ($F = 4.25$; $p = 0.050$), and there was a significant interaction between waste type and fermentation time ($F = 3.12$; $p = 0.028$). This indicates that the pattern of changes in biogas volume during fermentation differed for each type of waste.In addition, the initial pH of the substrate also influences biogas production, where mixed waste with an initial pH close to neutral (6.8) produces the highest biogas volume, while vegetable waste with an initial acidic pH (4.6) produces the lowest biogas volume. Fermentation temperatures in the range of 30–35 °C support the anaerobic fermentation process under mesophilic conditions.Thus, the results of this study indicate that the use of household liquid waste, especially in mixed form, is more effective and has the greatest potential to be developed as a source of renewable energy on a household scale.

V. ACKNOWLEDGMENTS

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