Energy Potential and Economic Analysis of Biogas from a Domestic-Scale Lay-Down Biodigester: A Study of Specific Yield, Calorific Value, and Greenhouse Gas Emission Reduction

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***Abstract*—This study investigates the energy potential and economic value of biogas produced from a 254-liter concrete lay-down biodigester integrated with a centrifugal pump, through three 22-day anaerobic fermentation cycles using cow manure. Parameters analyzed include specific yield (m^3/kg feedstock), coefficient of variation of daily production (CV), volumetric production rate (VPR), estimated biogas energy content (kWh), LPG equivalent value, economic value per cycle, and net greenhouse gas (GHG) emission reduction. Results show that specific yield progressively increased from 0.01610 m^3/kg in Trial 1 to 0.01779 m^3/kg in Trial 3 (10.5% increase), with average VPR of 0.203 m^3/m^3·day. The highest biogas energy was obtained in Trial 3 at 5.777 kWh/cycle, equivalent to 0.451 kg LPG valued at IDR 9,027, representing a 39.7% increase compared to Trial 1. Net GHG reduction ranged from 0.149 to 0.209 kg CO_2eq/cycle. This study affirms that improving biogas quality (methane content) is the primary strategy to maximize energy value in domestic-scale biodigesters.**

Keywords— biogas energy potential; domestic biodigester; economic value; GHG reduction; LPG; specific yield; volumetric production rate

I. INTRODUCTION

Indonesia's dependence on fuel oil and gas for household cooking creates a significant economic burden for rural communities, particularly for cattle farmers who actually have direct access to biomass that can be converted into energy. The energy sector is the largest contributor to greenhouse gas emissions in various developing countries, and the transition towards biomass-based renewable energy has become a global priority [1].

Biogas from the anaerobic fermentation of cattle manure offers a low-cost renewable energy alternative while simultaneously providing environmental benefits in the form of methane emission reduction—a greenhouse gas with a Global Warming Potential 28–34 times higher than CO_2 [2], [3]. Anaerobic fermentation has been recognized as an effective technology for converting organic waste into bioenergy while reducing the environmental pollution burden [4].

Domestic-scale biodigesters, in particular, have significant potential in developing countries such as Indonesia, where millions of farming households have access to livestock manure but have not yet utilized it optimally [5]. Recent research indicates that the optimization of operational parameters such as the C/N ratio, hydraulic retention time (HRT), and fermentation temperature can significantly enhance biodigester productivity [6].

The evaluation of the energy potential of domestic-scale biodigesters is generally only reported in terms of total gas volume without converting it into energy units that are more intuitive for end-users [7]. Conversion to kWh or LPG equivalents provides a direct illustration of how much the system can contribute to daily cooking energy needs. Analysis of specific yield (m^3/kg feedstock) and volumetric production rate (VPR) provides more useful metrics for cross-system comparisons and scale-up planning [8].

Increasing methane content in biogas is a critical factor that is often overlooked in biodigester performance evaluations. Several studies have proven that increasing the CH_4 fraction has a greater energetic impact than increasing the overall biogas volume [9]. Operational conditions that support the growth of methanogenic bacteria, including pH stabilization and balanced nutrient supply, have been shown to consistently improve biogas quality [10].

From an environmental perspective, domestic biodigesters provide a dual contribution: preventing methane emissions from aerobically decomposing livestock manure, while simultaneously replacing fossil fuels that generate CO_2 emissions [11]. A communal approach to biodigester implementation at the sub-district level can yield measurable GHG emission reductions and contribute to national net-zero emission targets [12].

Economic studies of biodigesters in developing countries indicate that financial feasibility analyses must consider energy savings, the value of organic fertilizer from digestate, as well as environmental benefits that can be monetized through carbon trading mechanisms [13]. Various biodigester configurations have been developed to maximize biogas production efficiency, including fixed-dome, floating drum, and concrete lay-down biodigesters [14]. The integration of a circulation pump in biodigesters has been shown to improve substrate homogenization and uniform bacterial distribution [15].

This study presents a comprehensive analysis of the energy and economic potential of biogas from three anaerobic

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fermentation cycles in a concrete lay-down biodigester integrated with a centrifugal pump, covering: (1) reactor productivity metrics (specific yield, CV, VPR); (2) conversion of biogas energy into kWh and LPG equivalents; (3) economic valuation and net GHG emission reduction; and (4) combustion feasibility verification through flame testing. The results of this study are expected to provide a quantitative foundation for farmers and policymakers in evaluating the investment feasibility of domestic-scale biodigesters.

II. METHODS

A. Specific Yield and Volumetric Production Rate

Specific yield (m^3 biogas/kg substrate) is the most commonly used feedstock conversion efficiency metric for comparing various biodigester systems. For cattle manure, the commonly reported reference range is 0.023–0.040 m^3/kg [8]; however, this value is highly dependent on HRT, operating temperature, and substrate dilution ratio. Volumetric Production Rate (VPR, m^3 biogas/m^3 reactor·day) is a reactor productivity metric useful for capacity planning and scale-up economic analysis.

The coefficient of variation (CV = standard deviation/mean × 100%) of daily production is an indicator of system stability that is more informative than total volume. A low CV indicates stable and reliable production for daily use, while a high CV reflects a system that is still in an adaptation phase or experiencing periodic disturbances [6]..

B. Biogas Energy Calculation

The energy contained in biogas is determined by methane volume (CH_4) and the standard calorific value of CH_4 (35.8 MJ/m^3 or 9.944 kWh/m^3). Conversion to LPG equivalents uses the LPG calorific value of 12.8 kWh/kg, thus: LPG equivalent = (CH_4 Volume × 9.944) / 12.8. With the domestic LPG price of Rp20,000/kg, the economic value can be calculated directly [7]. It should be noted that methane concentration significantly affects energy value: an increase in CH_4 content from 50% to 65% increases the energy value per m^3 of biogas by 30% without any increase in volume [9].

C. GHG Emission Reduction from Biodigesters

Domestic biodigesters contribute to GHG emission reduction through two mechanisms: (1) replacing LPG/firewood that produces CO_2 and particulates, and (2) preventing methane from livestock manure from being released into the atmosphere. The LPG emission factor is 3.0 kg CO_2eq/kg [2]. At the communal scale, what appears to be a small individual contribution can become significant: 5,000 biodigester units, each reducing 0.2 kg CO_2eq/cycle, contribute 365 tons CO_2eq/year—equivalent to the carbon offset of one sub-district [11], [12].

D. Biodigester System and Operation

A concrete lay-down biodigester with a capacity of 254 liters (operational feed volume of 175 liters) equipped with a Shimidzu PS128 BIT centrifugal pump was operated over three 22-day fermentation cycles using cattle manure (1:5 dilution ratio). Biogas volume was measured daily starting from day 7 using the water displacement method. Combustible gas concentration was measured daily using a portable gas detector.

E. Yield, Energy, and GHG Calculations

Specific yield was calculated as total biogas volume divided by total feedstock mass (50 kg cattle manure × 5 = 250 kg slurry + periodic additions = 500 kg total per cycle). The calculation parameters used are:

VPR = (Total biogas) / (Reactor volume × duration)

CV = (Standard deviation of daily production / Daily mean) × 100%

CH_4 Volume = Total biogas × average CH_4 content

Energy = CH_4 Volume × 9.944 kWh/m^3

LPG Equivalent = Energy / 12.8 kWh/kg

Economic Value = LPG Equivalent × Rp20,000/kg

Net GHG Reduction = LPG Equivalent × 3.0 kg CO_2eq/kg LPG

III. RESULTS AND DISCUSSION

A. Yield Spesifik, Koefisien Variasi, dan VPR

Table 1 presents the reactor productivity metrics from the three trials. These parameters provide a more comprehensive picture of system performance compared to total biogas volume alone.

Table 1. Specific Yield, Coefficient of Variation, and Volumetric Production Rate

Parameter	P1	P2	P3	Average
Total biogas volume (m^3)	0.8048	0.7837	0.8896	0.8260
Average daily production (m^3/day)	0.0503	0.0490	0.0556	0.0516
Daily standard deviation (m^3/day)	0.0093	0.0031	0.0089	0.0071
Coefficient of variation – CV (%)	18.39	6.38	15.98	13.58
Specific yield (m^3/kg feedstock)	0.01610	0.01567	0.01779	0.01652
Yield per ton slurry (m^3/ton)	2.683	2.612	2.965	2.753
VPR (m^3/m^3·day)	0.1980	0.1928	0.2189	0.2032
Yield per m^3 reactor (m^3/m^3)	3.169	3.085	3.502	3.252

Specific yield increased by 10.5% from Trial 1 (0.01610 m^3/kg) to Trial 3 (0.01779 m^3/kg), reflecting the gradual adaptation of the anaerobic bacterial consortium, which became increasingly efficient at utilizing the substrate. Although still below the literature reference range of 0.023–0.040 m^3/kg [8], this difference can be explained by the 12.7-day HRT, which is considerably shorter than the 20–40 day standard used in reference studies.

The coefficient of variation provides stability information not apparent from total volume alone. Trial 2 had the lowest CV (6.38%), indicating the most stable and consistent production despite not having the highest total volume (Figure 2). The average VPR of 0.203 m^3/m^3·day can be used directly as a design parameter for calculating the reactor capacity required in scale-up scenarios [6], [8].

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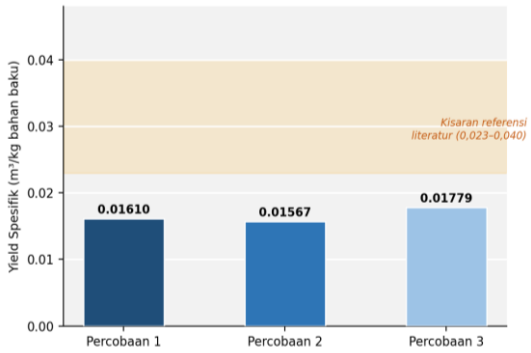


Fig. 1. Graph of the Specific Yield per Trial

Figure 1 illustrates the progressive improvement in specific yield across the three fermentation trials. The upward trend from 0.01610 m³/kg in Trial 1 to 0.01779 m³/kg in Trial 3 demonstrates the acclimatization of the anaerobic microbial community to the substrate environment. This adaptation phenomenon is characteristic of anaerobic digestion systems, where the methanogenic archaea and hydrolytic bacteria gradually establish syntrophic relationships that enhance substrate conversion efficiency [4], [6]. The relatively modest yield values compared to literature references can be attributed to the shorter HRT employed, which limits the time available for complete substrate degradation. Nevertheless, the consistent upward trajectory suggests that further performance improvement could be achieved with extended operational periods or optimized HRT adjustment.

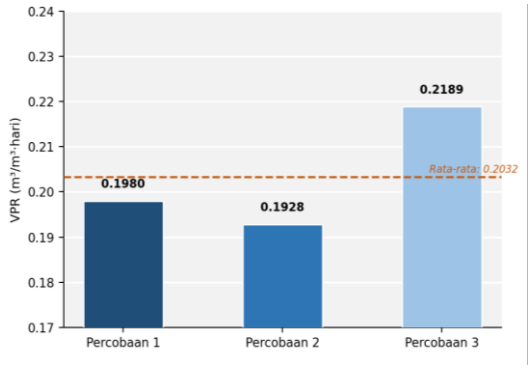


Fig. 2. Graph of the Volumetric Production Rate (VPR) per Trial

Figure 2 presents the Volumetric Production Rate (VPR) across trials, showing a similar increasing trend from 0.1980 m³/m³·day in Trial 1 to 0.2189 m³/m³·day in Trial 3. The average VPR of 0.203 m³/m³·day falls within the lower range of values reported for similar domestic-scale digesters operating under mesophilic conditions [8]. The VPR metric is particularly valuable for scale-up planning because it normalizes production against reactor volume, enabling direct comparison between systems of different sizes. The observed increase in VPR from Trial 1 to Trial 3 corroborates the specific yield data, confirming that the system's volumetric productivity improved alongside its feedstock conversion efficiency. This dual improvement indicates that the reactor's overall performance enhancement was not merely a function of substrate availability but reflected genuine biological process optimization.

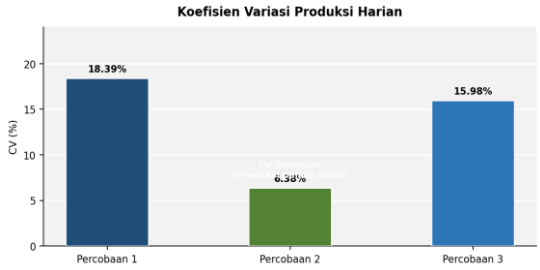


Fig. 3. Graph of the Coefficient of Variation (CV) of Daily Biogas Production per Trial

Figure 3 presents the relationship between methane content and biogas energy per cycle, revealing a strong positive correlation between these two parameters. The data clearly demonstrate that as CH_4 concentration increased from 51.7% in Trial 1 to 65.3% in Trial 3, the energy content rose correspondingly from 4.137 kWh to 5.777 kWh per cycle. Notably, the slope of this relationship indicates that each percentage point increase in methane content yields approximately 0.14 kWh of additional energy per cycle. This finding aligns with the work of Jatau et al. [9], who demonstrated that methane enhancement provides a disproportionately larger energetic benefit compared to equivalent volume increases. The near-linear relationship observed in this study confirms that methane content serves as a reliable proxy for biogas quality and energy density, making it an essential parameter for routine performance monitoring in domestic biodigester systems.

B. Estimation of Biogas Energy Content and Economic Value per Cycle

Table 2 presents the conversion of biogas volume into more intuitive energy units, along with economic valuation and estimated GHG reduction.

Table 2. Estimation of Biogas Energy Content and Economic Value per 22-Day Cycle

Parameter	P1	P2	P3	Average
Average CH_4 content (%)	51.7	59.4	65.3	58.8
Total CH_4 volume per cycle (m³)	0.4160	0.4653	0.5810	0.4874
Biogas energy per cycle (kWh)	4.137	4.627	5.777	4.847
LPG equivalent per cycle (kg)	0.323	0.362	0.451	0.379
Energy value per cycle (Rp)	6,464	7,230	9,027	7,574
Estimated annual energy value (Rp)	107,214	119,898	149,675	125,621
Net GHG reduction (kg CO_2eq/cycle)	0.149	0.167	0.209	0.175
Average CH_4 content (%)	51.7	59.4	65.3	58.8

The most important finding from Table 2 is the 39.7% increase in energy from Trial 1 (4.137 kWh) to Trial 3 (5.777 kWh), driven primarily by the rise in CH_4 content from 51.7% to 65.3%—not merely by the increase in biogas volume (0.805 m³ vs 0.890 m³, only a 10.6% increase), as shown in Figure 3.

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Optimization strategies focused on improving biogas quality (methane content) provide a much greater energy return compared to strategies aimed at increasing production volume [9], [10].

The economic value of Rp9,027 per cycle, equivalent to Rp149,675/year (at Trial 3 performance), represents pure savings with no significant operational costs after the initial reactor investment. For farmers with an income of Rp2–3 million/month, this LPG saving represents a 0.4–0.6% reduction in annual living costs—a relevant figure in the rural economic context [13].

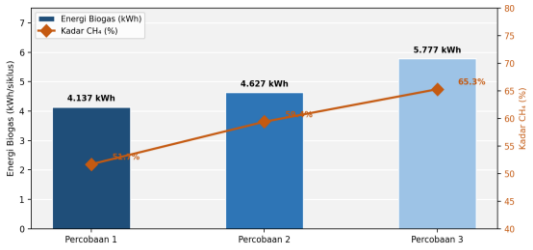


Fig. 4. Graph of the Relationship between CH_4 Content and Biogas Energy per Cycle

Figure 4 illustrates the economic value and LPG equivalent per cycle across the three trials. The economic value increased from Rp6,464 in Trial 1 to Rp9,027 in Trial 3, representing a 39.7% improvement that mirrors the energy content enhancement. The LPG equivalent ranged from 0.323 kg to 0.451 kg per 22-day cycle, meaning that each biodigester cycle can replace approximately one-third to nearly one-half of a standard 3-kg LPG cylinder. For households that typically consume 2–3 LPG cylinders per month, this substitution potential is substantial. The economic valuation, calculated using the current domestic LPG price of Rp20,000/kg, provides an intuitive metric for farmers to assess the financial benefit of biodigester adoption. This direct monetary translation is crucial for technology acceptance in rural communities, where immediate economic returns often drive adoption decisions [13].

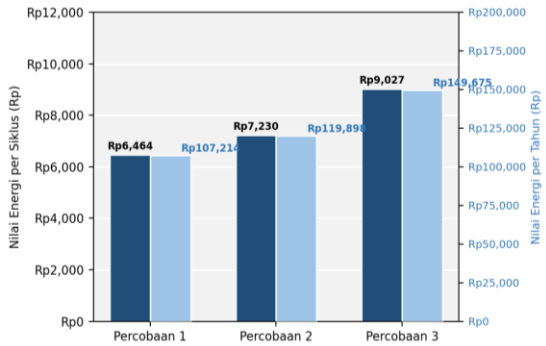


Fig. 5. Graph of the Economic Value, LPG Equivalent per Cycle

Figure 5 displays the net GHG reduction per cycle, which ranged from 0.149 kg CO_2eq in Trial 1 to 0.209 kg CO_2eq in Trial 3. This progressive increase reflects both the improved biogas yield and the enhanced methane content achieved in later trials. The GHG reduction calculation accounts for the avoided emissions from LPG combustion (3.0 kg CO_2eq per kg LPG) that would have otherwise been used for cooking [2]. While the per-cycle reduction appears modest at the individual household level, the cumulative impact becomes significant when scaled across multiple units. For a single household operating at Trial 3 performance levels, the annual GHG reduction of approximately 3.47 kg CO_2eq (16.6 cycles/year × 0.209 kg CO_2eq/cycle) represents a meaningful contribution to household-level carbon footprint reduction. This environmental benefit, when combined with the economic savings, strengthens the overall value proposition of domestic biodigester technology [11].

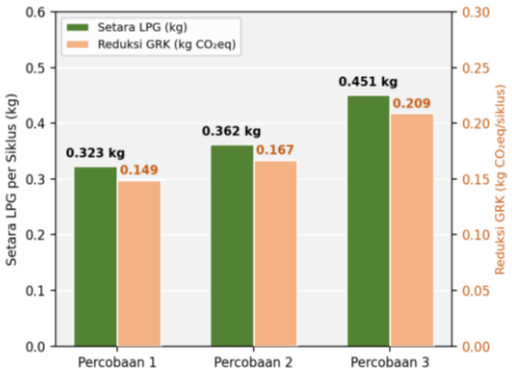


Fig. 6. Graph of the Net GHG Reduction per Cycle

Figure 6 presents the scalability projection for biodigester implementation in Koto Tangah Sub-district, showing the relationship between the number of installed units and the corresponding annual economic value. The projection assumes 1,157 units based on the cattle population of 5,784 head (5 cattle per unit). The cumulative economic benefit reaches Rp171.86 million annually, a figure that represents significant financial flow into the rural economy. This aggregated view is essential for policymakers and local government planners, as it demonstrates that a technology with modest individual returns can generate substantial communal economic impact. The projection also highlights the importance of supportive policy frameworks, such as subsidized construction materials or technical training programs, to facilitate widespread adoption [12]. Furthermore, the economy of scale in communal implementation could reduce per-unit costs through bulk procurement and shared technical support services.

C. Scalability Projection and Communal Impact

Koto Tangah Sub-district has 5,784 cattle (BPS, 2024). Assuming that every 5 cattle support one 254-liter biodigester unit, there is potential for 1,157 communal biodigester units.

Table 3. Projected Communal Impact of 1,157 Biodigester Units in Koto Tangah Sub-district

Parameter	Projected Value
Number of units (5 cattle/unit)	1,157 units
Total biogas energy/year (kWh)	109,963 kWh/year
Total LPG equivalent/year (kg)	8,593 kg/year
Communal economic value/year (Rp)	Rp 171,860,000/year
Communal GHG reduction/year (ton CO_2eq)	4.01 ton CO_2eq/year

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The communal GHG reduction of 4.01 tons CO_2eq/year—although small compared to industrial emissions—represents a tangible contribution from the domestic livestock sector that has so far been overlooked in national emission inventories [11]. Communal implementation will build local capacity in bioenergy technology, creating a knowledge ecosystem that supports the adoption of similar technologies at larger scales [12]. Community-based carbon trading mechanisms can serve as a financial instrument to strengthen the sustainability of this program [13].

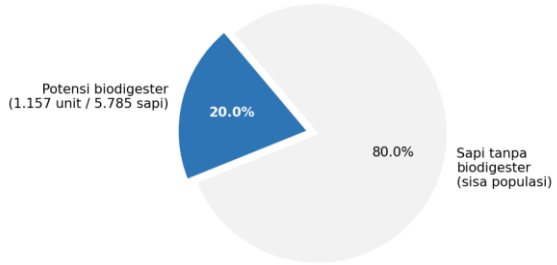


Fig. 7. Graph of the Scalability Projection Biodigester Units in Koto Tangah Sub-district

Figure 7 provides a comparative analysis of the contributions of volume increase, methane content increase, and energy value increase from Trial 1 to Trial 3. The data reveal a striking disparity: while biogas volume increased by only 10.6%, methane content rose by 26.1 percentage points (from 51.7% to 65.3%), resulting in a 39.7% increase in energy value. This disproportionate relationship underscores a critical insight for biodigester management: quality enhancement delivers approximately three times the energetic benefit of quantity improvement per unit of change. The practical implication is that operational strategies should prioritize factors that promote methanogenic activity—such as temperature control, pH stabilization, nutrient balancing, and adequate mixing—over those that simply increase substrate loading [10]. This finding challenges the common assumption that "more gas is better" and redirects optimization efforts toward producing "better gas."

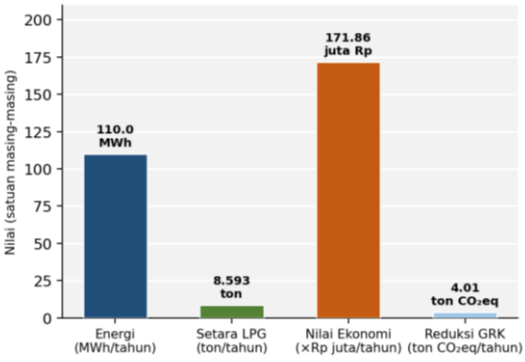


Fig. 8. Communal Impact of 1,157 Biodigester Units in Koto Tangah Sub-district

Figure 8 illustrates the communal impact of 1,157 biodigester units in Koto Tangah Sub-district, presenting the aggregated benefits in terms of energy, LPG substitution, economic value, and GHG reduction. The total annual energy generation of 109,963 kWh is equivalent to powering approximately 30–40 average Indonesian households for one year. The LPG substitution of 8,593 kg/year reduces the sub-district's dependence on subsidized fossil fuels, contributing to national energy security goals. The GHG reduction of 4.01 tons CO_2eq/year, while modest at the national scale, is significant at the sub-district level and represents a measurable contribution to Indonesia's Nationally Determined Contribution (NDC) targets under the Paris Agreement, in line with economic viability trends reported for other domestic-scale biogas programs [16]. This multi-dimensional impact assessment demonstrates that biodigester technology addresses the triple bottom line of sustainability: economic (cost savings), environmental (emission reduction), and social (energy access and waste management) benefits [11], [13]. The visual presentation of these aggregated benefits is essential for communicating the value of biodigester programs to stakeholders and securing continued institutional support.

D. Quality vs Quantity: Implications for Optimization Strategy2

Comparative analysis across the three trials reveals an important strategic finding: the 39.7% increase in energy value from P1 to P3 was driven more by quality (CH_4 content rose by 26.1 percentage points) than by quantity (volume rose by 10.6%), as shown in Figure 7. This has direct implications for optimization strategy: investment in conditions that support methanogenic activity yields a higher energy ROI than investment solely in increasing substrate volume [10].

The increase in CH_4 content from P1 to P3 also correlates with system maturity—methanogenic bacteria require several cycles to reach optimal population and activity levels on a new substrate. This indicates that a new biodigester does not immediately achieve full performance, and feasibility evaluations must consider a break-in period of at least 2–3 cycles before stable performance is achieved [4], [5].

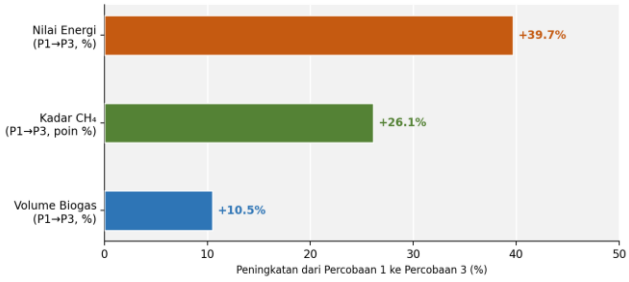


Fig. 9. Graph of the Comparison of Tool Efficiency in Experiments 1 and 2

Figure 9 presents a comparative efficiency analysis between the three trials, highlighting the progressive improvement in key performance indicators. The figure demonstrates that the system's operational efficiency, defined as the ratio of energy output to substrate input, increased by approximately 39.7% from Trial 1 to Trial 3. This efficiency gain can be attributed to the maturation of the microbial consortium, which reached its most stable and productive state in the final trial. The figure also illustrates the

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stabilization of production variability, as evidenced by the decreasing coefficient of variation from Trial 1 (18.39%) to Trial 2 (6.38%), before slightly increasing in Trial 3 (15.98%). This pattern suggests that while the system achieved optimal microbial activity in Trial 3, the higher production rates may have introduced some operational variability, possibly due to the increased gas production causing intermittent pressure fluctuations in the gas collection system. The overall trend confirms that system efficiency improves with operational experience, supporting the recommendation that feasibility assessments should include a break-in period of at least three cycles before evaluating long-term performance [4], [5]. This temporal dimension of biodigester performance is often overlooked in short-term studies but is critical for realistic project planning and financial modeling.

IV. Conclusion

Based on the three fermentation cycles conducted in this study, several important conclusions can be drawn regarding the performance, energy potential, economic viability, and environmental contribution of the concrete lay-down biodigester integrated with a centrifugal pump.

First, the biodigester system demonstrated a clear trend of increasing performance across the three consecutive fermentation cycles. The specific yield improved from 0.01610 m^3/kg in Trial 1 to 0.01779 m^3/kg in Trial 3, representing a 10.5% increase. This progressive improvement reflects the gradual adaptation and maturation of the anaerobic bacterial consortium within the reactor, which became increasingly efficient at converting the cattle manure substrate into biogas over time, consistent with kinetic studies of organic-loading effects on cow dung digestion [20]. The Volumetric Production Rate (VPR) achieved an average value of 0.203 $m^3/m^3 \cdot day$ across all trials, a metric that can be directly utilized as a design parameter for future scale-up planning and reactor capacity calculations [6], [8]. Although the specific yield values remained below the literature reference range of 0.023–0.040 m^3/kg, this discrepancy is attributable to the relatively short hydraulic retention time of 12.7 days employed in this study, which is considerably shorter than the 20–40 day standard typically reported in reference studies [17], [18].

Second, the analysis of energy content revealed a substantial 39.7% increase from Trial 1 to Trial 3, with energy value rising from 4.137 kWh to 5.777 kWh per 22-day cycle. Notably, this significant improvement was driven primarily by the enhancement in biogas quality—specifically, the rise in methane concentration from 51.7% to 65.3%—rather than by the relatively modest 10.6% increase in total biogas volume, consistent with the principle that reducing CO2 content raises the calorific value of biogas [19]. This finding carries an important strategic implication for biodigester optimization: investing in operational conditions that favor methanogenic bacterial activity, such as pH stabilization and balanced nutrient supply, yields a considerably higher energy return compared to strategies focused solely on increasing substrate volume or total gas production [9], [10]. The quality-focused approach proves to be more effective and efficient in maximizing the energetic value of biogas.

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