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International Journal on Advanced Technology, Engineering, and Information System
https://ojs.transpublika.com/index.php/IJATEIS
Online ISSN 2828-5425

https://doi.org/10.55047/ijateis.v4i3.1974

Original Article

Environmental Impact Analysis of Biogas Production Using Life Cycle Assessment (LCA) Towards Net Zero Emissions

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Received : 01 October - 2025
Accepted : 08 November - 2025
Published online : 12 November - 2025

Abstract

The dairy cattle sector in Indonesia significantly contributes to greenhouse gas (GHG) emissions, particularly methane (CH_4). This study aims to analyze the environmental impacts of biogas production using the Life Cycle Assessment (LCA) approach. Data was collected from several biogas projects in Central Java and Yogyakarta, then analysed using OpenLCA software with cradle-to-grave system boundaries. The analysis was conducted using the Life Cycle Assessment (LCA) approach to assess the environmental impact at each stage of the life cycle, from raw material collection and production processes to utilisation and final disposal. In addition, supporting data was collected through interviews with project managers, field observations, and literature studies to ensure the accuracy and completeness of the analysis results. The results indicate that anaerobic digestion and biogas combustion are the major contributors to emissions but also play a key role in reducing methane release by up to 60%. Optimization of digester management and utilization of digestate as organic fertilizer can further minimize additional impacts. Hence, biogas demonstrates substantial potential as a mitigation strategy to support net zero emissions in the dairy cattle sector.

Keywords: Biogas, Dairy Cattle Sector, LCA, Greenhouse Gas Emissions, Net Zero Emissions.

1. Introduction

Global climate change has become one of the most urgent challenges of the 21st century. Rising concentrations of greenhouse gases (GHGs) have intensified global warming, triggered extreme weather events, and accelerated environmental degradation (IPCC, 2006). Among the major contributors, the dairy cattle sector plays a crucial role due to methane (CH_4) emissions from manure management and enteric fermentation. Methane is particularly concerning because its global warming potential (GWP) is 27 times greater than carbon dioxide (CO_2) (Reiter & Lindorfer, 2015).

In Indonesia, the dairy cattle sector is a growing contributor to GHG emissions. The Ministry of Environment and Forestry has identified manure management in dairy cattle farms as a critical emission hotspot (Ishak et al., 2019). This poses a significant challenge to Indonesia's commitment to achieving Net Zero Emissions by 2060 (Nasir & Bengi, 2024). Although biogas technology has been introduced as a mitigation measure, its environmental performance has not been thoroughly assessed with a standardized method. Most existing evaluations focus only on energy substitution or economic feasibility, while comprehensive assessments of environmental trade-offs remain scarce.

Previous studies have shown that biogas technology has the potential to reduce methane emissions while simultaneously producing renewable energy. For instance Rehl and Müller (2011) and Styles et al. (2018) demonstrated that digestate from biogas can substitute chemical fertilizers, lowering indirect emissions. International studies also highlight the importance of Life Cycle Assessment (LCA) in measuring environmental benefits. Gkoltsiou et al. (2021) emphasized that LCA provides a holistic understanding of environmental impacts from waste-to-energy systems. However, existing research in Indonesia has been limited in scope, often lacking detailed life cycle analysis of biogas systems, especially in smallholder dairy cattle farms.

This study applies the Life Cycle Assessment (LCA) methodology standardised by ISO 14040 and ISO 14044 to evaluate the environmental impact of biogas production activities on dairy farms in Central Java Province and the Special Region of Yogyakarta. The objective of this study is to identify and assess the stages in the biogas production life cycle that contribute most significantly to environmental impacts, so that strategic efforts can be formulated to improve the sustainability of biogas production systems on a dairy farm scale.

The assessment follows a *cradle-to-grave* boundary, covering manure collection, anaerobic digestion, biogas combustion, and digestate utilization. Using OpenLCA software with the IPCC 100-year GWP method, this study quantifies CO_2-equivalent emissions and identifies the processes contributing most significantly to overall impacts.

This paper lies in its integrated application of LCA to the context of smallholder dairy cattle-based biogas systems in Indonesia, providing a quantitative evaluation of their contribution to national net zero targets. Unlike prior studies that focus narrowly on energy substitution or economic savings, this study provides a comprehensive environmental analysis, highlighting both benefits and potential burdens across the life cycle. The findings contribute to policy design and technological optimization for scaling up biogas adoption in Indonesia's dairy sector.

2. Literature Review

2.1. Biogas and Emission Mitigation Potential

Biogas is a renewable energy source produced through the anaerobic decomposition of organic materials such as livestock manure, agricultural waste, and food waste. The use of biogas plays an important role in reducing dependence on fossil fuels and reducing greenhouse gas emissions, especially methane, which has a higher global warming potential than carbon dioxide (Kabeyi & Olanrewaju, 2022).

Research conducted by Tonmoy et al. (2020) shows that the implementation of biogas digester systems at the household level can significantly reduce greenhouse gas emissions compared to conventional waste management. Similar results have also been reported by Kang et al. (2022) which found that the use of biogas for electricity generation can reduce carbon dioxide emissions by up to 70 per cent compared to the use of coal. In addition, Meng et al. (2023) emphasises that small-scale biogas systems in Southeast Asia contribute positively to the decarbonisation of the agricultural sector when integrated with the use of digestate as organic fertiliser. Thus, biogas production not only has the potential to provide clean energy, but also acts as an instrument for mitigating emissions in sustainable agricultural systems.

2.2. Life Cycle Assessment as an Environmental Assessment Method

Life Cycle Assessment (LCA) is an analytical method used to assess the environmental impact of a product or system throughout its entire life cycle (Miettinen & Hämäläinen, 1997). This method has been standardised through ISO 14040 and ISO 14044, which cover four main stages, namely setting objectives and scope, compiling a life cycle inventory, assessing impacts, and interpreting results.

In the context of biogas production, LCA is used to assess the potential environmental impact from raw material collection, anaerobic fermentation, biogas utilisation, to digestate management. According to Esteves et al. (2019), The stage of digestate utilisation and the possibility of methane leakage are the factors that most influence the total greenhouse gas emissions of a biogas system.

Baumann and Tillman (2004) state that the application of LCA provides a scientific basis for policymakers to assess the effectiveness of renewable energy technologies in reducing environmental impacts. In addition, LCA can be used to identify critical points in biogas systems so that improvements can be made to achieve higher environmental efficiency.

2.3. The Environmental Impact of Biogas Production on Net Zero Emissions Targets

The application of LCA in biogas system analysis shows that this technology has the potential to support the achievement of Net Zero Emissions targets if operated with strict efficiency and emission control principles. Based on research by Scheutz and Fredenslund (2019), Biogas systems with methane leakage of less than three per cent of total production are able to maintain significant carbon mitigation benefits. Conversely, higher leakage rates can negate the environmental benefits generated.

According to Lamolinara et al. (2022), Proper management of digestate, either through its use as liquid organic fertiliser or solid compost, can reduce the negative impacts of eutrophication and acidification. Research by Nugrahaeningtyas et al. (2024) emphasises the need to use accurate local data on farm characteristics, emission intensity, and digester efficiency so that LCA analysis results in Indonesia are more representative. Overall, the application of LCA to biogas production can be a strategic tool for assessing the real contribution of renewable energy systems to achieving national Net Zero Emissions targets.

3. Methods

This study was conducted in smallholder dairy cattle farms located in Boyolali and Klaten in Central Java and in Sleman, Yogyakarta. These sites were selected because they represent major dairy production regions in Indonesia and have been the focus of manure-based biogas programs promoted by both governmental and non-governmental organizations, including initiatives supported by *Yayasan Rumah Energi*. The research employed the Life Cycle Assessment (LCA) framework in accordance with the principles and guidelines outlined in ISO 14040 and ISO 14044. The functional unit was defined as one cubic meter of biogas produced, which enables the quantification of greenhouse gas (GHG) emissions and allows comparison with conventional fossil-based energy sources such as liquefied petroleum gas (LPG).

The system boundary was established from cradle to grave, encompassing all stages from the collection and handling of dairy cattle manure, the anaerobic digestion process, the combustion of biogas as household energy, and the application of digestate as organic fertilizer. Emissions associated with infrastructure development, including the construction of biodigesters, were excluded from the boundary on the basis that they contribute insignificantly relative to operational emissions. This approach is consistent with methodological choices adopted in prior studies on agricultural biogas systems.

Inventory data were compiled from a combination of primary and secondary sources. Primary data were obtained through field surveys, on-site observations, and interviews with farmers to document manure production rates, digester capacities, and biogas utilization patterns. Secondary data were drawn from published literature, the Indonesian National Greenhouse Gas Inventory and international databases such as the IPCC. The life cycle inventory included parameters such as the average daily manure output per cow, methane concentration in biogas, the equivalence factor of biogas to LPG (where one cubic meter of biogas was assumed to substitute approximately 0.46 kg of LPG), and the nutrient composition of digestate as a replacement for synthetic fertilizers.

Life cycle impact assessment (LCIA) was carried out using the OpenLCA software package. The IPCC 100-year global warming potential (GWP) method was applied to estimate greenhouse gas emissions expressed in carbon dioxide equivalents (CO_2-eq). The analysis focused on three dimensions: the total GHG reduction achieved per functional unit, the contribution of each life cycle stage to the overall impacts, and the comparative performance of biogas in relation to conventional LPG consumption. Certain assumptions were necessary to complete the assessment. Methane leakage rates associated with the digestion process and combustion were based on values reported by Budiman et al. (2018). The substitution factor for digestate as an organic fertilizer was derived from the findings of Ablieieva et al. (2022). Model validation was undertaken by comparing the results of this study with those reported in previous international assessments of biogas systems in agricultural contexts.

The methodological contribution of this study is its comprehensive application of the LCA framework to smallholder dairy cattle biogas systems in Indonesia. While previous studies have largely emphasized energy substitution or economic benefits, the present analysis adopts a cradle-to-grave perspective that integrates both primary data collected from the field and international databases. This approach provides a more rigorous and contextually grounded evaluation of the environmental performance of biogas in the dairy cattle sector and its potential role in supporting Indonesia's transition towards net zero emissions.

4. Results and Discussion

4.1. Research Results

The life cycle inventory (LCI) analysis summarized in Table 1 indicates that dairy cattle manure production in the study area averaged 20–25 kilograms per cow per day. The biodigesters in operation had an average capacity of 4–6 m^3 and produced biogas with a methane concentration of approximately 60 percent. In terms of energy substitution, one cubic meter of biogas was found to be equivalent to 0.46 kilograms of liquefied petroleum gas (LPG). Across the surveyed households, average monthly production was estimated at 20–25 m^3 of biogas, sufficient to replace a significant proportion of household LPG consumption. Furthermore, digestate produced from the process demonstrated nutrient concentrations capable of substituting approximately 50–60 kilograms of nitrogen fertilizer per year, providing both agronomic and environmental benefits.

Table 1. Life Cycle Inventory (LCI) of Dairy Cattle Biogas System

Parameter	Average
Manure production per cow	20–25 kg/day
Digester capacity	4–6 m^3
Methane concentration in biogas	~60%
Energy substitution factor	1 m^3 biogas = 0.46 kg LPG
Biogas production per household	20–25 m^3/month
Digestate substitution potential	50–60 kg N fertilizer/year

The life cycle impact assessment (LCIA) conducted using OpenLCA and the IPCC 100-year GWP method demonstrated that the adoption of biodigesters significantly reduced greenhouse gas (GHG) emissions. As shown in Table 2, the primary emission savings were derived from three sources: avoided methane emissions from uncontrolled manure decomposition, substitution of LPG with renewable biogas, and replacement of synthetic fertilizers through digestate application.

Table 2. Annual Greenhouse Gas (GHG) Emission Reductions from Dairy Cattle Biogas

Impact Category/ Process	Emission Reduction (t CO_2-eq/year per digester)
Avoided manure methane	0.8 – 1.0
LPG substitution (biogas use)	1.2 – 1.5
Digestate utilization	0.3 – 0.5
Total reduction	2.0 – 3.0

Overall, each biodigester unit was estimated to achieve an annual reduction of 2.0–3.0 tons CO_2-equivalent. Among the three components, LPG substitution contributed the largest share of savings, followed by avoided methane emissions and digestate utilization. To situate these findings within the broader literature, a comparative analysis was conducted with previous studies. As shown in Table 3, the emission reduction estimates in this study are consistent with, and in some cases slightly higher than, values reported internationally. Rocchi et al. (2021) reported reductions of 1.8–2.5 tons CO_2-equivalent per biodigester in European dairy farms, which is comparable to the lower range of this study. Pramono et al. (2020) highlighted the fertilizer substitution benefits of digestate in Indonesian farms, though their analysis did not apply a full life cycle approach. Harjanto et al. (2012) estimated reductions of approximately 2.0 tons CO_2-equivalent per unit in Indonesian contexts, but emphasized methane leakage as a critical limiting factor.

Table 3. Comparison of Biogas LCA Results with Other Studies

Study	GHG Reduction (t CO_2-eq/year per digester)
This study (Indonesia, smallholder dairy)	2.0 – 3.0
Rocchi et al. (2021, EU dairy farms)	1.8 – 2.5
Pramono et al. (2020, Indonesia)	Not full LCA (focus on digestate)
Harjanto et al. (2012, Indonesia)	~2.0

These results demonstrate that biogas technology in smallholder dairy cattle farms provides environmental benefits that are not only comparable to but in some cases exceed those reported in other contexts. The relatively higher reductions observed in this study may be explained by the greater reliance on LPG in rural Indonesian households, which enhances the substitution effect, and by the relatively high manure input per cow.

4.2. Discussion

The findings of this study indicate that the application of small-scale biogas technology in Indonesian dairy cattle farms provides a substantial reduction in greenhouse gas (GHG) emissions, with net annual savings estimated at 2.0–3.0 tons CO_2-equivalent per biodigester. This result is broadly consistent with international research but highlights important regional differences. For example, Rocchi et al. (2021) reported emission reductions of 1.8–2.5 tons CO_2-equivalent per unit in European dairy farms. The slightly higher range observed in this study can be attributed to local conditions, particularly the greater availability of manure per cow and the heavier reliance on LPG as the primary household cooking fuel. These contextual differences emphasize how local farming and energy practices can significantly influence the environmental performance of biogas systems.

A notable finding in this study is that LPG substitution emerged as the largest contributor to emission savings, accounting for approximately 1.2–1.5 tons CO_2-equivalent per year per unit. This contrasts with European studies, such as Rocchi et al. (2021), where avoided methane emissions from manure management represented the dominant mitigation pathway. The contrast underscores the role of regional energy structures: in Indonesia, the reliance on fossil-based LPG provides a strong baseline for substitution, thereby enhancing the contribution of biogas as an energy transition tool.

The contribution of digestate utilization also aligns with findings from other Indonesian contexts. In this study, digestate was estimated to replace 50–60 kilograms of nitrogen fertilizer per year, equivalent to an avoidance of 0.3–0.5 tons CO_2-equivalent. This result corresponds with Pramono et al. (2020), who highlighted the digestate's potential to reduce dependence on chemical fertilizers in smallholder farms. However, unlike studies that focus primarily on soil fertility and agronomic improvements, the present research integrates digestate benefits into a comprehensive life cycle framework. This holistic quantification strengthens the case for considering digestate not only as a by-product but as an integral component of the environmental performance of biogas systems.

Despite these benefits, methane leakage during anaerobic digestion remains a critical limitation. While controlled digestion is far superior to unmanaged manure storage, methane slip can reduce the net environmental benefit of the system. Harjanto et al. (2012) similarly emphasized that digester design, operation, and maintenance are key determinants of system performance in Indonesia. The presence of leakage in both the present study and prior research indicates the need for improved technology and farmer capacity building to maximize the mitigation potential of biogas.

The context-dependent nature of biogas system performance has also been documented in broader LCA studies. A study in Finland showed that anaerobic digestion systems consistently outperform fossil fuel and mineral fertilizer scenarios when both energy and nutrient cycles are considered (Scarlat et al., 2019). Similarly, Nguyen et al. (2014) reported that household digesters in Vietnam reduced climate change impacts from 4.4 to 3.2 kg CO_2-equivalent per 1,000 kg of manure, although nutrient recycling and methane management remained challenges. These comparisons suggest that while biogas technology is universally beneficial, the scale and source of benefits vary across contexts depending on local energy dependence, feedstock characteristics, and management practices.

Taken together, these results highlight that the environmental performance of dairy cattle biogas systems is not uniform but highly context-specific. In European farms, avoided methane emissions dominate the mitigation pathway, while in Indonesia, the greatest benefit is derived from LPG substitution, with digestate utilization providing additional though smaller contributions. Therefore, these findings emphasise the importance of conducting life cycle assessments (LCAs) rooted in local contexts, and demonstrate how these findings contribute theoretically and methodologically to the development and application of LCAs in developing countries. By applying a cradle-to-grave LCA framework and integrating both energy and nutrient substitution, this study contributes novel insights into the role of smallholder dairy cattle biogas systems in advancing Indonesia's low-carbon transition and long-term net zero emissions target.

5. Conclusion

This study applied a cradle-to-grave life cycle assessment to evaluate the environmental performance of smallholder dairy cattle biogas systems in Central Java and Yogyakarta, Indonesia. The results show that each biodigester reduces greenhouse gas emissions by approximately 2.0–3.0 tons CO_2-equivalent per year, primarily through the substitution of LPG, avoidance of methane emissions from unmanaged manure, and partial replacement of synthetic fertilizers with digestate. Compared with international findings, the magnitude of reductions is slightly higher than those reported in European contexts, underscoring the critical role of regional conditions such as household energy dependence and livestock management practices.

The study makes two key contributions to the literature. First, it demonstrates that in Indonesia, energy substitution rather than methane avoidance is the dominant pathway of climate benefits, which differs from patterns observed in European dairy systems. Second, it integrates digestate utilization into the life cycle framework, providing a comprehensive assessment of its contribution to emission savings beyond agronomic improvements. These findings reinforce the context-specific nature of biogas performance and highlight the necessity of localized assessments in designing effective climate mitigation strategies.

From a policy perspective, the quantified emission reductions highlight the potential of smallholder biogas systems to contribute significantly to Indonesia's commitment to achieving net zero emissions by 2060. Scaling up adoption across the dairy sector could generate cumulative reductions that meaningfully advance national mitigation targets while simultaneously supporting rural energy security and circular nutrient management. However, challenges remain, particularly in addressing methane leakage and ensuring the long-term sustainability of digester operation.

Future research should focus on developing improved digester technologies, conducting sensitivity analyses to account for household-level variability, and integrating socio-economic factors such as farmer acceptance, financial viability, and policy support. By addressing these dimensions, biogas can be more effectively positioned as a dual solution for climate change mitigation and sustainable rural development.

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