DIGIMO: MODULAR IOT-BASED BIOGAS AND BIO-SLURRY SYSTEM FOR LIVESTOCK ENERGY TRANSITION

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Abstract. *The transformation of livestock waste into renewable energy presents a promising pathway to support Indonesia's low carbon energy transition, especially in rural communities. This paper introduces DIGIMO (Digester Modular IoT and Bio- Slurry), an innovative biogas system designed for small scale farming villages. DIGIMO integrates three key innovations: a modular digester design that allows scalable and flexible installation based on the number of livestock, a low cost IoT based monitoring system using sensors to track temperature, gas pressure, and gas volume for optimal fermentation, and a bio-slurry refinement unit that converts biogas residue into high-nutrient organic liquid fertilizer. The biogas produced is primarily distributed directly to local households for cooking and daily energy use, reducing their reliance on fossil-based fuels. Meanwhile, the processed slurry provides additional economic value as a sustainable agricultural input. This model not only reduces greenhouse gas emissions but also promotes circular economy principles by closing the loop between energy and agriculture. The proposed DIGIMO system aims to be replicable across Indonesia's rural areas, combining environmental benefits, energy security, and rural economic empowerment. This paper highlights the design, process flow, and potential impacts of DIGIMO as a feasible low carbon energy business innovation for Indonesia's sustainable energy future..*
Keywords: *biogas, bio-slurry, IoT, modular digester, low-carbon transition*

INTRODUCTION

Indonesia's rural livestock-based communities generate substantial volumes of cattle manure, yet lack efficient and scalable mechanisms to convert this organic waste into clean energy or agricultural inputs. It is estimated that Indonesia's cattle and buffalo population numbering over 17 million, produces approximately 345,700 tons of manure daily, which could be a significant biogas resource if appropriately harnessed (Faculty of Animal Science UGM, 2021). Despite this potential, the actual deployment of biogas systems remains limited in many rural areas due to rigid infrastructure, lack of real time process control, and insufficient post digestion waste management. As a consequence, there are still so many villages remain highly dependent on fossil fuels such as LPG and diesel for cooking and daily energy needs, reflecting Indonesia's broader reliance on non-renewable energy sources and hindering progress toward a low-carbon rural energy transition. The persistence of these gaps highlights a pressing need for community-adaptable, affordable, and integrated solutions that align with the circular economy principles and local socio-technical contexts.

Recent studies underscore the benefits of integrating technology with resource valorization Xu Wenzhi, et al. (2021), demonstrated that using biogas slurry in place of chemical fertilizer significantly improves crop yield and forage quality, confirming the agricultural potential of digestate. Despite these findings, most rural implementations treat biogas and digestate management as separate issues rather than an integrated, scalable package. The novelty and need for a more holistic system persist in rural livestock regions.

In response to these challenges, this paper introduces DIGIMO, an integrated innovation combining digester modular design, IoT-based monitoring, and bio- slurry refinement into a cohesive system. DIGIMO enables adaptability in system scale, real time fermentation control, and transformation of residue into nutrient rich fertilizer, tailored to the context of livestock-based villages. The system distributes biogas directly to nearby households for cooking and daily use, reducing reliance on fossil fuels and enhancing community energy resilience. Simultaneously, the refined bio-slurry supports sustainable agriculture, closing the loop in resource utilization. As a result, DIGIMO provides a replicable model for empowering rural areas through low-cost technology, economic value creation, and fossil fuel substitution.

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METHODOLOGY

The methodology applied in this paper combines field observation, stakeholder interview, literature review, and conceptual modeling. Initial insights were obtained through direct observation and informal interviews during a visit to Wisata Village, Tritip, Balikpapan, East Kalimantan in 2022. This study employs a descriptive and exploratory approach, focusing on understanding the contextual needs and challenges in rural livestock communities. The method does not involve hypothesis testing or quantitative data collection, but instead integrates empirical findings from the field with supporting literature to reconstruct and develop a feasible innovation model. By combining real-world experience with current academic insights, this approach ensures that the proposed solution is both locally grounded and technically relevant.

DIGIMO System Design

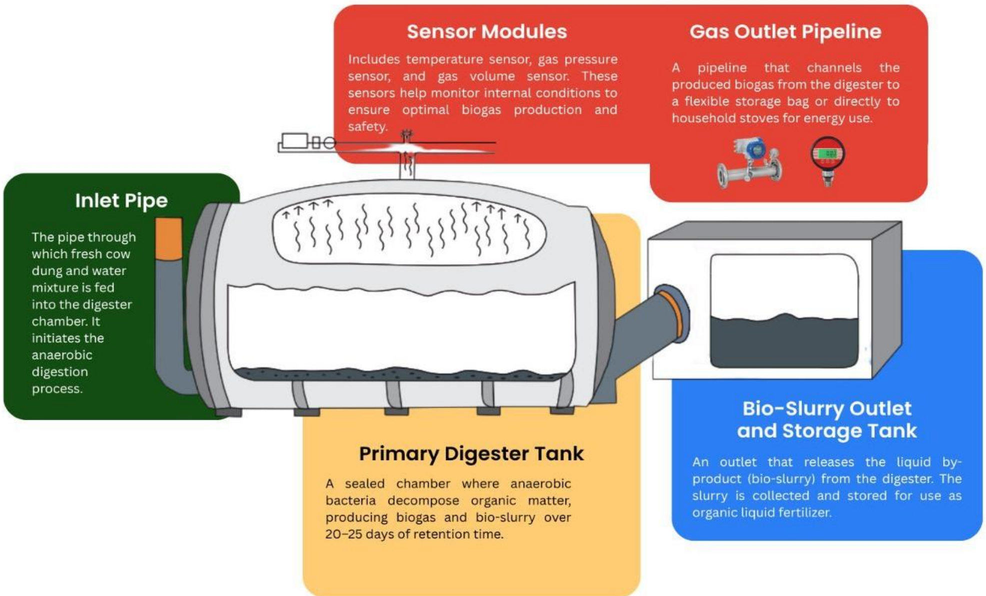

Figure 1. Schematic design of the DIGIMO modular biogas system.

Biogas is a renewable energy source generated through anaerobic digestion, a microbial process that decomposes organic matter, such as cow manure in the absence of oxygen. According to Putri et al. (2023), cow dung is a favorable feedstock due to its high organic load and abundance in rural livestock areas. The digestion process produces methane rich gas and a liquid byproduct known as bio-slurry, which contains essential nutrients for agriculture. Furthermore, the digestate can be refined into liquid organic fertilizer, offering environmental and economic benefits for farmers.

The DIGIMO system was developed as a modular, scalable biogas solution tailored to the needs of small-scale cattle farmers in rural communities. Its design emphasizes simplicity, adaptability, and community-level operability. Figure 4 illustrates the schematic layout of DIGIMO, which integrates key functional components to enable the transformation of cattle manure into usable energy and organic fertilizer. The system begins with an inlet pipe, where fresh cow dung mixed with water is fed into the digester. This mixture enters the primary digester tank, a sealed chamber where anaerobic bacteria decompose organic matter over a retention period of 20-25 days, producing methane-rich biogas and a nutrient-rich liquid residue. Mounted on top of the tank are sensor modules, including a temperature sensor, gas pressure sensor, and gas volume sensor. These sensors monitor internal process parameters in real time to optimize biogas production and ensure operational safety. Produced gas is directed through the gas outlet pipeline, which channels the biogas either to a flexible gas storage unit or directly to household stoves for energy use. Meanwhile, the remaining digestate exits through the bio-slurry outlet and is collected in a dedicated bio-slurry storage tank. This liquid by product, rich in nitrogen, phosphorus, and potassium, is suitable for use as an organic fertilizer in local agricultural practices.

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A simplified version of the DIGIMO prototype was successfully constructed and trialed during a community service program in 2022, in collaboration with local residents in Tritip, Wisata Village. The installation utilized a 60-liter HDPE drum as the primary digester tank and demonstrated basic biogas production capabilities using cow manure as the sole input. The pilot test confirmed that even with minimal infrastructure, the system could produce usable biogas. However, at that stage, the system had not yet been equipped with the planned IoT sensor modules due to resource limitations. Figure 5 presents field documentation of the initial prototype installed adjacent to a local cattle pen.

Figure 2. Field documentation of the early DIGIMO prototype built during a community service program in Tritip, Wisata Village, 2022 (Photo by author).

IoT-Based Monitoring Components

A modular digester is a system designed for flexibility and scalability, enabling gradual installation based on the number of livestock and space availability. Modular biogas units have been recommended for rural applications due to their ease of assembly and maintenance (Thiruketheeswaranathan, 2021). Integration with Internet of Things (IoT) technology enables real-time monitoring of temperature, pressure, and gas volume improving the reliability of the biogas production process. Prakoso and Yulita (2020) demonstrated the effectiveness of low-cost MQ-4 sensors for methane detection and transmission of data to cloud dashboards for operational control.

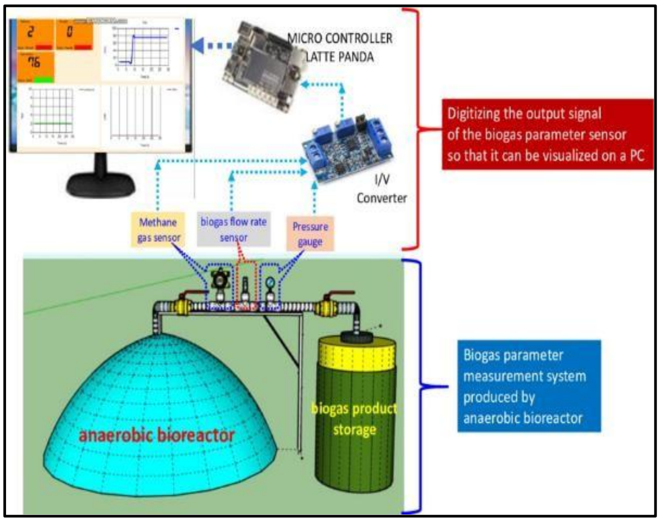

Figure 3. IoT-enabled monitoring architecture for biogas plant, including pressure and flow sensors, edge computing, and cloud dashboards (adapted from Soehartanto et al., 2023)

Several researchers have examined the isolated potential of biogas systems, particularly in enhancing yield through specialized processing. Yuana et al. (2025) highlighted that optimizing the anaerobic digestion of cow manure, such as through thermal steam explosion, can significantly improve biogas production efficiency by breaking down recalcitrant lignocellulosic materials. From the technological side, Prakoso and Yulita (2020) implemented an IoT-based monitoring system in a small-scale digester using methane gas

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sensors connected to a web-based platform. This approach enabled real-time remote monitoring of gas levels, improving both operational safety and process control.

Despite the growing number of biogas-related studies, most existing systems focus on singular components, either on production, fertilizer application, or digital monitoring. These systems often lack integration and scalability, limiting their long-term sustainability. Moreover, many digesters operate without standardized monitoring tools, leading to inconsistent gas quality and inefficient conversion. The DIGIMO system addresses these limitations by combining three technologies. This innovation reinforces circular resource utilization in rural Indonesia, aligning with national strategies for low-carbon transition.

To support operational reliability and real-time performance analysis, the DIGIMO system integrates an IoT-based monitoring module that tracks critical parameters within the digester. The sensor array consists of two key components.

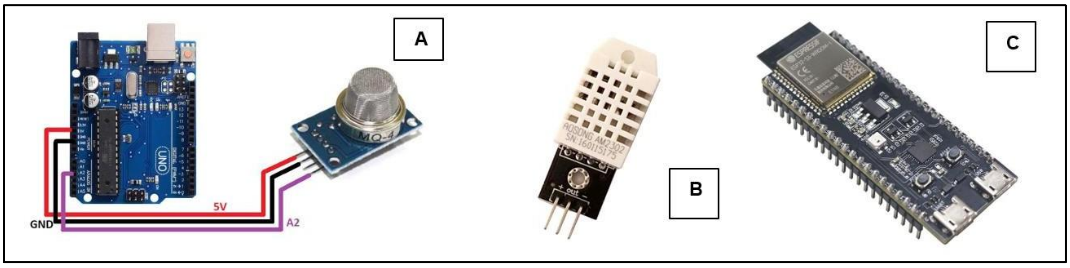

Figure 4. Components of the DIGIMO IoT monitoring system

First, the MQ-4 gas sensor is employed to detect methane (CH_4) concentrations in the digester headspace. This sensor has a detection range of 200–10,000 ppm and is highly sensitive to flammable gases. It operates with a circuit voltage of 5 V and requires a 24-hour preheating period for optimal accuracy. Second, the system uses a DHT-22 sensor to measure ambient temperature and humidity inside the biogas chamber. This sensor supports digital output and has high reliability for low-power microcontroller applications.

All sensor data is collected and processed by an ESP32 microcontroller, which is equipped with built-in Wi-Fi capability. The device transmits sensor readings to a web-based monitoring dashboard, which displays real-time methane levels and environmental data. As shown by Novantri and Oktiawati (2022), this approach enables users to monitor system performance from any location via internet- connected devices, significantly reducing risks related to gas accumulation and uncontrolled pressure buildup. Moreover, their system provided automatic alerts based on methane levels categorized into "normal," "monitor frequently," or "alert" depending on thresholds such as 50 ppm or 600 ppm. This classification can be adopted in DIGIMO to ensure safety protocols are triggered when gas levels become hazardous. Although the DIGIMO prototype built in 2022 did not include the IoT module due to resource limitations, future development will integrate this monitoring system fully to enhance usability, safety, and efficiency.

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RESULTS AND DISCUSSION

Results

Field Context and Initial Observations

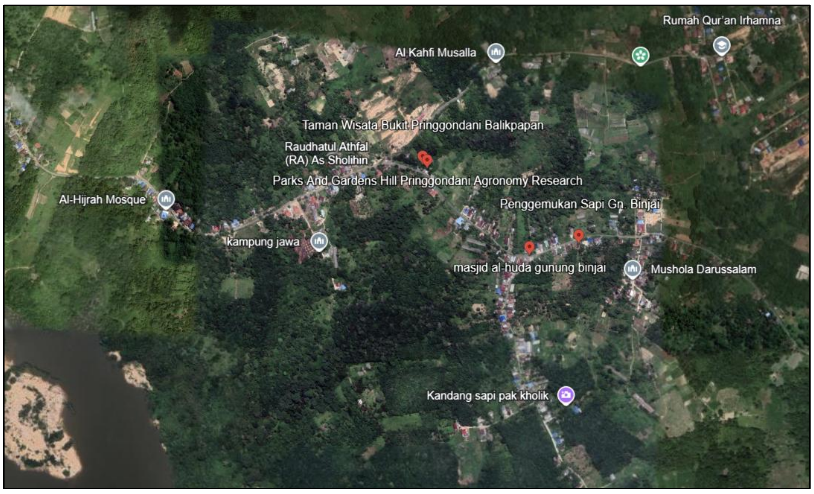

Figure 5. Field observation area in Tritip, East Balikpapan, Kalimantan, Indonesia

The field observation was conducted in 2022 at Wisata Village, Tritip located in East Balikpapan, Kalimantan. This area is characterized by semi-rural household clusters, where cattle farming is commonly practiced as a supplemental source of income. Cattle are typically raised in small-scale backyard sheds, with an average of 2 to 5 cows per household. Despite the consistent generation of cow manure, most residents do not yet implement sustainable waste management practices. Manure is often left untreated in open areas, occasionally composted, or disposed of directly into the surrounding environment.

Figure 6. Cattle shed behind a local household in Tritip Village, East Balikpapan

During the observation, a small-scale prototype of the biogas system was piloted in collaboration with one local resident, Ms. Ruwi Rahayu. Informal interviews with her confirmed that most cattle owners in the village had never considered converting animal waste into biogas or fertilizer, citing a lack of knowledge, resources, and accessible technology. Manure was perceived primarily as waste rather than a potential energy source. Furthermore, the absence of organized waste handling or cooperative models contributed to underutilization of this biomass potential. Visual inspection of the cattle shed environment revealed the accumulation of raw manure behind residential units, emitting odor and attracting pests. This situation reflects a widespread untapped opportunity for integrating low- cost renewable energy systems that align with rural daily practices.

Bio-Slurry Production and Characteristics

In the DIGIMO system, the anaerobic digestion of cow manure produces a liquid residue known as bio-slurry, which is discharged via the outlet pipe into a storage tank. Quantitatively, field trials using manure from two cows yielded approximately 15–18 liters of bio-slurry per week, which was manually collected and stored. Laboratory analysis from previous studies indicates that this by-product typically contains 1–3.6% nitrogen

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(N), 0.13–1.8% phosphorus (P), and 0.12–3.6% potassium (K) in its liquid form, along with organic matter and beneficial microorganisms that enhance soil fertility (Yusmiati & Singgih, 2018).

No.	Jenis Analisa	Satuan	Jenis Ternak			
			Sapi			Babi*
			Pupuk Padat	Kompos	Pupuk Vermikompos	Pupuk Padat
1	C-Organik	%	15,5 - 25,6	14,4	25,4	15,6
2	C/N		8 - 18,4	10,2	18,7	10
3	pH		7,5 - 8			
4	Nutrisi Makro					
	N	%	1,4 - 2,1	1,6	1,4	1,6
	P_2O_5	%	0,2 - 2,7	1,2	2,4	1,9
	K_2O	%	0,02 - 0,9	0,3	0,3	0,4
	Ca	ppm	13.935 - 28.300		15.042	-
	Mg	ppm	800 - 6.421		6.838	-
	S	%	1,7		1,4	-
5	Nutrisi Mikro					
	Fe	ppm	3,2 - 23		4,5	-
	Mn	ppm	132,5 - 1.905		235	-
	Cu	ppm	9 - 36,2		50,9	-
	Zn	ppm	40 - 97,1		110,3	-
	Co	ppm	3,1 - 51		4,9	-
	Mo	ppm	29,7 - 3.223		20,3	-
	B	ppm	243,8 - 665		228,1	-

Figure 7. Dry matter composition analysis of bio-slurry organic fertilizer (Yayasan Rumah Energi-BIRU, 2020).

Moreover, initial characterization studies by Kusuma and Afrianisa (2021) report that bio-slurry contains approximately 75% water and 25% dry matter, with dry matter consisting of 18–27% organic content and detectable levels of micronutrients like calcium, magnesium, and sulfur. These nutrient levels justify the consideration of bio-slurry as a viable replacement or supplement to inorganic fertilizers. Furthermore, the liquid form allows for easier soil infiltration and nutrient availability compared to raw manure or compost. This attribute enhances its suitability for precision application in smallholder farming contexts. The integration of bio-slurry utilization in DIGIMO strengthens the circular economy principle transforming livestock waste into valuable agricultural inputs and contributing to sustainable rural livelihood models.

Bio-slurry can be directly applied to agricultural land immediately after being discharged from the digester outlet, as the anaerobic digestion process significantly reduces pathogen content and odor intensity. However, when stored for an extended period, residual microbial activity may cause odor to reappear. To mitigate this, short aeration or mixing with dry organic materials, such as fine compost, can be applied to neutralize the smell while maintaining its nutrient content.

Gas Utilization Potential

The biogas generated from the DIGIMO system primarily consists of 50–70% methane (CH_4), 30–40% carbon dioxide (CO_2), and trace amounts of hydrogen sulfide (H_2S) and water vapor. In the prototype trial at Tritip Village, the gas output from the modular digester was channeled via a PVC pipeline to nearby households for direct use in cooking stoves. This local distribution model aligns with the system's community-oriented design, eliminating the need for complex infrastructure such as mini-grid integration. Field measurements using a portable biogas analyzer indicated a methane concentration of approximately 58–62%, sufficient for efficient combustion in standard biogas burners. The generated gas volume, based on manure input from two cattle, averaged 0.8–1.2 m^3/day, providing enough fuel for 3–4 hours of cooking for one household.

Previous studies further underline the value of localized biogas use. For instance, Rachmawatie et al. (2022) observed that rural communities around Yogyakarta were gradually substituting LPG with biogas,

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improving energy access despite cultural and financial hurdles. Furthermore, IRENA (2020) reported household cost savings up to 50% following a switch from LPG to biogas, while Rumah Energi's (2020) user survey found a reduction of 5.5 kg/month in LPG consumption per household. These findings underscore the potential of the DIGIMO system to reduce fossil fuel dependency and improve rural energy resilience.

Figure 8. Direct utilization of biogas from the DIGIMO system for household cooking in Tritip Village

Discussion

Rural Livestock Waste Challenges & Opportunities

Rural livestock-based communities in Indonesia generate substantial quantities of manure, yet its management remains largely underdeveloped. In areas such as Tritip Village, Balikpapan, East Kalimantan, most smallholder farmers keep cattle in backyard pens, producing manure daily without structured waste handling systems. In many cases, the waste is left untreated or partially used as compost by a few households, resulting in both underutilized resource potential and environmental concerns such as odor, methane emissions, and water contamination. The lack of affordable, scalable, and technically manageable solutions further limits farmers' ability to turn livestock waste into valuable products.

Despite these challenges, the consistent availability of raw material presents a significant opportunity for renewable energy generation and organic fertilizer production. Studies have shown that cattle manure has a high biogas yield potential, containing 50–60% methane when processed through anaerobic digestion, making it a viable alternative to fossil fuel-based cooking energy (Putri et al., 2023). Furthermore, the anaerobic digestion process produces bio-slurry, a nutrient-rich by-product that can be applied directly to agricultural fields, contributing to soil fertility improvement and reducing dependence on chemical fertilizers. Thus, rural livestock waste, when effectively processed, holds the dual potential of addressing energy needs while supporting sustainable agricultural practices.

Advantages of Modular IoT-Enabled Design

The modular nature of the DIGIMO system enables flexible adaptation to varying scales of livestock operations, from smallholder households to community- level installations. This scalability is particularly relevant in rural Indonesia, where livestock populations and manure availability can differ significantly between villages. Modular digesters allow capacity expansion by simply adding additional units, thereby reducing the need for costly infrastructure overhauls. Moreover, the standardized modular design simplifies assembly, maintenance, and user training, ensuring that technical barriers remain minimal for local operators.

Integrating IoT-based monitoring enhances this flexibility by providing real- time data on key process parameters such as temperature, gas pressure, and production volume. As demonstrated by Prakoso and Yulita

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(2020), IoT-enabled systems in small-scale digesters can improve operational control and safety by allowing remote supervision and early detection of anomalies. In the DIGIMO configuration, low-cost sensors feed data into a simple interface accessible via mobile devices, empowering users to make informed operational decisions without requiring on-site technical experts. This combination of modularity and IoT monitoring not only optimizes system performance but also prolongs equipment lifespan, reduces downtime, and supports consistent biogas output even under fluctuating input conditions.

Circular Economy & Bio-Slurry Utilization

The DIGIMO system aligns closely with the principles of a circular economy by ensuring that livestock waste is fully valorized rather than discarded. Through anaerobic digestion, cattle manure is transformed into two valuable products: biogas for household energy needs and bio-slurry as an organic fertilizer. This dual output closes the resource loop, reducing environmental pollution while generating additional revenue streams for rural households. In particular, bio-slurry offers high concentrations of nitrogen, phosphorus, and potassium in plant-available forms, making it a cost-effective alternative to synthetic fertilizers (Yayasan Rumah Energi, 2020).

Unlike untreated manure, bio-slurry is pathogen-reduced and odor-minimized, enabling direct application to crops without further processing. However, when storage is required, mild odor re-emergence can occur; this can be mitigated through short aeration or blending with dry organic matter such as fine compost. By integrating bio-slurry utilization into local agricultural cycles, villages can reduce chemical input dependency, improve soil health, and strengthen food security. Moreover, sales of surplus bio-slurry products, either in liquid or dried form create opportunities for microenterprise development, further embedding the circular economy model into rural livelihoods.

Impact on Low-Carbon Energy Transition

The DIGIMO system contributes directly to Indonesia’s low-carbon energy transition by replacing fossil fuel consumption with renewable biogas in rural households. Given the high dependency on LPG for cooking in many livestock- based villages, even partial substitution with locally produced biogas can significantly reduce greenhouse gas (GHG) emissions. Each cubic meter of biogas contains approximately 50–60% methane, which, when combusted, emits substantially less CO_2-equivalent compared to the methane that would otherwise be released from unmanaged manure (Putri et al., 2023). By capturing and utilizing methane, the system not only offsets fossil fuel use but also mitigates one of the most potent GHGs.

Furthermore, the integration of bio-slurry into agricultural systems reduces reliance on energy-intensive synthetic fertilizers, indirectly lowering emissions from industrial fertilizer production. When deployed at scale, modular and IoT- enabled designs enable rapid replication across rural regions without requiring extensive infrastructure, supporting Indonesia’s renewable energy mix target and the net-zero emissions goal by 2060. Beyond environmental benefits, DIGIMO strengthens local energy security, fosters community resilience, and demonstrates how decentralized renewable solutions can be tailored to specific rural contexts within a broader national strategy.

CONCLUSIONS AND SUGGESTION

Conclusions

The DIGIMO system, integrating a modular digester, IoT-based monitoring, and bio-slurry utilization, demonstrates how rural livestock waste can be transformed into both renewable energy and agricultural inputs. The results indicate that such a system can address the current challenges of fossil fuel dependence and unmanaged manure emissions, while also providing economic benefits to local communities. Its adaptability to different operational scales, coupled with real-time monitoring, ensures more stable biogas production and improved process safety. The integration of bio-slurry into agricultural practices further strengthens the link between waste management and local food production, making DIGIMO a strategic contribution to Indonesia’s low-carbon energy transition.

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Practical Suggestions

Based on these findings, the implementation of modular biogas systems could be considered as part of rural energy and waste management initiatives. Opportunities exist for local communities to develop microenterprises centered on bio-slurry products, particularly when supported by cooperative frameworks or partnerships with technology providers. Encouraging knowledge transfer and capacity building at the village level would help maintain operational efficiency and foster a sense of ownership among users. Integrating simple IoT monitoring tools could further enhance the system's reliability without imposing significant technical burdens.

Suggestions for Future Research

Further exploration is needed to assess the long-term performance of DIGIMO under different climatic conditions and manure supply levels. Studies could also focus on refining sensor systems for greater accuracy and developing user-friendly data platforms tailored to rural contexts. In addition, an economic feasibility assessment covering both energy savings and bio-slurry market potential would provide valuable insights for scaling up this approach.

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