Integrated Design of a Small-Scale Biogas Reactor for Restaurant Organic Waste

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**Abstract.** The conversion of food-service organic waste into renewable energy offers a sustainable solution to energy scarcity and waste accumulation. However, many small-scale biogas systems suffer from inadequate design, structural failure, and low methane yields, limiting their long-term viability. This study presents an integrated approach for designing a compact biogas reactor tailored to restaurant waste, incorporating structural engineering, biological optimization, and economic evaluation within a unified framework. A design-based methodology was employed, including digester sizing based on a 20-day hydraulic retention time (HRT), geometric modeling using dimensionless correlations, and structural assessment via thin-walled pressure vessel theory. Material selection and cost estimation were also conducted to ensure feasibility. The reactor was designed to process 52.126 kg/day of organic waste, resulting in a digester volume of 2.979 m³ and a diameter of 1.88 m. Estimated daily methane production reached 1.12 m³, with a specific yield of 0.0215 m³ CH₄/kg substrate. Structural calculations confirmed that the internal pressure of 2.036 bar remained safely below the allowable limit of 4.57 bar for a 5 mm ST41 steel vessel. A decision matrix considering cost, reliability, safety, and maintainability supported the final design selection. The estimated construction cost was Rp 11,090,800 (~USD 690), indicating economic viability for small enterprises. This study addresses a critical gap by integrating mechanical design and biogas optimization for decentralized applications. The proposed methodology enhances structural safety, biogas productivity, and affordability, offering a scalable model for sustainable energy production in food-service settings.

**Keywords**. Biogas reactor; Restaurant waste; Anaerobic digestion; Methane production; Economic feasibility

# introduction

Small-scale anaerobic digesters represent a viable and sustainable solution for managing organic waste while producing renewable energy in biogas [1]. In particular, restaurant and food-service establishments generate large quantities of biodegradable waste, which can serve as effective anaerobic digestion (AD) substrates [2]. This process offers dual benefits: mitigating the burden of organic waste disposal and producing methane gas that can be used as a clean energy source for cooking or electricity generation [3].

Many developing countries have adopted household and community-scale biogas systems due to their low operational costs and simplicity. For example, China has installed over 60 million domestic-scale digesters. However, despite widespread implementation, operational inefficiencies remain a serious challenge. Reports indicate that only approximately 60% of China’s small digesters operate effectively, while about 20% are known to leak methane. Similar issues have been documented in other countries, such as Bangladesh, where 76% of units were found to have structural or functional defects [4]. These findings underscore a common problem in small-scale biogas deployment: inadequate design and maintenance practices, which not only compromise gas yield and safety but also reduce user confidence in the technology.

Recent studies have incorporated multidisciplinary approaches integrating engineering, biological, and economic aspects in digester development to address these challenges. From the engineering perspective, applying thin-walled pressure vessel theory has proven effective in improving structural safety. For instance, Nkoi et al. redesigned a floating-drum digester using stainless steel and pressure relief systems, adhering to ASME standards to ensure it could withstand biogas pressure accumulation [5]. Simultaneously, from a biological standpoint, optimizing parameters such as retention time, feedstock characteristics, temperature, and mixing has enhanced microbial activity and methane production [6]. Digesters operated under mesophilic conditions (around 45 °C) with 20–25 days of retention consistently yield the highest biogas output. Conversely, higher thermophilic temperatures may induce microbial stress and reduce overall efficiency [7].

In addition to engineering and biological performance, economic viability is a critical factor for successfully adopting small-scale digesters [8]. A study in Uganda demonstrated that a low-cost digester constructed with locally available materials achieved payback within one year when used under optimal conditions [9]. However, other studies have emphasized that high initial costs, material degradation, and lack of user training hinder long-term system sustainability. These recurring issues highlight the need for a more integrated approach that balances technical, operational, and financial factors to ensure small-scale digesters are both functional and replicable across diverse contexts [10].

Despite these advancements, most existing research addresses the biological optimization or mechanical design of small digesters in isolation. Very few studies attempt to synthesize both aspects into a unified framework. Castillo Alvarez et al. emphasized that the absence of a holistic design methodology that simultaneously considers reactor geometry, structural reliability, biogas performance, and cost-effectiveness limits the scalability of small biogas systems in real-world applications [4]. This gap is particularly relevant in food-service sectors where space, safety, and daily waste input vary significantly, requiring structurally sound reactors, easy to maintain, and capable of delivering high methane yields.

This study aims to fill that gap by proposing an integrated design methodology for a small-scale biogas reactor tailored to restaurant waste. The research objectives are threefold: (1) to develop a pressure-based structural design for a compact reactor using thin-walled pressure vessel theory and modern material considerations, (2) to estimate methane yield potential under controlled operational parameters suitable for food waste substrates, and (3) to evaluate the system’s structural safety and economic feasibility through analytical modeling. By bridging the gap between engineering rigor and biological efficiency, this work contributes a comprehensive solution to the persistent challenges in small-scale biogas system deployment.

# literature review

## Design Considerations for Small-Scale Biogas Reactors

Design quality is critical to biogas reactor performance, particularly in small-scale systems. Issahaku et al. (2024) conducted a comprehensive review of small biogas digester operation and maintenance, identifying inadequate construction practices as a leading cause of early system failures. Frequent issues include poor mixing mechanisms, lack of thermal regulation, and biogas leakage, which collectively impair system efficiency and reliability. Castillo Alvarez et al. further reported that nearly 40% of digesters in developing countries fail due to flawed design and improper feedstock handling. In their case study conducted in Peru, strategic modifications such as increasing the active volume to create a gas buffer and adding thermal insulation resulted in methane yields of approximately 63.8 L CH₄/kg substrate [4]. Despite these improvements, most small digester designs remain ad hoc and context-dependent. Issahaku et al. attempted to develop a universal method for tubular digesters, yet widespread adoption remains limited due to varying local needs and technical capacities [11]. In summary, the literature emphasizes the necessity for standardized yet adaptable design methodologies incorporating structural, operational, and control elements to improve reliability and long-term functionality.

## Feedstock and Biogas Yield Performance

The selection and management of feedstock are vital in determining biogas production efficiency. Organic kitchen and food waste are considered high-potential substrates due to their rich carbohydrate and lipid content. Ajay et al. highlighted that properly managed biodigesters using segregated kitchen waste can deliver substantial methane output. They provided a design procedure emphasizing systematic feeding and pretreatment to maximize gas production. Co-digestion techniques such as combining food waste with manure have proven effective in optimizing the carbon-to-nitrogen (C/N) ratio, thus enhancing methane generation by 30–50% [1]. For example, a study in Peru demonstrated that a 30:70 mixture of food waste and cattle manure solved waste disposal issues and increased biogas yield beyond average levels [4]. Operational parameters such as temperature, pH, and retention time further influence microbial activity. Uzorka and Wonyanya found that digesters operated at 45 °C with a 25-day hydraulic retention time achieved optimal methane output, while thermophilic conditions around 55 °C reduced efficiency due to microbial inhibition. These findings highlight the need to adjust operational conditions to the specific characteristics of the waste stream [9].

**Structural Design and Material Selection**

Structural integrity is a frequently overlooked yet essential component in small-scale digester design. Unlike large industrial reactors, many small digesters are constructed manually using local materials and informal methods. Traditional units typically utilize masonry, concrete, or mild steel, offering durability but often resulting in higher construction costs. Obileke et al. reviewed the materials used in domestic digesters and emphasized the trade-off between cost, strength, and ease of transport. In remote or rural areas, flexible bag digesters made from PVC or rubber composites are increasingly favored due to their portability and lower fabrication costs [11]. However, these materials can lack durability under pressure or prolonged exposure to biogas. Digesters must be structurally engineered to withstand internal gas pressure to ensure safety. Yolanda Mapantsela et al. indicated that most small digesters qualify as thin-walled pressure vessels, enabling the use of ASME-based design formulas. Nkoi et al. applied this approach using stainless steel (AISI 304) and included allowances for corrosion and weld efficiency, ensuring their reactor could safely withstand pressure buildup [12]. Small mechanical innovations, such as incorporating pumps or pressure-regulating mechanisms, can improve gas delivery to standard stoves. Nevertheless, structural enhancement must be balanced with cost and material availability to remain viable for small businesses or rural users.

## Economic Feasibility and Implementation Challenges

The economic viability of small-scale biogas systems is essential for broad implementation, especially in low-income and rural contexts. Wang et al. evaluated a biogas program in Japan and concluded that economic feasibility depends on consistent gas utilization and short payback periods [13]. More recently, Tian et al. conducted a life-cycle and cost–benefit analysis of decentralized food waste digesters, concluding that net economic and environmental gains are possible under optimized operational conditions [14]. Empirical evidence from Uganda showed that even a small 1–2 m³ household digester can recover its capital cost within one year through reduced fuel expenses. However, these promising results are often contingent on consistent maintenance and usage. Barriers such as high upfront costs, limited financial support, and lack of technical assistance frequently delay payback and discourage adoption [9]. Mwirigi et al. reported that policy inconsistencies and user training deficits continue to hinder biogas development in parts of Africa [15]. Nevertheless, Castillo Alvarez et al. argue that with proper system scaling and operational management, small digesters can be profitable even without government subsidies [16]. Therefore, enhancing gas yield through better reactor design and ensuring system longevity are pivotal for improving economic feasibility.

# methods

A design-oriented engineering framework was adopted to develop a biogas reactor suitable for small-scale restaurant applications. The study was conducted at a restaurant in Sengkaling, Malang Regency, Indonesia, which served as the waste input reference site. The methodological approach comprised five main stages: (i) quantification of daily organic waste generation; (ii) digester sizing based on hydraulic retention time (HRT); (iii) geometric and structural design using empirical and semi-empirical models; (iv) design selection through morphological and decision matrices; and (v) economic and operational feasibility assessment.

The restaurant generated approximately 52.126 kg/day of organic waste with an average density of 350 kg/m³, yielding a daily volume of 0.149 m³. Using a 20-day HRT, the required digester volume was determined to be 2.979 m³. The reactor was configured as a vertical cylindrical tank with a hemispherical bottom and flat top, segmented into three functional zones: gas storage, sludge layer, and fermentation chamber. Dimensionless design formulas were used to determine critical parameters such as diameter (1.88 m), effective height (1.072 m), and surface area (11.88 m²).

Three-dimensional modeling was performed using Autodesk Inventor to verify spatial integrity and visualize assembly. Structural safety was evaluated using thin-walled pressure vessel equations, applying a safety factor 3. The selected construction material, ST41 steel with a tensile strength of 410 MPa, and a wall thickness of 5 mm, yielded a maximum allowable working pressure of 4.57 bar—safely exceeding the projected internal biogas pressure of 2.036 bar.

A morphological matrix was constructed to identify combinations of design variables to select the optimal design. These alternatives were evaluated using a weighted decision matrix with six criteria: cost, efficiency, reliability, maintainability, safety, and environmental adaptability. The highest-ranking concept was advanced to final design. Material cost was estimated based on steel mass (466 kg), current market rates (Rp. 17,000/kg), and a fabrication overhead of 40%, yielding a total reactor cost of Rp. 11,090,800.

A preventive maintenance protocol was developed to ensure reliability and service life. It consists of daily checks for gas leaks and valve integrity, weekly inspections for sludge flow and sealing, monthly functional tests on gas and sludge outlets, and an annual assessment of corrosion and structural soundness. Manual sludge removal was enabled via top access ports. All technical assessments were benchmarked against relevant codes and prior research to ensure engineering validity and field applicability.

# results and discussions

## Reactor Design Capacity and Geometry

The designed biogas reactor is tailored to treat organic waste generated from a medium-sized restaurant, quantified at 52.126 kg/day (see Figure 1). Assuming a waste density of 350 kg/m³, the daily waste volume was estimated at 0.149 m³/day. Applying a hydraulic retention time (HRT) of 20 days, a common standard for anaerobic digestion of high-organic-content substrates, the digester volume was calculated using Equation 1, resulting in a total volume of 2.979 m³. This ensures the substrate remains within the reactor long enough to undergo complete anaerobic degradation.

(1)

To accommodate gas storage and sludge settlement, the reactor geometry was further delineated into three functional zones: gas holding space (0.55 m³), sludge zone (0.33 m³), and the primary fermentation chamber (2.0 m³). These were derived using dimensionless design ratios relative to the reactor diameter (1.885 m). The dimensional breakdown guarantees that methane accumulation and substrate stratification occur efficiently, promoting stable biogas production while minimizing risk of overflow or substrate short-circuiting.

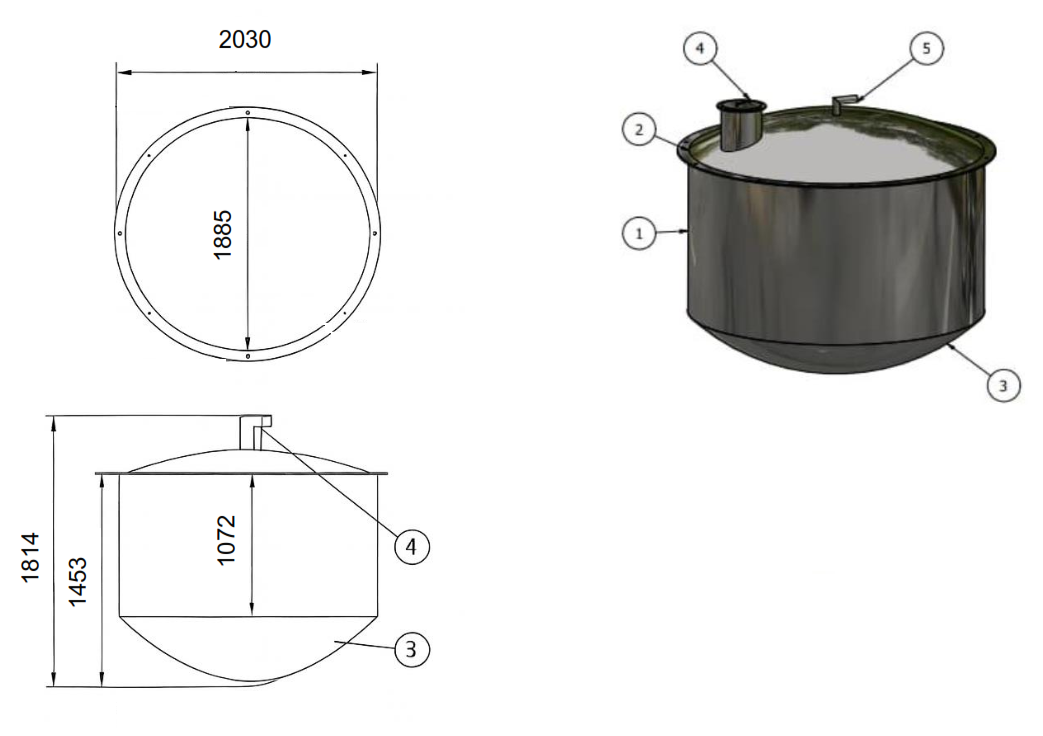


Figure 1. 3D Design of the Biogas Reactor (in mm unit).

Component Descriptions:

1. Reactor Body

This is the main cylindrical chamber where the anaerobic digestion process takes place. It is fabricated using ST41 steel with a thickness of 5 mm to ensure both structural rigidity and gas-tightness. The internal volume is calculated based on the hydraulic retention time and daily waste input.

1. Up Cover

The upper cover seals the reactor chamber and supports mounting inlet and outlet components. It is designed to be removable or accessible for inspection and maintenance while maintaining pressure integrity.

1. Bottom Cover

The base of the reactor is dome-shaped to facilitate sludge settling and improve flow distribution within the digester. The curved geometry also enhances structural strength and ease of sludge removal.

1. Waste Inlet

Located on the top side of the reactor, this pipe serves as the entry point for organic kitchen waste. Its vertical design ensures the waste is evenly distributed into the fermentation chamber without causing blockages.

1. Methane Gas Outlet

This is the dedicated outlet for collecting biogas, primarily methane, from the reactor headspace. Depending on the system configuration, the outlet is connected to a flexible gas line or storage system and may be equipped with a pressure valve or flow meter.

## Methane Production Potential and Specific Yield

Based on empirical biogas yields from organic waste, a conservative production rate of 0.04 m³/kg was employed. This yields a daily biogas production of 2.085 m³. Literature indicates that methane typically constitutes approximately 50–60% of biogas content depending on substrate type and digestion conditions. Using a 54% methane fraction, the estimated daily methane volume was 1.12 m³, translating to a specific methane yield of 0.0215 m³ CH₄/kg substrate. This yield falls within the expected range reported in comparable studies involving food and kitchen waste, which contain a balanced composition of polysaccharides, amino acids, and lipids favourable for methanogenesis. This methane production is significant, as 1.12 m³/day can fuel low-pressure burners or be utilized for water heating and light cooking. The daily yield could cover several operational hours for a small commercial kitchen if stored properly. This finding supports the feasibility of applying decentralized biogas reactors to reduce fossil fuel dependence in the culinary sector.

## Operating Pressure and Structural Safety Analysis

The volume of gas generated (1.12 m³/day) exceeds the immediate holding capacity of the gas chamber (0.55 m³), necessitating a pressure calculation to ensure operational safety. Using the ideal gas relationship, the resulting gas pressure was found to be 2.036 bar. This is within acceptable limits for small-scale biogas systems. To verify structural integrity, the reactor was designed using ST41 carbon steel with an ultimate tensile strength of 410 MPa. Applying a safety factor 3, the allowable design stress is 137 MPa. With a wall thickness of 5 mm and an internal diameter of 1.88 m, the maximum permissible internal pressure is 13.7 bar, while the working pressure (divided by safety factor) is 4.57 bar. Thus, the operating pressure of 2.036 bar is well below the structural limit, confirming that the digester is mechanically safe for biogas retention under standard operating conditions.

## Material Usage and Economic Feasibility

The tank construction requires 466 kg of ST41 steel, based on a surface area of 11.88 m² and wall thickness of 5 mm, with a steel price of Rp. 17,000/kg, the raw material cost reaches Rp. 7,922,000. Including a fabrication overhead of 40%, the total reactor construction cost is Rp. 11,090,800. This relatively modest investment highlights the potential for scalable implementation in small and medium enterprises (SMEs), particularly in urban restaurant districts where organic waste is abundantly available. Given the low maintenance requirements and fuel-saving potential, the return on investment (ROI) is promising, especially in areas facing high LPG or diesel fuel prices. Environmental advantages, such as reduced methane emissions from unmanaged waste and enhanced waste valorization, further strengthen the economic benefit.

## Maintenance Protocol for Reactor Longevity

To ensure sustained functionality and safety, a four-tier maintenance protocol was proposed. Daily inspections focus on pressure readings and gas line leak detection. Weekly maintenance checks include inspection of sludge input ports and environmental sealing. Monthly assessments involve functional testing of gas and sludge outlets and internal agitator mechanisms. Annual evaluations prioritize structural inspections for corrosion or cracks, and sludge removal using vacuum or manual tools. These routine measures are crucial for preserving reactor efficiency and minimizing downtime. The system design's simplicity allows restaurant staff to be trained in basic operational management, aligning with the goal of user-friendly renewable energy systems.

## Comparison with Previous Studies

The findings of this study align with and extend previous research on small-scale biogas systems tailored to food-service establishments[17]. For instance, Arifin et al. developed a 250-liter plastic drum digester, which achieved a total biogas production of 12.15 m³ over 30 days, averaging 0.405 m³/day, with methane output enabling a cooking flame for approximately 51 minutes [18]. In comparison, the reactor proposed in this study achieves a substantially higher daily methane yield of 1.12 m³/day, facilitated by larger capacity (2.979 m³) and optimized reactor geometry. This confirms that scale-up and tailored design directly enhance production efficiency and usability for daily energy needs.

Moreover, Alfanz et al. introduced a monitoring-integrated biodigester system that recorded peak methane production at 95,672 ppm at 34°C and 67% RH [19]. Although the present design does not yet integrate automated sensors, the daily methane output is consistent with those conditions, supporting that proper substrate selection and reactor volume are critical drivers for stable methane generation, even without real-time instrumentation.

From a design perspective, this study incorporated a morphological matrix and engineering design selection, which is rarely adopted in previous studies focused on small-scale biogas systems. Most literature focuses on either experimental yield or basic digester construction. At the same time, the present work introduces a structured methodology combining volumetric calculations, pressure safety validation, and cost analysis, bridging the gap between academic research and applied engineering for renewable energy infrastructure in SMEs.

The methane-specific yield obtained in this study (0.0215 m³ CH₄/kg waste) is comparable to other studies on food waste digestion. This indicates that restaurant waste, with its high content of carbohydrates and fats, remains a highly viable feedstock for decentralized biogas applications. This study contributes a comprehensive reactor design tailored for real-world restaurant waste management while producing competitive biogas outputs. It provides a practical and scalable pathway toward circular energy utilization, especially relevant in urban and peri-urban food service environments.

# CONCLUSIONs

This study presents the design and analysis of a restaurant-scale biogas reactor capable of converting 52.126 kg/day of organic waste into renewable methane energy. Through volumetric and geometric calculations based on a 20-day hydraulic retention time, the reactor volume was determined to be 2.979 m³, with an optimized configuration consisting of a 1.88 m diameter, dome-shaped bottom, and integrated gas storage zone. This geometry ensures effective stratification, fermentation, and methane collection.

The reactor demonstrated a projected daily biogas production of 2.085 m³, corresponding to 1.12 m³ of methane with a specific methane yield of 0.0215 m³/kg. Structural analysis verified that the operating gas pressure (2.036 bar) remains safely below the allowable design pressure (4.57 bar), confirming that the reactor meets mechanical integrity and safety requirements for continuous anaerobic operation. Economically, the estimated total fabrication cost of Rp. 11,090,800 makes the system financially feasible for small and medium-sized enterprises in the foodservice industry.

A comparative review with prior studies shows that this design offers higher methane yield, better safety margins, and a more structured design methodology than existing small-scale digesters. Integrating a morphological matrix and engineering design decision-making tools further enhances the reactor's innovation and practical applicability for decentralized waste-to-energy conversion. In conclusion, the proposed reactor design provides a sustainable, safe, cost-effective solution for managing organic waste while producing valuable methane gas. Its modular and maintainable structure makes it suitable for deployment in urban restaurant settings, supporting the broader transition to circular energy systems and renewable energy adoption in food-based industries.

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# References

[1] C. M. Ajay, S. Mohan, and P. Dinesha, “Decentralized energy from portable biogas digesters using domestic kitchen waste: A review,” *Waste Management*, vol. 125, pp. 10–26, 2021, doi: https://doi.org/10.1016/j.wasman.2021.02.031.

[2] A. Dhir, S. Talwar, P. Kaur, and A. Malibari, “Food waste in hospitality and food services: A systematic literature review and framework development approach,” *J Clean Prod*, vol. 270, p. 122861, 2020, doi: https://doi.org/10.1016/j.jclepro.2020.122861.

[3] B. S. Dhanya, A. Mishra, A. K. Chandel, and M. L. Verma, “Development of sustainable approaches for converting the organic waste to bioenergy,” *Science of The Total Environment*, vol. 723, p. 138109, 2020, doi: https://doi.org/10.1016/j.scitotenv.2020.138109.

[4] Y. C. Alvarez, R. J. Borges, C. D. P. Vidal, F. M. C. Leon, J. S. P. Buendia, and J. A. S. Nolasco, “Design Improvements and Best Practices in Small-Scale Biodigesters for Sustainable Biogas Production: A Case Study in the Chillon Valley, Perú,” *Energies (Basel)*, vol. 18, no. 2, Jan. 2025, doi: 10.3390/en18020338.

[5] B. Nkoi, T. Lebele-Alawa, and B. Odobeatu, “Design and Fabrication of a Modified Portable Biogas Digester for Renewable Cooking-Gas Production,” *European Journal of Engineering Research and Science*, vol. 3, pp. 21–29, Mar. 2018, doi: 10.24018/ejers.2018.3.3.647.

[6] A. Adeleye, A. Amoo, and I. Madu, “Maximizing Efficiency in Biogas Production: A Comprehensive Review of Operational Parameters,” vol. 8, pp. 48–63, Jun. 2023, doi: 10.5281/zenodo.8093879.

[7] M. Alam, M. B. Sultan, M. Mehnaz, C. S. U. Fahim, S. Hossain, and A. H. Anik, “Production of biogas from food waste in laboratory scale dry anaerobic digester under mesophilic condition,” *Energy Nexus*, vol. 7, p. 100126, 2022, doi: https://doi.org/10.1016/j.nexus.2022.100126.

[8] M. Issahaku, N. S. A. Derkyi, and F. Kemausuor, “A systematic review of the design considerations for the operation and maintenance of small-scale biogas digesters,” *Heliyon*, vol. 10, no. 1, p. e24019, 2024, doi: https://doi.org/10.1016/j.heliyon.2024.e24019.

[9] A. Uzorka and M. Wonyanya, “Design and performance evaluation of small-scale biogas digesters using locally available materials in rural Uganda,” *Renew Energy*, vol. 246, p. 122994, 2025, doi: https://doi.org/10.1016/j.renene.2025.122994.

[10] M. Issahaku, N. Sarfo, N. Derkyi, and F. Kemausuor, “Operation and Maintenance of Small-Scale Biogas Digesters: Scoping Review and Bibliometric Analysis of Literature,” *American Scientific Research Journal for Engineering, Technology, and Sciences*, vol. 89, pp. 184–215, Sep. 2022.

[11] K. C. Obileke, H. Onyeaka, and N. Nwokolo, “Materials for the design and construction of household biogas digesters for biogas production: A review,” *Int J Energy Res*, vol. 45, Oct. 2020, doi: 10.1002/er.6120.

[12] Y. Mapantsela, P. Mukumba, K. C. Obileke, and N. Lethole, “Portable Biogas Digester: A Review,” Sep. 01, 2024, *Multidisciplinary Digital Publishing Institute (MDPI)*. doi: 10.3390/gases4030012.

[13] J. Wang, Y. Chai, Y. Shao, and X. Qian, “Techno-economic Assessment of Biogas Project: a Longitudinal Case Study from Japan,” *Resour Conserv Recycl*, vol. 164, p. 105174, 2021, doi: https://doi.org/10.1016/j.resconrec.2020.105174.

[14] Z. Fan, H. Dong, Y. Geng, and M. Fujii, “Life cycle cost–benefit efficiency of food waste treatment technologies in China,” *Environ Dev Sustain*, vol. 25, no. 6, pp. 4935–4956, 2023, doi: 10.1007/s10668-022-02251-4.

[15] J. Mwirigi *et al.*, “Socio-economic hurdles to widespread adoption of small-scale biogas digesters in Sub-Saharan Africa: A review,” *Biomass Bioenergy*, vol. 70, Mar. 2014, doi: 10.1016/j.biombioe.2014.02.018.

[16] L. O. Freire, L. M. Navarrete, B. P. Corrales, and J. N. Castillo, “Efficiency in thermoelectric generators based on Peltier cells,” *Energy Reports*, vol. 7, pp. 355–361, 2021, doi: https://doi.org/10.1016/j.egyr.2021.08.099.

[17] Kusmiyati, D. Wijaya, and B. J. Hartono, “Advancements in Biogas Production from Cow Dung: A Review of Present and Future Innovations,” *E3S Web of Conferences*, vol. 448, Nov. 2023, doi: 10.1051/e3sconf/202344804005.

[18] J. Arifin, F. Herlina, A. Amin, and H. Iman, “Analisis dan Perancangan Alat Biogas Sebagai Energi Alternatif Skala Rumah Tangga Dalam Pemanfaatan Limbah Kotoran Sapi,” *Jurnal Engine: Energi, Manufaktur, dan Material*, vol. 7, p. 70, Nov. 2023, doi: 10.30588/jeemm.v7i2.1610.

[19] R. Alfanz, A. Nurhadi, and J. Arya Laksmono, “Perancangan dan Implementasi Sistem Monitoring Produksi Biogas pada Biodigester,” *Jurnal Nasional Teknik Elektro*, vol. 5, Mar. 2016, doi: 10.20449/jnte.v5i1.216.