Advance Sustainable Science, Engineering and Technology (ASSET)
Vol. 8, No.3, July 2026, pp. 02603019-01 ~ 02603019-010
ISSN: 2715-4211 DOI: https://doi.org/10.26877/asset.v8i3.2422

Performance Evaluation of a Community-Scale Fiberglass Anaerobic Digester for Biogas and Nutrient Recovery

Rahmat Sabani[1]*, Ari Handono Ramelan[2], Pranoto[3], Mohammad Masykuri[4]

[1]Doctoral Program of Environmental Science, Postgraduate School, Universitas Sebelas Maret, Kentingan Jl. Ir. Sutami No.36, Jebres, Surakarta, Indonesia

[2]Department of Physics, Faculty of Sciences and Mathematics, Universitas Sebelas Maret, Kentingan Jl. Ir. Sutami No.36, Jebres, Surakarta, Indonesia

[3]Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret, Kentingan Jl. Ir. Sutami No.36, Jebres, Surakarta, Indonesia

[4]Department Science Education, Faculty of Teacher Training and Education, Universitas Sebelas Maret, Kentingan Jl. Ir. Sutami No.36, Jebres, Surakarta, Indonesia

*rahmatsabani@student.uns.ac.id

Abstract. The management of organic waste using an anaerobic reactor offers the potential for renewable energy production and nutrient recovery. This study evaluates the performance of a 3,000 L fiberglass anaerobic reactor designed to treat a mixture of kitchen waste, cow manure, and water in a 1:1:1 ratio. The process was conducted under mesophilic conditions (30–38 °C) over a 40-day batch cycle. The reactor produced a total of 63.75 m^3 of biogas with an average methane content of 59.3%, equivalent to 0.193 m^3 CH_4/kg VS. Additionally, the system produces approximately 2,700 kg/month of liquid effluent and 900 kg/month of stabilized solids. These results demonstrate the efficiency of substrate bioconversion and the potential for utilizing residues as organic fertilizer. This study emphasizes the technical feasibility of using a community-scale fiberglass reactor for organic waste treatment with measurable performance parameters.

Keywords: Anaerobic digestion, fiberglass biodigester, methane yield, organic waste treatment, renewable energy recovery.

(Received 2025-07-24, Revised 2025-09-17, Accepted 2025-10-09, Available Online by 2026-05-25)

1. Introduction

The management of household organic waste and livestock manure remains a challenging technical issue, especially in rural and semi-urban communities that lack modern waste treatment infrastructure [1], [2],

[3]. Globally, household organic waste accounts for over 60% of urban solid waste and when not managed properly, it contributes to methane emissions, water pollution, and the spread of diseases [4,5]. The decomposition of organic waste in landfills is estimated to generate up to 20% of global anthropogenic methane emissions [6]. This situation underscores the need for waste processing technologies that not only reduce environmental impacts but also enable energy and nutrient recovery at the community level [7,8].

Anaerobic digestion (AD) has long been used to convert organic waste into biogas and nutrient-rich digestate [9–12]. At the decentralized scale, AD offers flexibility to process wet waste near its source [13–15]. However, the adoption of this technology in community contexts is often hindered by limitations in construction materials. Concrete or steel digesters, which are the most commonly used, are prone to corrosion, require skilled labor, and have high material and maintenance costs [16,17]. Additionally, many small-scale systems fail to adapt to seasonal variations and substrate heterogeneity, leading to operational sustainability issues.

As an alternative, fiberglass offers technical advantages such as corrosion resistance, light weight, thermal stability, and relatively long service life in tropical conditions [18]. Previous studies have evaluated the potential of fiberglass-based biodigesters in rural and semi-urban environments and demonstrated that co-digestion approaches can enhance methane efficiency and system stability [19–21]. Digestate from the AD process has also been shown to improve soil fertility and reduce dependence on synthetic fertilizers [22]. However, most research remains limited to basic technical aspects, without full integration between technical, environmental, and economic assessments. Empirical evidence related to financial sustainability, such as through Net Present Value (NPV) analysis, Internal Rate of Return (IRR), and payback period, is also rarely reported.

Based on this research gap, this study aims to comprehensively evaluate the technical, environmental, and economic performance of a 3,000-liter fiberglass anaerobic biodigester operated in field conditions with a mixture of household kitchen waste and livestock manure. This research seeks to answer the main question: can fiberglass material serve as a viable alternative to concrete and steel in the context of community-scale AD systems? The contribution of this research lies in providing integrated empirical data covering biogas productivity, digestate quality, emission mitigation potential, and financial viability indicators, thereby serving as a foundation for the development of more efficient, durable, and community-appropriate biodigester technology tailored to the needs of resource-constrained communities.

2. **Methods**

2.1 research design

This study used a quantitative experimental design to evaluate the technical performance of a community-scale fiberglass anaerobic reactor. The reactor was operated in mesophilic batch mode (30–38 °C) for a retention period of 40 days, based on stable and energy-efficient practices for organic waste treatment [13,23]. The focus of the study was on measuring biogas volume, methane content, and digestate production. The experiment was conducted as a single batch, using a consistent substrate to maintain uniform processing conditions.

2.2 research samples and site characteristics

The substrate consists of local household waste (food scraps, vegetable peels, minimal protein residues) and fresh cow manure, collected from 15–20 households and small-scale farms. The substrate is mixed with water in a volumetric ratio of 1:1:1, producing 3,000 L of homogeneous slurry. Characterization of the material based on literature values and field tests confirmed the following: the density of kitchen waste slurry ranged from 0.6–0.8 kg/L, cow manure from 0.9–1.1 kg/L, and water was considered to be 1.0 kg/L. The average density of the combined substrate was calculated to be 0.9 kg/L, resulting in an estimated total mass of 2,700 kg. The total solids (TS) content of the sludge was around 9%, and volatile solids (VS) contributed 80% of the TS, consistent with empirical values from previous AD studies [24].

The experiment was conducted in a semi-urban village in West Lombok Regency, Indonesia, with mesophilic environmental temperatures ranging from 30°C to 38°C. These temperature conditions are ideal for mesophilic microbial populations and do not require external heating, in line with the low-energy operational objectives in rural application scenarios [16].

2.3 Materials and apparatus

The horizontal fiberglass reactor has a total capacity of 4,000 L and an effective working volume of 2,800 L (70%), chosen for its light weight, corrosion resistance, and stability in tropical conditions [25]. Biogas volume is measured daily using a water displacement meter, while gas composition (CH_4, CO_2, H_2S, O_2, N_2) is analyzed using the Geotech BIOGAS 5000. Internal temperature is monitored with a digital thermometer, pH is measured weekly, and digestate is separated into liquid and solid fractions at the end of the batch.

2.4 Substrate preparation procedure

Before loading, food waste is manually sorted to remove inorganic contaminants, then ground using a mechanical crusher to reduce the particle size to less than 5 mm. Cow manure is screened to remove sand and bedding material. Both materials are mixed with water in a clean mixing tank until a homogeneous mixture is obtained. The resulting slurry is loaded into the digester through the top inlet valve using a manual pump. The digester is immediately closed after loading to start the anaerobic phase. No additional materials are added during the 40-day batch cycle.

2.5 Operational Conditions

The reactor is operated without external heating or mechanical agitation, relying on natural convection and microbial thermogenesis. The retention time is set at 40 days, and the pH is maintained at 6.8–7.3 for optimal methanogenic activity [10]. Biogas is collected through an inverted drum and the volume is recorded daily. At the end of the batch, the digestate is separated into liquid and solid fractions for analysis.

2.6 Parameter Measurements and Analytical Methods

The research monitored five primary parameters:

1. Biogas volume (m^3) – Measured daily using water displacement method
2. Gas composition (%) – CH_4, CO_2, H_2S, O_2, N_2, with Portable Biogas Analyzer/Gas Analyzer (Multigas Analyzer) Geotech BIOGAS 5000 and gas chromatography
3. Methane yield (m^3 CH_4/kg VS) – Calculated from total VS input and cumulative CH_4 produced
4. Digestate output – Quantified in both liquid and solid fractions (kg/month)
5. GHG emissions offset (tons CO_2e) – Estimated using IPCC default CH_4 equivalence factors

The methane yield was calculated as:

$$Y\mathrm{CH_4} = \frac{\text{Total Methane}\left(\mathrm{m^3}\right)}{\text{Volatile Solids }\left(\mathrm{kg}\right)}$$

Environmental impact was assessed by estimating the CH_4 emissions avoided from diverting organic waste from unmanaged landfilling, using IPCC Tier 1 default emission factor of 0.6 m^3 CH_4/kg VS.

2.7 Economic evaluation methods

The financial feasibility of the system was evaluated based on actual costs and revenue projections. The initial capital investment was recorded at Rp 85,000,000. Operational and maintenance costs were estimated at Rp 500,000/month. Revenues were calculated from three sources:

1. Biogas substitution for LPG: based on CH_4 calorific equivalence
2. Liquid digestate: valued at Rp 2,000/L
3. Solid compost: valued at Rp 1,200/kg

A 10-year cash flow model was developed using Microsoft Excel. Financial indicators included Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period. The analysis used an 8% annual discount rate, consistent with rural development investment benchmarks.

3. Results and Discussion

3.1 Biogas performance and methane yield

The fiberglass anaerobic digester yielded significant biogas production over the 40-day batch operation under mesophilic conditions. A total volume of 63.75 m³ of biogas was collected, with daily production peaking between days 8 and 14. Gas composition analysis revealed an average methane concentration of 59.3%, with a methane yield of 0.193 m³ CH_4 per kilogram of volatile solids (VS). These values indicate effective microbial activity and efficient degradation of organic matter during the digestion cycle. Figure 1 illustrates the trend in daily biogas production and methane content, confirming typical batch digestion kinetics with an early exponential phase followed by a gradual plateau.

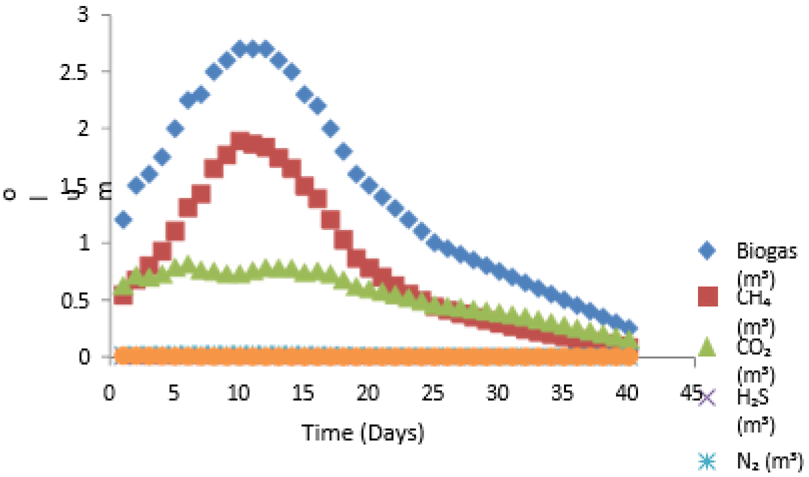

Figure 1. Daily biogas and methane concentration profiles over 40 days

The findings indicate that fiberglass reactors are capable of supporting active methanogenesis without external stirring or heating, providing evidence of significant passive operational efficiency. The early rise in methane concentration indicates active methanogenesis by day 3, supported by the C:N balance of the 1:1:1 substrate mix. These results are in line with Aboud et al. [20], where co-digestion of kitchen waste and livestock manure under mesophilic conditions produced 55–62% methane. Without external heating or additional stirring, this passive system remained efficient. Methane production of 0.193 m³/kg VS is also in line with the global average for co-digestion, as reviewed by Bouallagui et al. [26], indicating that the substrate and operating conditions support optimal biogas conversion.

3.2 Degradation of organic waste and recovery of energy and nutrients

The system processed a total of 3000 liters (2700 kg) of organic slurry composed of equal parts food waste, cow manure, and water. Based on field measurements and supporting literature, the slurry contained approximately 9% total solids (TS), with volatile solids (VS) accounting for 80% of TS. This results in an estimated 195.75 kg of VS available for degradation.

By the end of the 40-day digestion cycle, complete bioconversion of the VS was assumed, supported by the stable methane production plateau and absence of odor in the final digestate. The outputs included approximately 2700 liters of liquid digestate and 900 kg of compostable solid residue, consistent with material balance principles. These outputs represent a full conversion of degradable organic matter into energy and nutrients.

Table 1. Input substrate characteristics and digestate output quantities

Parameters	Value
Total slurry input	3000 L
Substrate Mass	2700 kg

Total Solids (TS)	9% (243 kg)
Volatile Solids (VS)	80% of TS (195.75 kg)
Biogas produced	63.75 m^3
Methane produced	37.83 m^3 (59.3% avg)
Methane yield	0.193 m^3 CH_4/kg VS
Liquid digestate (monthly)	2700 L
Solid digestate (monthly)	900 kg

This result underscores the value of co-digestion in maximizing both energy and nutrient recovery. The balanced substrate mixture not only ensured stable gas production but also yielded digestate suitable for direct agricultural application. As reported by Yadav et al. [11], the liquid fraction of digestate from similar systems contains significant concentrations of nitrogen, phosphorus, and micronutrients that improve soil fertility, while the solid residue can enhance soil organic matter content.

In practical terms, the digestate volume generated in this research is sufficient to fertilize over 1 hectare of mixed cropping systems per month, assuming conventional application rates. This aligns with the findings of [27–29] who highlighted the role of digestate as a sustainable alternative to synthetic fertilizers in smallholder farming contexts.

3.3 Environmental quality improvement and scalability

One of the primary environmental benefits of anaerobic digestion is the reduction in methane emissions associated with unmanaged organic waste. In this research, the conversion of 195.75 kg of VS into 37.83 m^3 of methane avoided the release of approximately 117.45 m^3 of CH_4 that would have otherwise escaped into the atmosphere under landfill conditions. Based on the IPCC [6] global warming potential (GWP) of CH_4 at 28 times that of CO_2, this equates to approximately 3.29 tons of CO_2-equivalent avoided in just one batch cycle.

On an annualized basis, the system could divert and degrade an estimated 31.8 tons of organic waste (based on 2.65 tons/month input), preventing the release of over 250 tons CO_2e/year and eliminating approximately 9.5 tons of biological oxygen demand (BOD) from entering water bodies through leachate or runoff.

Table 2. Environmental performance

Parameters	Value
GHG Emissions Avoided	117.45 m^3 CH_4 avoided 21.14 tons CO_2e/month
Pollution Load Reduced	795 kg/month not entering soil/water
Waste Diversion	31.8 tons/year of wet organic waste diverted from open dumping or burning
Organic waste diverted from landfill	2.65 tons/month
Soil Fertility Improvement Potential	2.7 tons/month of liquid bio-slurry
Avoided CH_4 emissions	900 kg/month of compostable residue 20–25 tons CO_2e/year

Additionally, by converting degradable organics into controlled products, the system effectively eliminates the conditions that promote vector breeding, unpleasant odors, and groundwater contamination. These benefits position the biodigester not merely as a waste-to-energy unit, but as a tool for holistic environmental remediation and sustainable community development.

The use of fiberglass as the construction material provides scalability advantages over traditional biodigester materials like brick or steel. As shown by Zhang et al. [31], fiberglass-based systems can be prefabricated and deployed with minimal technical input, making them particularly suitable for remote or resource-limited areas. This modularity and durability support replication across rural and peri-urban zones, aligning with decentralized waste management strategies endorsed by UNEP and FAO [4,5].

3.4 *Economic feasibility*

The economic assessment revealed that the system is highly viable for community-level deployment. The total capital investment of Rp 85,000,000 covered construction, material procurement, and installation. Monthly operational expenses were estimated at Rp 500,000, primarily for minor maintenance and monitoring. Revenue streams included the monetary value of biogas used in place of LPG, liquid digestate sold at market fertilizer prices, and composted solids marketed locally.

Table 3. Economic Indicators for the fiberglass biodigester system

Economic Indicator	**Value**
Capital cost	Rp 85,000,000
Operational cost	Rp 500,000/month
Monthly revenue	Rp 6,910,000
Net Present Value (NPV)	Rp 367.900,000n (10 years)
Internal Rate of Return (IRR)	63%
Payback Period	1.3 years

These figures highlight the financial sustainability of the system, with payback achieved in just over one year and a high IRR indicative of profitability and low risk. Comparable studies, such as those by Kumar et al. [32] and Jha et al. [33], report longer payback periods and higher dependence on subsidies, whereas this system operates independently with local inputs and real revenue.

The ability to generate both energy and high-value fertilizers creates opportunities for micro- enterprise and community empowerment. Furthermore, the low-maintenance design and durable material ensure that operational costs remain minimal over time, further improving the return on investment [34].

3.5 *Biogas performance and methane yield*

The biogas production profile observed in this research demonstrates a typical batch digestion curve, characterized by an initial lag phase, followed by an exponential rise in gas production and subsequent decline. The cumulative production of 63.75 m^3 of biogas over 40 days aligns closely with results from similar co-digestion experiments, reinforcing the viability of mixed substrate anaerobic digestion systems. The average methane concentration of 59.3% confirms effective methanogenesis and suggests that the 1:1:1 slurry of food waste, cattle manure, and water provided a balanced C/N ratio conducive to microbial activity, as supported by prior work on co-digestion efficiency [20,21].

The achieved methane yield of 0.193 m^3/kg VS reflects a high conversion efficiency considering the passive nature of the system, with no external heating or mechanical mixing. This value is within the standard range (0.18–0.25 m^3/kg VS) documented in literature for kitchen waste and manure blends [26]. The use of ambient mesophilic conditions also highlights the potential for implementing such systems in tropical and subtropical regions without added energy inputs. The fiberglass digester's thermal properties may have contributed to maintaining stable internal temperatures, further supporting microbial performance [31]. These results underline the system's robustness and suitability for decentralized deployment, particularly in communities lacking energy infrastructure.

3.6 *Organic waste degradation and nutrient recovery*

The complete degradation of 195.75 kg of volatile solids indicates that the biochemical potential of the substrate was effectively harnessed. The co-digestion strategy not only stabilized the pH and enhanced methane yield but also resulted in substantial digestate outputs approximately 2700 liters of liquid bio-slurry and 900 kg of compostable solids per month. These outputs are consistent with findings from similar studies, which suggest that AD systems can convert up to 90% of organic inputs into energy and nutrient-rich products [11].

The liquid digestate, typically rich in ammonium, phosphorus, and potassium, presents a valuable alternative to chemical fertilizers. Its nutrient profile supports soil fertility, improves moisture retention, and enhances microbial activity when applied to crops [20]. The solid residue, once composted or dried, can serve as a stable organic amendment to improve soil structure. Together, these products contribute to circular nutrient management and reduce reliance on fossil-derived inputs in agriculture.

The results also illustrate how bioconversion systems offer dual resource recovery pathways energy and nutrients which are both locally reusable. This supports the concept of a circular bioeconomy, where waste is revalorized within the same socio-ecological system that produced it. The integration of digestate use in local farming systems reinforces community resilience and food-energy- soil synergies, as emphasized in sustainable agroecological models [10].

3.7 Environmental impact and system scalability

From an environmental perspective, the system achieved significant outcomes in terms of pollution reduction and greenhouse gas (GHG) mitigation. By converting degradable organic waste into biogas rather than allowing it to decompose anaerobically in unmanaged landfills, the system avoided an estimated 117.45 m^3 of methane emissions per cycle, equivalent to 3.29 tons CO_2e. Annualized, this translates to more than 250 tons CO_2e avoided, illustrating the climate mitigation potential of community-scale digesters, especially when deployed across multiple villages or municipalities [6].

The reduction of biological oxygen demand (BOD) load estimated at ~795 kg/month also points to a considerable decrease in organic pollution that would otherwise affect soil and water bodies. This aligns with the findings of Singh et al. [35], who noted that well-managed digesters can reduce environmental pollutant loads by over 60%. Furthermore, the elimination of open dumping and uncontrolled burning practices reduces vector-borne disease risk and improves air quality.

Regarding scalability, the system's modular design, based on prefabricated fiberglass components, enables rapid replication and low technical barriers to adoption. The lightweight and corrosion-resistant properties of fiberglass make it preferable over concrete or metal in humid, rural environments where maintenance expertise is limited [31]. The system's passive operation with no dependency on grid electricity or advanced monitoring positions it for broad dissemination in resource-constrained settings.

Importantly, the system demonstrates that decentralized AD units can operate successfully in close proximity to waste sources and end users of both energy and digestate, thereby minimizing transportation costs and losses. This is aligned with the recommendations of UNEP and FAO [4,5] which advocate for integrated community-based solutions to address waste and resource insecurity.

3.8 Economic viability and socioeconomic value

Financial analysis of the system confirmed its strong economic feasibility. With a total capital cost of Rp 85,000,000 and monthly operational expenses of Rp 500,000, the system generated a total monthly revenue of Rp 6,572,000 from three income streams: biogas substitution for LPG, liquid digestate sales, and compost product revenue. The resulting Net Present Value (NPV) of Rp 367.9 million over a 10-year period, an Internal Rate of Return (IRR) of 63%, and a payback period of only 1.3 years all affirm the system's profitability and financial sustainability.

These indicators surpass benchmarks established in previous evaluations of small-scale biodigesters, which often report longer payback periods and rely on external subsidies to ensure viability [32]. The high IRR and rapid return on investment suggest strong potential for adoption by farmer cooperatives, micro-entrepreneurs, and municipal programs targeting sustainable development goals. Moreover, the financial independence enabled by this system empowers communities to manage their organic waste while generating local value through energy savings and agricultural enhancement without requiring large-scale infrastructure or external technical support.

The implications extend beyond economic return. By valorizing local resources and circulating benefits within the community, the system supports inclusive development and builds capacity for environmental stewardship. This aligns with SDGs 7 (Affordable and Clean Energy), 11 (Sustainable Cities and Communities), and 13 (Climate Action), providing a practical tool for achieving integrated sustainability targets. Nonetheless, some limitations should be acknowledged. The economic analysis was based on stable market conditions and did not account for price fluctuations in LPG or fertilizer markets. Additionally, long-term performance under varying feedstock conditions and seasonal changes warrants further investigation. Future studies should explore the integration of solar-powered pre- treatment, hybrid operation modes, and nutrient balancing mechanisms to further optimize system performance.

4. Conclusion

This study concludes that fiberglass-based anaerobic biodigesters can operate reliably under passive mesophilic conditions without mechanical agitation or external heating. The system is capable of producing a total of 63.75 m^3 of biogas with an average methane concentration of 59.3% and a methane yield of 0.193 m^3 CH_4/kg VS. Additionally, the digester produces approximately 2,700 liters of liquid waste and 900 kg of compost solids per month, demonstrating the potential for nutrient recovery from organic waste. Economic analysis indicates that the system is financially viable, with a net present value (NPV) of Rp 367.9 million, an internal rate of return (IRR) of 63%, and a payback period of 1.3 years. These results confirm that fiberglass-based biodigesters can serve as a technically and economically viable alternative for decentralized organic waste treatment.

This study has several limitations, including operation only on a single community scale and the use of passive batch mode, so the performance of the system on a larger scale or in continuous operation mode is still unknown and requires further evaluation. Therefore, further research is recommended to explore operational optimization strategies, such as semi-continuous feedstock supply, improving methane production efficiency, and integrating nutrient recovery technology from waste. These efforts are expected to enhance biodigester performance, expand its application across various community-scale contexts, and provide more comprehensive information on the technical and economic potential of this system in decentralized organic waste processing.

Declaration of AI and AI assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT by OpenAI to assist in language editing, paraphrasing, grammar checking, and improving the clarity and structure of the manuscript. After using this tool, the authors carefully reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare no conflict of interest.

Acknowledgements

We would like to express our gratitude to all individuals and organizations that supported this research. Special thanks to the Department of Environmental Science at Universitas Sebelas Maret for providing the necessary resources and technical expertise. We also appreciate the assistance of local households and cattle farms in providing the organic waste and manure for the study.

Funding

This research did not receive any external funding.

References

[1] Pandyaswargo AH, Jagath Dickella Gamaralalage P, Liu C, Knaus M, Onoda H, Mahichi F, et al. Challenges and an Implementation Framework for Sustainable Municipal Organic Waste Management Using Biogas Technology in Emerging Asian Countries. Sustainability 2019;11:6331. https://doi.org/10.3390/su11226331

[2] Ayilara MS, Olanrewaju OS, Babalola OO, Odeyemi O. Waste Management through Composting: Challenges and Potentials. Sustainability 2020;12:4456. https://doi.org/10.3390/su12114456

[3] Mashi SA, Inkani AI, Jenkwe ED, Idris K. Determinants of urban waste recycling among smallholder farmers in Katsina, Nigeria: Awareness, adoption, and valorization. Cleaner Waste Systems 2025;12:100354. https://doi.org/https://doi.org/10.1016/j.clwas.2025.100354

[4] FAO. Global food losses and food waste: Extent, causes and prevention. Food and Agriculture Organization of the United Nations 2021. https://www.fao.org.

[5] UNEP. Global Waste Management Outlook 2. United Nations Environment Programme2 2022. https://www.unep.org.

[6] IPCC. Climate Change 2021: The Physical Science Basis. Intergovernmental Panel on Climate Change 2021. https://www.ipcc.ch.

[7] Roa ID, Henriquez JR, Dutra ED, Menezes RSC, Andrade MMM, Santos Junior EP, et al. Economic Feasibility of Biogas Microgeneration from Food Waste: Potential for Sustainable Energy in Northeastern Brazil. Sustainability 2024;16:10238. https://doi.org/10.3390/su162310238

[8] Gronwald F, Wang L. Advancing Renewable Energy : The Prospects of Hydrothermal Liquefaction (HTL) for Biomass into Bio-oil Conversion. International Journal of Environment, Engineering & Education 2024;6:132–44.

[9] Wang S, Xu C, Song L, Zhang J. Anaerobic Digestion of Food Waste and Its Microbial Consortia: A Historical Review and Future Perspectives. International Journal of Environmental Research and Public Health 2022;19:9519. https://doi.org/10.3390/ijerph19159519

[10] Mariappan I, Prabhakaran R, Vivekanand V, Poomani MS, Muthan K, Dhandayuthapani S, et al. Exploring Cutting-Edge Approaches in Anaerobic Digestion and Anaerobic Digestate Management. ChemBioEng Reviews 2024;11:573–94. https://doi.org/https://doi.org/10.1002/cben.202300063

[11] Yadav D, Kumar S, Mahapatra DM. Application of digestate from anaerobic digesters for agricultural nutrient recovery: A review. Waste Management 2021;121:105–16. https://doi.org/10.1016/j.wasman.2020.12.009

[12] Dutta S, He M, Xiong X, Tsang DCW. Sustainable management and recycling of food waste anaerobic digestate: A review. Bioresource Technology 2021;341:125915. https://doi.org/https://doi.org/10.1016/j.biortech.2021.125915

[13] Khanal SK, Lü F, Wong JWC, Wu D, Oechsner H. Anaerobic digestion beyond biogas. Bioresource Technology 2021;337:125378. https://doi.org/https://doi.org/10.1016/j.biortech.2021.125378

[14] Sevillano CA, Pesantes AA, Peña Carpio E, Martínez EJ, Gómez X. Anaerobic Digestion for Producing Renewable Energy—The Evolution of This Technology in a New Uncertain Scenario. Entropy 2021;23:145. https://doi.org/10.3390/e23020145

[15] González R, Peña DC, Gómez X. Anaerobic Co-Digestion of Wastes: Reviewing Current Status and Approaches for Enhancing Biogas Production. Applied Sciences 2022;12:8884. https://doi.org/10.3390/app12178884

[16] Srivastava A, Meena PK, Patane PM, Meena D, Shelare S, Wagle CS. Advancements in Biogas Digester Materials: A Review of Strength, Durability, and Suitability. Water Environment Research 2025;97:e70119. https://doi.org/https://doi.org/10.1002/wer.70119

[17] Pal S, Bello A, Muratova E, Chekanov A. A review of the materials utilized in the design and fabrication of biogas digesters. Renewable and Sustainable Energy Reviews 2025;211:115167. https://doi.org/https://doi.org/10.1016/j.rser.2024.115167

[18] Wijaya K, Sitompul H, Sebayang N, Sari RA, Idris I, Medan UN, et al. DEVELOPMENT OF RAMMED EARTH MATERIAL TECHNOLOGY BY UTILIZING PLASTIC WASTE AS REINFORCEMENT ON THE PARTITION WALLS OF THE BUILDING ROOM. Journal of Applied Engineering and Technological Science (JAETS) 2025;6: 1412–28.

[19] Zhao Z, Wang X, Zheng G. Low-cost digester materials for small-scale biogas production: A comparative research. Renewable Energy 2020; 145:739–748. https://doi.org/10.1016/j.renene.2019.06.087

[20] Aboud AA, El-Mashad HM, Zhang R. Effect of co-digestion ratios on biogas production and digester performance. Renewable Energy 2022;187:980–9. https://doi.org/10.1016/j.renene.2022.01.051

[21] Qiao W, Takayanagi K, Shimizu Y. Co-digestion of food waste and manure: Process synergy and operational optimization. Waste Management 2022;144:1–9. https://doi.org/10.1016/j.wasman.2022.02.007

[22] Martín-Sanz-Garrido C, Revuelta-Aramburu M, Santos-Montes AM, Morales-Polo C. A Review on Anaerobic Digestate as a Biofertilizer: Characteristics, Production, and Environmental Impacts from a Life Cycle Assessment Perspective. Applied Sciences 2025;15:8635.

https://doi.org/10.3390/app15158635

[23] Paranjpe A, Saxena S, Jain P. Biogas yield using single and two stage anaerobic digestion: An experimental approach. Energy for Sustainable Development 2023;74:6–19. https://doi.org/https://doi.org/10.1016/j.esd.2023.03.005

[24] Agrawal A, Chaudhari PK, Ghosh P. Anaerobic digestion of fruit and vegetable waste: a critical review of associated challenges. Environmental Science and Pollution Research 2023;30:24987–5012. https://doi.org/10.1007/s11356-022-21643-7

[25] Nielsen K, Roß C-L, Hoffmann M, Muskolus A, Ellmer F, Kautz T. The Chemical Composition of Biogas Digestates Determines Their Effect on Soil Microbial Activity. Agriculture 2020;10:244. https://doi.org/10.3390/agriculture10060244

[26] Bouallagui H, Touhami Y, Cheikh R Ben, Hamdi M. Biogas production from fruit and vegetable waste using anaerobic digestion: State of the art review. Bioresource Technology Reports 2020;12:100567. https://doi.org/10.1016/j.biteb.2020.100567

[27] Panuccio MR, Mallamaci C, Attinà E, Muscolo A. Using Digestate as Fertilizer for a Sustainable Tomato Cultivation. Sustainability 2021;13:1574. https://doi.org/10.3390/su13031574

[28] Piccoli I, Grillo F, Longo M, Furlanetto I, Ragazzi F, Obber S, et al. A farm-scale sustainability assessment of the anaerobic digestate application methods. European Journal of Agronomy 2023;146:126811. https://doi.org/https://doi.org/10.1016/j.eja.2023.126811

[29] Tavera CG, Raab T, Holguin Trujillo L. Valorization of biogas digestate as organic fertilizer for closing the loop on the economic viability to develop biogas projects in Colombia. Cleaner and Circular Bioeconomy 2023;4:100035. https://doi.org/https://doi.org/10.1016/j.clcb.2022.100035

[30] Akbar A, Sihabudin MY, Firdaus RE, Pahreji R. Perkembangan Demokrasi di Indonesia. Advances In Social Humanities Research 2023;1:627–35.

[31] Zhang J, Chen Y, Li Y. Performance evaluation of modular fiberglass digesters under tropical conditions. Bioresource Technology Reports 2023;21:101243.

[32] Kumar A, Gupta H, Sharma R. Techno-economic assessment of small-scale anaerobic digesters in rural India. Renewable Energy Focus 2022;41:135–44. https://doi.org/10.1016/j.ref.2021.12.008.

[33] Jha MK, Sreekrishnan TR, Kumar S. Financial assessment of decentralized biogas systems: Case studies and policy recommendations. Renewable and Sustainable Energy Reviews 2020;133:110266

[34] Suminah S, Anantanyu S, Suwarto S, Sugihardjo S, Padmaningrum D. The influence of empowerment towards agricultural business actors' ability in Surakarta, Indonesia. Social Sciences 2023;12:76. https://doi.org/10.3390/socsci12020076

[35] Singh RP, Ibrahim MH, Esa N, Ilangovan K. Reduction of environmental pollution through community biogas plants: A research from Southeast Asia. Environmental Technology & Innovation 2022;28:102678. https://doi.org/10.1016/j.eti.2022.102678