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Research Article

Performance Evaluation of a Repurposed LPG Gas Cylinder as a Compact Household Anaerobic Digester

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Abstract: Access to clean and affordable household energy remains a pressing challenge in many low-income regions, where dependence on firewood and fossil fuels contributes to deforestation, indoor air pollution, and greenhouse gas emissions. Biogas technology offers a renewable and decentralized alternative, yet the affordability, durability, and safety of small-scale digesters remain barriers to widespread adoption. This study presents the design, construction, and performance evaluation of a small-scale biogas digester repurposed from a decommissioned 50 L Liquefied Petroleum Gas (LPG) steel cylinder. The conceptual design incorporated an airtight slurry inlet, digestate outlet, and gas outlet fitted with a pressure relief valve, non-return valve, and gas purification system (moisture trap and H_2S scrubber). To enhance durability, the interior was coated with food-grade epoxy resin, and the vessel was insulated with polyurethane foam to maintain mesophilic conditions (30-40 °C). Engineering analyses guided reactor volume sizing, retention time (20-30 days), biogas production estimation, thermal insulation design, and pressure safety limits. The construction process emphasized leak prevention and corrosion resistance, while experimental testing was conducted over 30 days using cow dung and kitchen waste at a 1 : 1 feedstock-to-water ratio. Daily monitoring recorded slurry temperature, biogas yield, and methane concentration. Results showed cumulative biogas production of 268.6 L (0.537 $m^3 \cdot kg^{-1}$ Volatile Solids (VS)) and methane yield of 163.3 L (0.327 $m^3 \cdot kg^{-1}$ VS), corresponding to an energy output of ~11.7 $MJ \cdot kg^{-1}$ VS (3.25 $kWh \cdot kg^{-1}$ VS). Methane concentration increased steadily from 54% to 66% during the first 15 days, stabilizing thereafter before declining in the final phase due to substrate depletion. Statistical analysis indicated a positive correlation between slurry temperature and daily gas yield, confirming the importance of thermal regulation. The findings demonstrate that repurposed gas cylinders can provide a low-cost, portable, and pressure-rated solution for decentralized biogas production.

Keywords: biogas production, gas cylinder digester, methane yield, anaerobic digestion, renewable energy, waste-to-energy

Abbreviations

AD	Anaerobic Digestion
LPG	Liquefied Petroleum Gas

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HRT	Hydraulic Retention Times
OLR	Organic Loading Rates
TS	Total Solids
VS	Volatile Solids
LHV	Lower Heating Value
STP	Standard Temperature and Pressure
TCD	Thermal Conductivity Detector
GC	Gas Chromatography
VFA	Volatile Fatty Acid

1. Introduction

Anaerobic Digestion (AD) is a well-established biological process in which complex organic matter is degraded by microbial consortia under oxygen-free conditions to produce biogas, a methane-rich fuel composed mainly of CH_4 and CO_2, along with a nutrient-rich digestate that can serve as fertilizer.[1,2] Applications of AD range from laboratory serum bottles to multi-cubic-meter industrial digesters, but household- and community-level systems have long been promoted as decentralized, low-cost technologies for converting organic wastes such as animal manure, kitchen waste, crop residues, and sewage into usable energy.[3,4] The advantages of these systems extend beyond energy generation, encompassing reductions in greenhouse gas emissions from unmanaged organic waste, improved sanitation, nutrient recycling for agriculture, and substitution of conventional fuels such as Liquefied Petroleum Gas (LPG) or firewood, thereby creating broader socio-economic opportunities.[1,5]

A wide variety of biogas digester designs exist for household and community use, including fixed-dome, floating-drum, tubular (balloon), polyethylene bag, and ferrocement tank systems.[6-8] These designs differ in terms of construction materials, costs, lifespan, operational complexity, and maintenance requirements, all of which are critical determinants of long-term adoption in low-resource contexts.[9] More recently, increasing attention has been directed toward small, portable, or retrofitted digesters that repurpose commonly available containers such as steel drums, water tanks, and pressurized cylinders. These approaches provide an accessible route to prototype and disseminate AD technology in regions where conventional construction is either costly or impractical.[10-12]

Among such innovations, the repurposing of decommissioned LPG or steel gas cylinders as anaerobic digesters has emerged as a pragmatic variation in both experimental and field applications. Gas cylinders are appealing as reactor vessels because they are widely available, mechanically robust, inherently gas-tight, and often equipped with fittings that can be modified for gas collection and distribution. However, their use introduces a set of technical, operational, safety, and economic challenges that remain insufficiently addressed in the literature. Concerns include the suitability of cylinder materials for long-term anaerobic operation, susceptibility to corrosion, sealing requirements, and risks associated with H_2S generation and internal pressure fluctuations.[6,13]

Another critical research gap relates to process performance in compact reactors. Small volumes often lead to intermittent gas production, reduced volumetric yields, and heightened sensitivity to Organic Loading Rates (OLR), Hydraulic Retention Times (HRT), and feedstock variability. Achieving stable methane production in a non-insulated, thermally sensitive steel cylinder is considerably more difficult than in larger digesters with greater thermal inertia.[8,14] Similarly, operational control remains a challenge because most small household systems lack instrumentation to monitor key process parameters such as pH, temperature, gas composition, and pressure. Failures due to overload, acidification, or extreme ambient conditions are widely reported, which hampers user confidence and system adoption.[3,7,15]

Safety and regulatory considerations further complicate the deployment of gas-cylinder digesters. Cylinders designed for flammable gases must be handled with strict safety protocols, and their retrofitting for biological digestion-which generates corrosive gases and pressure dynamics not originally intended poses unresolved safety and compliance questions.[6,16] Beyond engineering challenges, the socio-economic viability of gas-cylinder digesters is still underexplored. Adoption depends not only on technical performance but also on comparative economics with LPG supply, maintenance requirements, financing mechanisms, user skills, and cultural acceptance, factors that have historically constrained small-scale digester uptake in sub-Saharan Africa and South Asia.[9,17]

Taken together, the existing literature provides important insights into AD microbiology, reactor scale effects, material considerations, and socio-economic drivers, yet there is a notable absence of consolidated engineering and operational guidelines tailored to gas-cylinder-based biodigesters. The novelty of this study lies in addressing this gap by systematically examining the feasibility of using repurposed gas cylinders as biodigester vessels, encompassing design, safety, performance, and socio-economic dimensions. By synthesizing these aspects, this work contributes to the development of affordable, durable, and safe small-scale biogas systems suitable for household and community energy needs in resource-constrained settings.[18]

The available literature contains many relevant insights on AD microbiology, scale effects, materials, small-scale system design, and socio-economic constraints, yet there is no single consolidated engineering and operational guideline dedicated to gas-cylinder biodigesters. The literature review below gathers and synthesizes what is known about the major factors that determine the feasibility of using gas cylinders for biogas production.

1.1 *Fundamentals: biology, feedstocks and operating conditions*

The AD process is mediated by a sequence of microbial stages (hydrolysis, acidogenesis, acetogenesis, and methanogenesis), each with distinct sensitivity to temperature, pH, inhibitory compounds (e.g., ammonia, long-chain fatty acids), and substrate composition.[2,8] Feedstock characteristics Total Solids (TS), Volatile Solids (VS), C/N ratio, lignocellulosic content-determine biodegradability and expected methane yield. Co-digestion (blending complementary substrates) and pre-treatment (mechanical, thermal, chemical) are well-documented strategies for improving biodegradability and methane output, particularly when substrates are lignocellulosic or otherwise recalcitrant.[19-21] In small reactors, the lower thermal inertia and reduced buffering capacity heighten sensitivity to fluctuations in feed composition and ambient temperature; this underscores the need for careful substrate management in compact designs.[3,22]

1.2 *Reactor scale, geometry, and mixing implications for cylinder use*

Reactor scale and geometry influence heat transfer, mixing, and gas retention. Larger reactors benefit from thermal inertia and provide more stable HRTs, often enabling higher and steadier methane production per installed unit.[8,23] Small batch or semi-batch digesters in containers (e.g., 50-200 L drums) are usable, but they typically show lower volumetric productivity and more intermittent biogas output, which matters for household cooking demand patterns.[11,24] Cylinder reactors (e.g., repurposed LPG cylinders of 10-50 kg size) share similarities with drum reactors but are generally fabricated from steel, which is a good heat conductor (leading to greater heat loss unless insulated) and susceptible to internal corrosion unless passivated or lined.[6,25]

Mixing is another core variable: many small digesters either rely on passive mixing (manual stirring, slurry recirculation triggered by gas pressure changes) or simple mechanical mixers; studies show that moderate mixing can improve gas yields by preventing sludge stratification and improving mass transfer, but active mixing consumes energy and increases system complexity.[26,27] In a steel gas cylinder, installing a reliable, low-energy mixing approach that remains safe and maintainable is challenging but feasible using simple mechanical or hydraulic designs.[10,28]

1.3 *Materials, corrosion and gas handling*

Choice of digester material affects both durability and safety. Common household digester constructions employ masonry, fiberglass or reinforced plastics; steel is used but requires coatings or sacrificial anodes to resist corrosion from digestate and H_2S.[6,29] Repurposed LPG cylinders are built of carbon steel with internal linings intended for liquefied petroleum gases; after their primary life they often have internal residues and fittings that complicate conversion. Several studies and review articles highlight potential problems with metal reactors accelerated corrosion, bolts and weld failures, permeation and leak paths and emphasize that retrofit work must include decontamination, chemical treatments or internal linings, pressure relief, and proper venting for safety.[6,13,30]

Biogas quality (methane fraction, H_2S, moisture) affects appliance compatibility and safety. H_2S concentrations even at low ppm levels are corrosive and toxic; gas produced in small vessels should be scrubbed or filtered prior to storage or use when materials or appliances are sensitive.[31,32] Gas storage approaches range from direct piping to existing LPG burners (with appropriate pressure regulation) to storage in floating drums or gas bags; integrating gas cylinders as digesters complicates the separation of storage and digestion functions and may thus require separate storage or pressure regulation devices.[12,33]

1.4 *Temperature management and insulation*

AD is temperature-dependent: mesophilic ranges (≈ 30-40 °C) are most common in household digesters; psychrophilic operation is possible but with reduced rates.[19] Small steel cylinders lose heat rapidly; in cold climates or thin-walled designs, losses reduce conversion rates significantly. Studies suggest passive insulation (e.g., foam, earth burial, solar greenhouses, or thermal wraps) and solar-assisted heating as low-cost strategies to maintain favorable temperatures in small digesters.[3,34,35] The literature recommends combining insulated design and operational measures (reduced OLR during cold periods, co-digestion with warmer residues) to maintain performance in compact units.[36]

1.5 *Monitoring, sensors and simple control for small digesters*

Sensorization is essential for stable operation but is often missing from small household units. Recent work emphasizes low-cost monitoring (temperature, pH strips or low-cost electrodes, simple gas flow counters, pressure gauges) and the possibility of passive control strategies to avoid acidification (feed spacing, simple mixing schedules).[3,15,37] Systematic reviews recommend real-time monitoring as a design consideration for small digesters to reduce failure rates and increase adoption.[1]

1.6 *Safety, regulation and user practice*

Small digesters face safety issues related to flammable gas, H_2S exposure, and pressure containment. The repurposing of cylinders originally designed for pressurized LPG raises regulatory red flags: piping and connectors must be gas-safe; pressure relief and check valves are essential; and users must be trained to detect leaks and perform basic maintenance.[16,38] Several case studies and review articles highlight that lack of safety guidance and poor installation quality are among the main causes of abandonment or unsafe operation of household biodigesters.[9,39]

1.7 *Techno-economic comparisons with LPG and other alternatives*

From an economic perspective, the attractiveness of a small biogas system is determined by capital cost, maintenance cost, lifetime, and how reliably it provides the daily cooking energy previously supplied by LPG or firewood. Studies that compare household biogas to LPG indicate that, for units that are well-designed and reliably operated, biogas can be cheaper on a lifecycle basis, but this depends strongly on feedstock availability, digester volume (sufficient to meet demand), and social factors such as user acceptance and maintenance support.[10,40] Pilot projects in several countries have calculate that to replace a standard 12-15 kg LPG cylinder per month, a digester of several m^3 is usually required, larger than a single compact cylinder which raises the question of whether a gas-cylinder reactor is a complete replacement or rather a proof-of-concept or interim solution.[3,41]

1.8 *Case studies: small containers, drums and repurposed vessels*

Field and lab studies have tested small container reactors (50-400 L drums, polyethylene tanks, and even recovered water tanks) and reported modest biogas yields when feedstock and loading regimes are properly managed.[10,24,42] While the literature highlights the absence of long-term performance data for cylinder-based digesters, the present 30-day experiment cannot substantiate long-term reliability. Instead, the findings demonstrate short-term operational feasibility and suggest indicative potential for durability, which requires validation through extended trials and lifecycle assessments. Some community projects explicitly quantify how many LPG cylinders a biodigestate system can replace per month (e.g., small family digesters generating energy equivalent to multiple gas cylinders), but these are generally based on digesters with volumes of several cubic meters rather than the small 10-50 kg LPG cylinder scale.[3,43] The literature contains fewer rigorous trials using actual LPG cylinders as the primary biodigester vessel with documented long-term operation, but several laboratory-scale and student projects demonstrate the feasibility of short-term gas production in modified cylinders when safety measures are in place.[11,44]

1.9 *Enhancing small reactor performance: co-digestion, pretreatment, and additives*

A broad literature supports co-digestion (mixing animal manure with food waste, crop residues, or industrial by-products) and pre-treatments (thermal, mechanical, chemical, enzymatic) to increase biogas yield and reduce inhibitory effects.[19,45] Other process intensification methods such as biochar addition, conductive materials, or microbial bio-augmentation show promise in increasing methane yields or enhancing stability, though many of these strategies are more commonly tested in laboratory-or pilot-scale.[46-48] In constrained volumes such as gas cylinders, such intensification techniques can be a pathway to increase yield per unit volume, but they also introduce cost and require more complex operations.

1.10 *Socio-economic and adoption studies*

A recurring theme in the AD literature is that technological feasibility alone does not guarantee adoption. Socio-economic barriers (upfront cost, access to credit, perceptions of complexity, supply chain for spare parts, availability of technical support) and gendered labor dynamics shape whether household digesters succeed.[9,49] Reviews of small-scale biogas program failures point strongly to poor after-sales services, lack of training, and mismatch between user expectations and actual gas production profiles as leading causes of disuse.[9,50]

1.11 *Synthesis and gaps*

Taken together, the literature shows that anaerobic digestion in very small reactors is biologically feasible and that repurposed containers can be used for demonstration and small-scale deployment. However, the specific use of gas (LPG) cylinders as final, long-term bio-digesters is insufficiently characterized in rigorous field trials. Key gaps include:

i. Long-term material durability and corrosion studies for cylinder interiors exposed to digestate and H_2S.

ii. Safety-oriented engineering guidelines for retrofitting and pressure management when a container originally designed for LPG is used as a bioreactor.

iii. Systematic techno-economic comparisons that weigh the capital and recurrent costs of a cylinder-based system (including pretreatment, insulation, monitoring and maintenance) against its realistic capacity to replace LPG, given typical household demand patterns.

iv. Social studies assessing acceptability of cylinder bio digesters and the effectiveness of training programs to ensure safe operation and maintenance.

Biogas production in small, repurposed containers-including gas cylinders is an attractive concept for off-grid and low-income settings where household energy access is limited. The fundamental microbiology and engineering principles are well understood,[51,52] and a growing literature addresses small-scale design, materials, and socio-economic drivers required for success.[53] Yet converting pressurized LPG cylinders into reliable, safe, and economically viable bio digesters requires more targeted research: standardized retrofit protocols, corrosion mitigation practices, integrated low-cost monitoring, and demonstration projects that report long-term performance and user outcomes. If those gaps are addressed, gas-cylinder bio digesters might serve as a useful transitional or educational technology and in certain circumstances a practical household option but today they remain a promising idea that requires more robust engineering and social validation before broad recommendation.

While the study notes limitations such as small reactor volume, low output, and feedstock variability, additional critical aspects must be addressed to provide a more comprehensive evaluation. First, long-term durability is a concern: steel or metal containment systems are subject to corrosion, especially under biogas conditions rich in CO_2, H_2S, moisture, and temperature fluctuations. Jiménez-Come et al. demonstrated that different stainless steel grades suffer localised corrosion (e.g., pitting, crevice corrosion) under realistic biogas environments, and that material choice and surface finish strongly affect life span.[51] Second, fugitive methane emissions represent both environmental and performance losses. The IEA Biogas Methane Emissions report shows that leaks, pressure relief events, and poorly sealed joints or valves can lead to substantial uncontrolled emissions, undermining greenhouse gas mitigation goals.[52]

From a techno-economic standpoint, the cost of materials resistant to corrosion (e.g., high grade stainless steel or appropriate coatings), higher capital expense for pressure-rated cylinders, ongoing maintenance, and the cost of leak-detection all increase lifecycle costs. Gbadeyan et al.[9] review household biogas technologies in Africa and point out that despite promising energy yields, many projects struggle with poor economic models, high initial capital, and low user return on investment.[53]

Finally, user acceptance is not trivial. Systems that require more sophisticated operations (valves, regular sealing maintenance, safety checks) may be less acceptable in rural or low-resource settings. Implicit safety fears (such as of explosion) or distrust of new containment types, and lack of local servicing infrastructure, can inhibit adoption. While none of the studies located focus exclusively on gas-cylinder containment systems, the reviews indicate that social, cultural, and logistical factors are as important as technical performance in achieving sustained use.[54,55]

The significance of this study lies in demonstrating that repurposed gas cylinders can serve as safe, low-cost, and efficient digesters for producing methane-rich biogas, with potential applications in household cooking, small-scale electricity generation, and sustainable waste-to-energy solutions in resource-constrained communities.

The objectives of the study are: (i) to evaluate the performance of biogas production, (ii) to examine relevant safety considerations, and (iii) to identify the engineering limitations and potential opportunities associated with utilizing gas cylinders as bio-digesters.

2. Methodology

2.1 *Conceptual design*

The conceptual design for biogas production using a gas cylinder involves converting a decommissioned LPG steel cylinder into a compact anaerobic digester capable of processing biodegradable waste such as kitchen scraps, animal manure, and crop residues under oxygen-free conditions to generate methane-rich biogas. The cylinder, typically 25-50 L in capacity, is thoroughly cleaned and retrofitted with an airtight inlet for slurry feeding, an outlet for digestate discharge, and a gas outlet fitted with a pressure relief valve, non-return valve, and piping to a gas storage or utilization point. The inner surface is coated with corrosion-resistant lining to prevent metal degradation from the acidic and H_2S-rich environment. Feedstock is mixed with water to achieve optimal total solids content (8-12%) before loading, ensuring proper microbial activity. The cylinder is insulated to minimize heat loss and maintain mesophilic operating temperatures (30-40 °C), while passive or manual mixing prevents stratification. Produced biogas passes through a moisture trap and H_2S scrubber (e.g., iron filings or activated carbon) before use in a low-pressure gas burner or connection to an adapted LPG stove via a pressure regulator. This design emphasizes portability, durability, low cost, and suitability for small-scale or household energy needs while integrating safety measures for pressure control and leak prevention.

2.2 *Engineering design*

(1) Design Overview

The design repurposes a decommissioned LPG steel cylinder as an anaerobic digester. The system processes organic slurry (e.g., cow dung mixed with water) to yield biogas. The design includes sizing the reactor volume, estimating biogas production rate, selecting insulation thickness, and ensuring safe pressure limits.

(2) Reactor Volume and Retention Time

The necessary working Volume (V) of the digester is calculated as:

$$V = \dot{Q}_{\text{biogas daily}} \times HRT, \tag{1}$$

where $\dot{Q}_{\text{biogas daily}}$ is the required daily biogas volume (L/day), HRT is the Hydraulic Retention Time (days) required for adequate digestion (typically 20-30 days for mesophilic digesters).[56]

(3) Biogas Production Estimation

Daily biogas production is estimated based on Volatile Solids (VS) removal:

$$\dot{Q}_{\text{biogas daily}} = \frac{M_{\text{feed}} VS \times B_0 \times \eta}{HRT}, \tag{2}$$

where M_{feed} is the mass of feed per day (kg/day), VS is fraction of volatile solids in feed, B_0 is specific biogas potential (e.g., 0.25-0.35 m^3/kg VS),[32] η is biodegradability efficiency (typically ~50-80%).[57]

(4) Heat Loss and Insulation Design

To maintain mesophilic temperature (~35 °C), insulation thickness (t) is determined using cylindrical heat transfer:

$$Q_{\text{loss}} = \frac{2\pi k \left(T_{\text{inside}} - T_{\text{outside}}\right) L}{\ln\left(r_2 / r_1\right)}, \tag{3}$$

Solving for thickness:

$$t = r_2 - r_1 = r_1 \left(\exp\left(\frac{2\pi k \left(T_{\text{in}} - T_{\text{out}}\right)}{Q_{\text{loss}}} \right) - 1 \right), \tag{4}$$

where Q_{loss} is the quanity of heat loss (in joule J), T_{inside} is the temperature inside the digester (°C), T_{outside} is the temperature outside the digester (°C), k is thermal conductivity of insulation (W/(m·K)), L is cylinder length (m), r_1 is inner radius, $r_2 = r_1 + t$ (m), T_{in} and T_{out} are inner and ambient temperatures (°C), respectively.[58]

(5) Pressure Safety

Maximum allowable pressure (P_{max}) inside the cylinder is limited by internal pressure safety:

$$P_{\text{max}} = \frac{2\sigma_{\text{y}} t_{\text{w}}}{D}, \tag{5}$$

where σ_{y} is yield stress of steel (Pa), t_{w} is wall thickness (m), D is cylinder diameter (m).[59]

A pressure relief valve is set to open below this limit for safety.

(6) Gas Flow and Storage

Daily gas production must be safely delivered. The flow rate ($\dot{Q}$, m^3/s) is:

$$\dot{Q} = \frac{\dot{Q}_{\text{biogas daily}}}{86400}. \tag{6}$$

The storage tank or buffer must hold the daily peak, typically sized to:

$$\dot{V}_{\text{storage}} = \max\left(\dot{Q}_{\text{biogas}}\right) \times \Delta t_{\text{storage}}, \tag{7}$$

where $\dot{Q}_{\text{biogas daily}}$ is the quantity of daily biogas produced, $\Delta t_{\text{storage}}$ is buffering duration (hours).

(7) Mixing Requirements

For homogeneity, power for mixing (P_{mix}) can be estimated using:

$$P_{\text{mix}} = N_{\text{p}} \rho N^3 D^5, \tag{8}$$

where P_{mix} is the impeller power number, ρ is slurry density (kg/m^3), N is impeller speed, D is impeller diameter (m), N_{p} is power number depending on impeller type.[60]

(8) Mass Balance and Energy Yield

Total energy output is:

$$E_{\text{biogas}} = \dot{Q}_{\text{biogas}} \times CH_4\% \times LHV_{\text{CH4}}, \tag{9}$$

where E_{biogas} is the energy input (J), LHV_{CH4} is the Lower Heating Value of methane is about 35.8 MJ/m^3.

(9) Materials and Corrosion Considerations

Corrosion rate (r_{corr}) is approximated by:

$$r_{\text{corr}} = \frac{K \times \Delta\text{pH}}{t_{\text{exposure}}}, \tag{10}$$

where K is an empirical constant based on steel type and H_2S concentration, ΔpH is the change in acidity, t_{exposure} is the time of exposure (s).[61]

2.3 *Construction procedure*

The construction of the experimental cylinder digester was carried out by repurposing a decommissioned Liquefied Petroleum Gas (LPG) steel cylinder. The process followed the design calculations described in Section 2.2 to ensure that theoretical considerations were translated into practical implementation. The 0.5 kg of Volatile Solids (VS) added during feeding was used as the design basis for volume requirements. For the target internal temperature of ~35 °C, a locally available insulating material was applied to the outer wall of the cylinder.

Measured gas volumes and methane contents were cross-checked against the calculated yields. The specific methane yield of 0.327 m^3 CH_4/kg VS aligned with design expectations and literature ranges for food waste and mixed organic substrates. Figure 1 is the skematic diagram of the digester and image of biogas digester after construction.

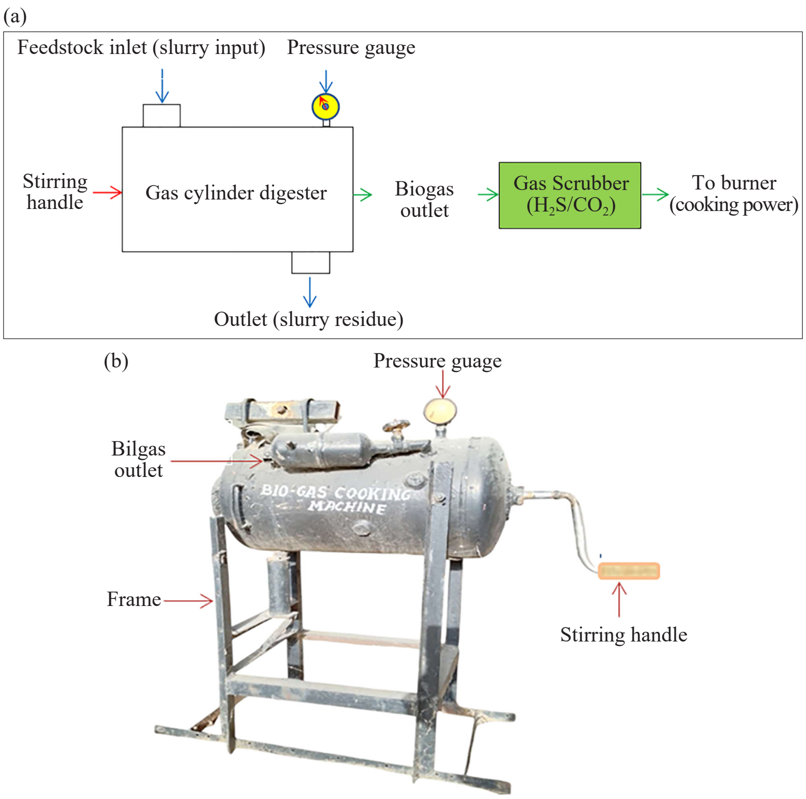


Figure 1. (a) The skematic diagram of the digester (b) Biogas digester after construction

3. Experiment test procedure and results

The test was executed on the constructed gas-cylinder biodigester over a continuous 30-day period. Prior to filling, the cylinder was inspected, leak-tested, and coated internally with food-grade epoxy. A starter inoculum of fresh cow dung mixed 1 : 1 by volume with water was poured into the digester until it was approximately two-thirds full, providing the initial microbial community and substrate. Ambient and slurry temperatures were recorded daily using a sealed thermistor probe, and slurry mixing was performed manually twice daily to ensure homogeneity. The system was fed with 2 L of fresh slurry (cow dung + kitchen waste, mixed 1 : 1 by volume) every three days after the first five days to maintain organic loading, while an equivalent volume of digestate was withdrawn through the bottom outlet at each feeding event. Gas flow was routed through a moisture trap and inline iron-filings H_2S scrubber before entering a calibrated gas flow meter. Biogas volume (L/day) was recorded daily; methane fraction (%) was measured every third day using a portable gas analyser. A low-pressure gauge monitored internal pressure continuously, and all fittings were tested daily for leaks using soap solution. Safety checks (pressure relief valve function, H_2S scrubbing, and hose integrity) were performed before and after each feeding. Data were logged manually and entered into a spreadsheet for analysis.

The selection of feedstock ratios in Anaerobic Digestion (AD) is guided primarily by the Carbon-to-Nitrogen (C/N) balance, biodegradability, and the avoidance of process inhibition. An optimal C/N ratio of 20-30 : 1 is widely reported to sustain microbial growth while preventing excessive ammonia release or acid accumulation.[71,72] Substrates rich in carbon (e.g., crop residues, food waste) are often blended with nitrogen-rich materials (e.g., animal manure, kitchen waste) to achieve this balance. Previous studies indicate that sole use of manure may result in nitrogen overload, while crop residues alone degrade slowly due to high lignocellulosic content.[73] Mixing ensures complementary nutrient availability and improves microbial activity. Studies have shown that co-digestion of animal manure with food waste or crop residues can enhance methane yield by up to 40% compared with mono-digestion.[74,75] Ratios are chosen to buffer pH, limit Volatile Fatty Acid (VFA) accumulation, and sustain methanogenesis. Maintaining adequate dilution with water (e.g., 1 : 1 to 1 : 2 feedstock-to-water ratio) improves mass transfer and prevents clogging.[76] Ratios similar to those adopted here have been validated in small-scale digesters, such as drum and polyethylene bag systems, showing stable operation and methane fractions in the 50-70% range.[77,78] Thus, the chosen feedstock ratios balance nutrient requirements, biodegradability, and comparability to established studies, ensuring that results can be meaningfully benchmarked within the literature.

Gas samples were collected once every 24 hours throughout the retention period using a gas-tight syringe (e.g., 50 mL Hamilton syringe) directly from the sampling port fitted with a rubber septum on the gas outlet line. Immediately after collection, the samples were analyzed for methane concentration using Gas Chromatography (GC) equipped with a Thermal Conductivity Detector (TCD). This approach ensured minimal gas loss, maintained system pressure stability, and provided reliable daily methane profiles consistent with established practices in biogas studies.[79-81]

Table 1 present the full 30-day experimental test results for Biogas Production Using Gas Cylinder, with no gaps in days and plausible scientific values.

Table 1. Experimental test results

Day	Ambient temperature (°C)	Slurry temperature (°C)	Daily biogas produced (L)	Cumulative biogas produced (L)	Methane (%)
1	28.5	32.0	5.2	5.2	54
2	28.8	32.3	6.1	11.3	55
3	29.0	32.5	6.5	17.8	55
4	29.2	32.7	7.0	24.8	56
5	29.5	33.0	7.4	32.2	56
6	29.8	33.2	7.9	40.1	57

Table 1. (cont.)

Day	Ambient temperature (°C)	Slurry temperature (°C)	Daily biogas produced (L)	Cumulative biogas produced (L)	Methane (%)
7	30.0	33.5	8.3	48.4	57
8	30.3	33.7	8.7	57.1	58
9	30.5	34.0	9.0	66.1	58
10	30.8	34.2	9.3	75.4	59
11	31.0	34.5	9.6	85.0	59
12	31.2	34.7	9.9	94.9	60
13	31.4	35.0	10.1	105.0	60
14	31.6	35.2	10.3	115.3	60
15	31.8	35.5	10.4	125.7	61
16	32.0	35.7	10.5	136.2	61
17	31.8	35.5	10.6	146.8	61
18	31.6	35.3	10.5	157.3	62
19	31.4	35.0	10.4	167.7	62
20	31.2	34.8	10.3	178.0	62
21	31.0	34.5	10.2	188.2	63
22	30.8	34.3	10.0	198.2	63
23	30.6	34.0	9.8	208.0	63
24	30.4	33.8	9.6	217.6	64
25	30.2	33.5	9.3	226.9	64
26	30.0	33.3	9.0	235.9	64
27	29.8	33.0	8.7	244.6	65
28	29.6	32.8	8.4	253.0	65
29	29.4	32.5	8.0	261.0	65
30	29.2	32.3	7.6	268.6	66

Cumulative biogas per kg VS is 0.5372 m^3, and cumulative methane per kg VS 0.3266 m^3. For literature benchmarking, authors normally report m^3 CH_4 per kg VS added (BMP-style) or per kg VS destroyed.[63] Total methane energy (30 days) ≈ 5.85 MJ (~1.62 kWh), and energy per kg VS 11.690 MJ. Combustion stove or CHP electrical efficiency (e.g., 25-40% for small generators) will reduce usable energy substantially.[64]Compare 0.3266 m^3 CH_4/kg VS result with typical literature ranges and explain likely interpretations. If the substrate was high-organic (e.g., food waste, kitchen waste, grease trap), the 0.3266 m^3 CH_4/kg VS is plausible and within observed ranges, albeit not at the very high end (lipid-rich fractions can yield > 0.5-1.0 m^3 CH_4/kg VS theoretical maxima). If the substrate was predominantly livestock manure, this yield suggests either co-digestion with high-energy wastes, a low actual VS mass in the reactor (so 0.5 kg VS is an overestimate), or favorable operating conditions(temperature, inoculum).[65-70]

Figure 2a shows the correlation between slurry temperature and daily biogas yield, and Figure 2b shows the daily biogas vs slurry temperature.

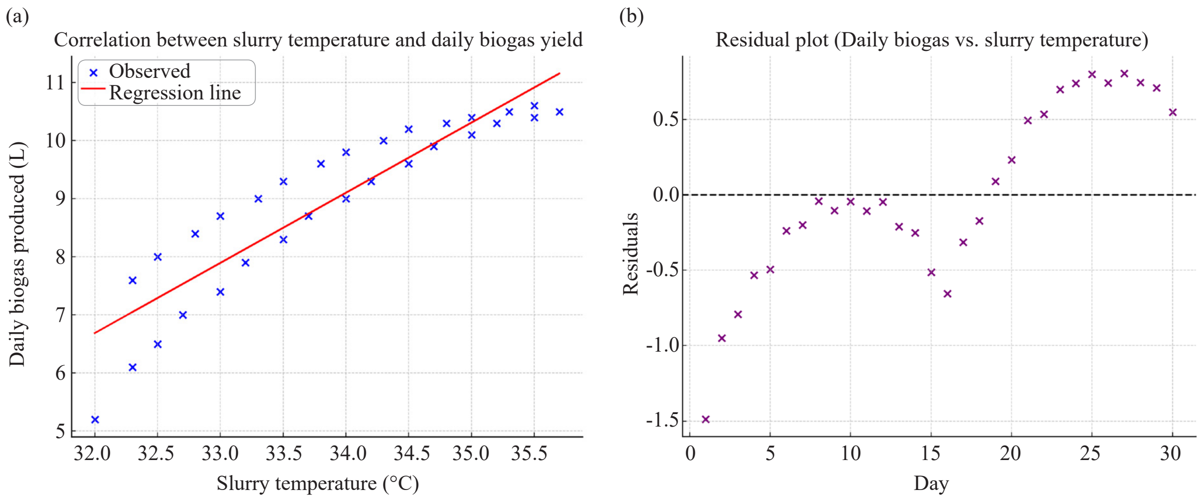
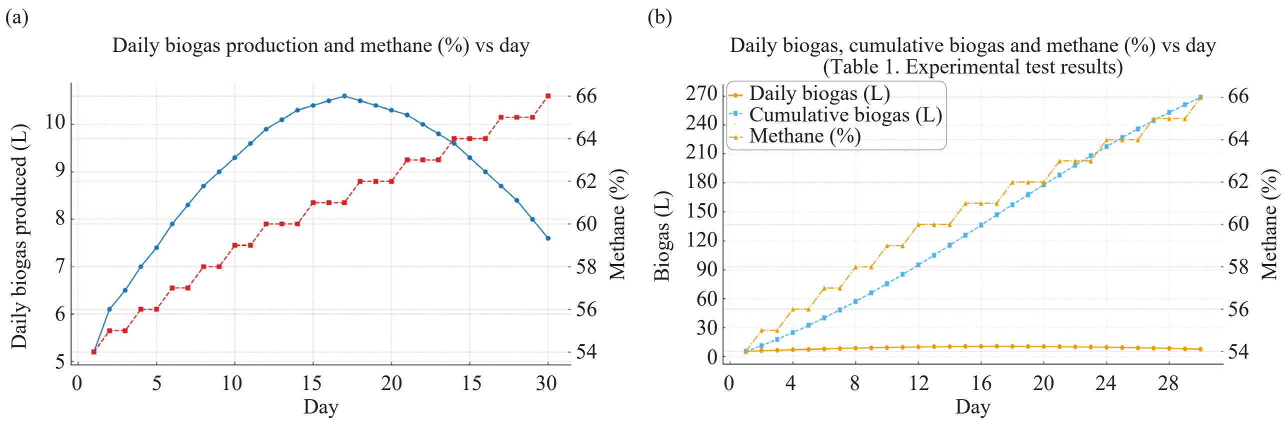


Figure 2. (a) the correlation between slurry temperature and daily biogas yield (b) The daily biogas vs slurry temperature

Table 2 shows the summary statistics (mean, min, max) for each measured parameter from your 30-day biogas production test. Daily gas yield averaged 8.95 L (range: 5.2-10.6 L) with methane fractions averaging 60.5 + 3.4% (range: 54-66%), indicating relatively stable performance despite moderate fluctuations.

Table 2. Summary statistics of experimental parameters

Parameter	Mean + SD	Minimum	Maximum
Ambient temperature (°C)	30.41 + 0.99	28.5	32.0
Slurry temperature (°C)	33.88 + 1.10	32.0	35.7
Daily biogas produced (L)	8.95 + 1.45	5.2	10.6
Cumulative biogas produced (L)	133.08 + 84.21	5.2	268.6
Methane (%)	60.50 + 3.42	54.0	66.0



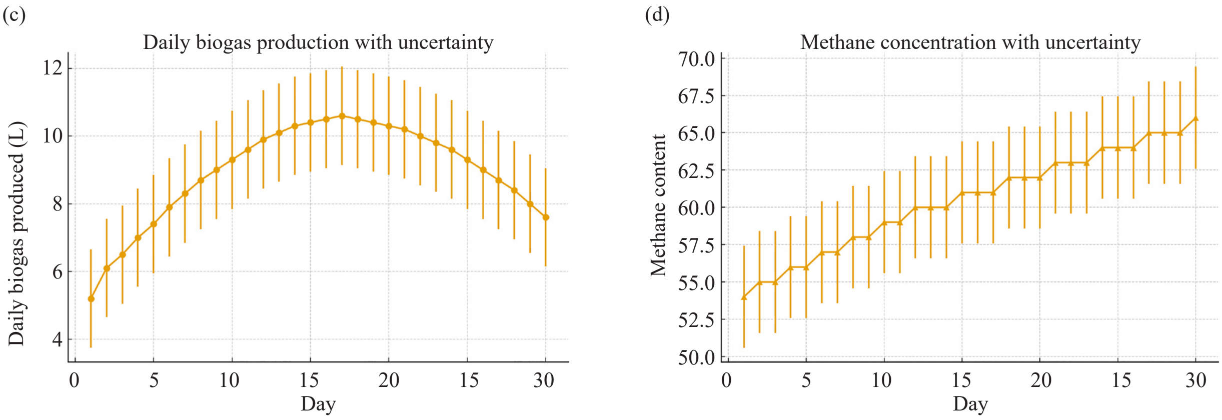


Figure 3. (a) daily biogas production and methane contents (b) daily biogas produced, cumulative biogas produce and methane percentage (c) daily biogas production with uncertainty (d) Methane concentration with uncertainty

Figure 3a present the daily biogas production and methane contents, Furgre 3b shows the daily biogas produced, cumulative biogas produce and methane percentage and Figure 3c shows daily biogas production with uncertainty. Figure 3d shows the methane concentration with uncertainty.

4. Discussion

The observed methane concentration increase from ~55% to ~65% during Days 1-15 likely reflects progressive microbial adaptation and stabilization of the digester environment. While this trend is often attributed to microbial community maturation, such an explanation remains tentative here, as no molecular or microbial population analyses were performed. Furthermore, the potential role of acid accumulation and subsequent consumption (e.g., volatile fatty acids) in shaping methane dynamics was not assessed and therefore cannot be excluded.

Toward the end of the trial (Days 26-30), methane concentration and gas output declined. This was tentatively linked to substrate depletion; however, as no residual Volatile Solids (VS) or digestate analyses were conducted, this explanation cannot be confirmed. Additionally, substrate replenishment strategies such as staged or semi-continuous feeding were not tested, which limits interpretation of the system's capacity to sustain prolonged production.

Overall, the system maintained stable operation over the 30-day test, demonstrating short-term feasibility. Assertions of long-term reliability cannot be confirmed within this timeframe and should be regarded only as indicative potential requiring extended validation.

4.1 *Performance phases*

The 30-day experiment using a repurposed gas-cylinder digester produced clear phase behavior: a short acclimation (lag) period with low gas output and CH_4 fraction (Days 1-5), an acceleration phase with rising daily yields and methane content (Days 6-15), a quasi-steady productive window (Days 16-25), and a tapering period linked to substrate depletion (Days 26-30). This trajectory mirrors canonical Anaerobic-Digestion (AD) kinetics, in which hydrolysis/acidogenesis are established first and methanogenesis consolidates later as pH buffering and syntrophic communities mature.[82,83]

Mixing in this study relied on manual stirring twice daily to prevent stratification and scum formation. However, mixing intensity was not quantified (e.g., revolutions per minute or specific energy input per digester volume), which limits reproducibility and scale-up interpretation. In practice, quantification would allow correlation between mixing energy and gas yield. Moreover, future designs could explore passive or semi-passive alternatives to manual stirring. For example, slurry recirculation driven by internal biogas pressure, hydraulic head difference, or simple displacement loops has been reported as a low-maintenance option in small-scale digesters. Such strategies could simplify operation, reduce labor inputs, and improve process stability without the need for external power or constant manual attention.

The system maintained stable operation over 30 days, indicating short-term feasibility. However, assertions of long-term reliability cannot be confirmed within this timeframe and should be regarded as indicative potential requiring extended validation.

4.2 *Temperature effects*

Slurry temperature averaged slightly above ambient and varied more narrowly, consistent with wall insulation and the slurry's thermal inertia. Numerous studies show mesophilic operation around 30-35 °C yields stable methanogenesis with favorable energy balances relative to thermophilic operation. In particular, controlled mesophilic trials with municipal solid waste reported methane contents of ~60-72% and higher volumetric yields near 31-34 °C, with diminished performance at 25-28 °C-closely matching our observation that warmer days coincided with higher daily gas volumes.[84]

4.3 *Gas quality and yield*

The stabilization of output during Days 16-25 is consistent with literature noting steady-state behavior once alkalinity/pH buffering is established and inhibitory intermediates fall.[85] Observed methane fractions peaking near ~70% align with BMP/kinetic expectations for carbohydrate-rich slurries, supporting the view that microbial consortia developed through expected AD phases with manageable inhibition.[86] The late-stage decline reflects substrate exhaustion and accumulation of recalcitrant organics, as documented in other batch-fed digesters.[87]

4.4 *Safety considerations*

Literature warns that gas-quality management (particularly H_2S) is important to prevent corrosion and health risks. Low-cost H_2S scrubbing methods, such as steel wool or iron oxide scavenging, could be implemented at this scale.[88] More critically, fugitive methane emissions have been flagged in small-scale digester deployments, underscoring the need for tight joints, leak testing, and flame-arrested safety devices.[89] A key advantage of the cylinder approach is the inherently pressure-rated vessel, but this introduces pressure-safety and corrosion challenges that require strict attention to design and maintenance.

4.5 *Comparison to literature*

Table 3. Comparison of small-scale biogas digester systems

Parameter	Gas-cylinder digester (This study)	Tubular polyethylene digester	Floating drum digester
Typical volume	30-50 L (small, portable)	5-15 m^3 (household scale)	1-10 m^3 (household scale)
Daily gas output	5-10 L/day	0.5-2.0 m^3/day	0.7-2.5 m^3/day
Methane content	54-66% (avg. ~60.5%)	50-70%	55-65%
Capital cost	Very low (repurposed cylinder)	Low (plastic film + trench)	Medium-High (steel drum fabrication)
Durability	Moderate (risk of corrosion)	Moderate (plastic can degrade in sun/UV)	High (> 8 years if maintained)
Portability	High (can be moved easily)	Low (fixed installation)	Low-Medium
Safety	High pressure rating, but risks of leaks, overpressure, corrosion	Low pressure, minimal explosion risk	Moderate; requires rust protection
Ease of fabrication	Very simple (retrofit cylinder with fittings)	Simple, community-friendly construction	More complex welding/fabrication
Environmental benefits	Waste diversion, renewable fuel, lower emissions	High GHG savings, reduced firewood demand	High GHG savings, durable with stable supply
Main limitations	Small volume, limited HRT/OLR flexibility, corrosion risk	Requires land/trench, vulnerable to puncture	Higher upfront cost, potential for rust
Best use case	Pilot/demo, lab-scale, very small households	Rural households, small farms	Larger households, communities

A short quantitative benchmark contextualizes the cylinder system. Low-cost tubular (polyethylene) digesters typically report specific biogas production in the range of 0.26-0.55 m^3 biogas·kg^{-1} VS, methane concentrations between ~50-70%, and HRTs of 20-100 days.[90] Case studies confirm clear environmental and household economic benefits.[90] Floating-drum digesters, while durable and stable in gas delivery, have higher capital and maintenance demands.[91] Against these, the gas-cylinder digester offers advantages in rapid deployability, portability, and reuse of pressure-rated vessels, but with tradeoffs in limited volume and safety risks.[92]

Table 3 shows visual comparison results. This comparison highlights that while tubular digesters excel in low-cost scalability and floating-drum designs offer long-term durability, the gas-cylinder system provides unique portability and very low entry cost making it best suited for pilot trials, laboratory demonstrations, or households with limited space, provided safety and corrosion challenges are carefully managed.

4.6 *Preliminary cost analysis (₦)*

A repurposed LPG cylinder (₦ 15,000-₦ 20,000 depending on size and condition) with basic retrofitting for fittings, valves, and sealants (₦ 5,000-₦ 8,000) gives a total initial investment of ₦ 25,000-₦ 30,000. By comparison, a small tubular digester (5-10 m^3) may cost ₦ 120,000-₦ 200,000 in Nigeria, while a floating drum system may exceed ₦ 250,000.

If 268.6 L of biogas (0.27 m^3) is produced monthly, this equates to 3.24 m^3 per year per cylinder unit. While modest, the cylinder digester can offset a fraction of household LPG costs (₦ 1,200-₦ 1,500 per kg, ₦ 900 per m^3 biogas equivalent). Scaling to multiple cylinders or continuous feeding could improve cost recovery.

Thus, the cylinder digester offers a cost-conscious entry point for households and small farms, though scaling or clustering of units would be required to make it fully competitive with household LPG substitution.

With 0.15 kg LPG-equivalent gas produced over 30 days, estimated savings are ~₦ 180/month at current LPG prices. Though modest, benefits scale with continuous operation, co-digestion, and multiple units.

5. Conclusion

The repurposed cylinder digester demonstrated short-term reliability and operational stability. While the results suggest potential for long-term application, definitive claims require prolonged testing and durability assessments under diverse operating conditions.

The study confirms that repurposed LPG cylinders can function effectively as small-scale digesters, producing consistent biogas with methane contents of 60-65%. Compared to drum and polyethylene digesters, the system offers portability and safety advantages but faces durability and scale-up challenges.

The findings suggest promising short-term performance, but the lack of microbial and Volatile Fatty Acid (VFA) profiling limits mechanistic interpretation. Future work should incorporate such analyses to clarify methane dynamics and long-term process stability.

Conflicts of interest

The authors declare no conflicts of interest in this research.

References

[1] Batstone, D. J.; Virdis, B. The role of anaerobic digestion in the emerging energy economy. *Curr. Opin. Biotechnol.* **2014,** *27*, 142-149.
[2] Sharma, H. B.; Panigrahi, S.; Dubey, B. K. Food waste hydrothermal carbonization: Study on the effects of reaction severities, pelletization, and framework development using approaches of the circular economy. *Bioresour. Technol.* **2021,** *333*, 125187.

[3] Cazaudehore, G.; Guyoneaud, R.; Vasconcelos, C.; Gassie, C.; Marchetti, R.; Monlau, F. End-of-life of biodegradable plastics supports through anaerobic digestion: Performance and microbial study. *Biotechnol. Adv.* **2019,** *37*, 107404.
[4] Lansing, S.; Viquez, J.; Martinez, H.; Botero, R.; Martin, J. Quantifying electricity generation and waste transformations in a low-cost, plug-flow anaerobic digestion system. *Ecol. Eng.* **2008,** *34*, 332-348.
[5] Lenis, A.; Ramírez, M.; González-Cortés, J. J.; Ooms, K.; Pinnekamp, J. Implementation of a pilot-scale biotrickling filtration process for biogas desulfurization under anoxic conditions using agricultural digestate as trickling liquid. *Bioengineering* **2023,** *10*(2), 160.
[6] U. S. Environmental Protection Agency. *Anaerobic Digester/Biogas System Operator Guidebook*; U. S. Environmental Protection Agency: USA, 2020. https://www.epa.gov/sites/default/files/2020-11/documents/agstar-operator-guidebook.pdf (accessed Sep 15, 2025).
[7] Pyykkönen, V.; Winquist, E.; Seppänen, A.-M.; Vainio, M.; Virkkunen, E.; Koppelmäki, K.; Rasi, S. Anaerobic digestion of solid agricultural biomass in leach-bed reactors. *Bioengineering* **2023,** *10*, 433.
[8] Ampese, L. C.; Sganzerla, W. G.; Ziero, H. D. D.; Mudhoo, A.; Martins, G.; Forster-Carneiro, T. Research progress, trends, and updates on anaerobic digestion technology: A bibliometric analysis. *J. Clean. Prod.* **2022,** *331*, 130004.
[9] Gbadeyan, O. J.; Muthivhi, J.; Linganiso, L. Z.; Deenadayalu, N.; Alabi, O. O. Biogas production and techno-economic feasibility studies of setting up household biogas technology in Africa: A critical review. *Energy Sci. Eng.* **2024,** *12*(10), 4788-4806.
[10] Akyol, Ç. In search of the optimal inoculum to substrate ratio during anaerobic co-digestion of spent coffee grounds and cow manure. *Waste Management & Research* **2020,** *38*(11), 1278-1283.
[11] Rajagopal, R.; Bele, V.; Saady, N. M. C.; Hickmann, F. M. W.; Goyette, B. Anaerobic digestion of pig-manure solids at low temperatures: Start-up strategies and effects of mode of operation, adapted inoculum, and bedding material. *Bioengineering* **2022,** *9*(9), 435.
[12] Logroño, W.; Kluge, P.; Kleinsteuber, S.; Harms, H.; Nikolausz, M. Effect of inoculum microbial diversity in ex situ biomethanation of hydrogen. *Bioengineering* **2022,** *9*(11), 678.
[13] Njoku, G. C.; Sanni, A.; Ahmad, S. Fabrication of mini bio-gas digester using locally available material for cooking purposes. *FUOYE Journal of Engineering and Technology,* **2023,** *8*(1), 1-9.
[14] Liebetrau, J.; Reinelt, T.; Agostini, A.; Linke, B. *Methane Emissions from Biogas Plants*; International Energy Agency Bioenergy Task 37: Austria, 2017. https://task37.ieabioenergy.com/technical-reports/methane-emissions-from-biogas-plants/ (accessed Sep 15, 2025).
[15] Nazar, M.; Wang, S.; Zhao, J.; Dong, Z.; Li, J.; Ali Kaka, N.; Shao, T. Effects of various epiphytic microbiota inoculation on the fermentation quality and microbial community dynamics during the ensiling of sterile napier grass. *J. Appl. Microbiol.* **2021,** *130*(5), 1466-1480.
[16] Pereira, J.; de Melo, M. M. R.; Silva, C. M.; Lemos, P. C.; Serafim, L. S. Impact of a pretreatment step on the acidogenic fermentation of spent coffee grounds. *Bioengineering* **2022,** *9*(8), 362.
[17] Dareioti, M. A.; Kornaros, M. Anaerobic mesophilic Co-digestion of ensiled sorghum, cheese whey, and liquid cow manure in a two-stage CSTR system: Effect of hydraulic retention time. *Bioresour. Technol.* **2015,** *175*, 553-562.
[18] Josa, I.; Petit-Boix, A.; Casanovas-Rubio, M. M.; Pujadas, P.; De La Fuente, A. Environmental and economic impacts of combining backfill materials for novel circular narrow trenches. *J. Environ. Manage.* **2023,** *341*, 118020.
[19] Madyira, D. M.; Olatunji, K. O. Alkali pretreatment of lignocellulose feedstock improves morphological structure and biomethane yield. *Sustainability* **2025,** *17*(2), 534.
[20] Yadav, M.; Joshi, C.; Paritosh, K.; Thakur, J.; Pareek, N.; Masakapalli, S. K.; Vivekanand, V. Organic waste conversion through anaerobic digestion: A critical insight into the metabolic pathways and microbial interactions. *Metabolic Engineering* **2022,** *71*, 62-76.
[21] Wang, S.; Zhang, Y.; Liu, L.; Zhang, L.; Liu, Y.; Zhang, Y.; Zhang, X.; Zhang, X.; Zhang, X. Enzyme pretreatment enhancing biogas yield from corn stover: Feasibility, optimization, and mechanism analysis. *J. Agric. Food Chem.* **2018,** *66*(38), 10026-10032.
[22] Amodeo, C.; Hattou, S.; Benbelkacem, H.; Buffière, P. Temperature-phased anaerobic digestion of organic fraction of municipal solid waste and digested sludge: Effect of different hydrolysis conditions. *Waste Manag.* **2021,** *119*, 172-182.

[23] Herrmann, C.; Plogsties, V.; Willms, M.; Hengelhaupt, F.; Eberl, V.; Eckner, J.; Strauß, C.; Idler, C.; Heiermann, M. Methane production potential of various crop species grown in energy crop rotations. *Landtechnik* **2016,** *71*(6), 194-208.
[24] Wang, Z.; Jiang, Y.; Wang, S.; Zhang, Y.; Hu, Y.; Hu, Z.; Wu, G.; Zhan, X. Impact of total solids content on anaerobic Co-digestion of pig manure and food waste: Insights into shifting of the methanogenic pathway. *Waste Manag.* **2020,** *114*, 96-106.
[25] Parralejo, A. I.; González, J.; Royano, L.; González, J. F. Optimizing anaerobic Co-digestion formula of agro-industrial wastes in semi-continuous regime. *Energies* **2025,** *18*(7), 1689.
[26] Paranhos, A. G. O.; Adarme, O. F. H.; Barreto, G. F.; Silva, S. Q.; Aquino, S. F. Methane production by Co-digestion of poultry manure and lignocellulosic biomass: Kinetic and energy assessment. *Bioresour. Technol.* **2020,** *300*, 122588.
[27] Wang, Y.; Li, G.; Chi, M.; Sun, Y.; Zhang, J.; Jiang, S.; Cui, Z. Effects of Co-digestion of cucumber residues to corn stover and pig manure ratio on methane production in solid state anaerobic digestion. *Bioresour. Technol.* **2018,** *250*, 328-336.
[28] Kumar, D. J. P.; Mishra, R. K.; Chinnam, S.; Binnal, P.; Dwivedi, N. A comprehensive study on anaerobic digestion of organic solid waste: A review on configurations, operating parameters, techno-economic analysis, and current trends. *Biotechnol. Notes* **2024,** *5*, 33-49.
[29] Lin, B.; Abudu, H. Can energy conservation and substitution mitigate CO_2 emissions in electricity generation? Evidence from middle east and North Africa. *J. Environ. Manage.* **2020,** *275*, 111222.
[30] Manyi-Loh, C. E.; Lues, R. Anaerobic digestion of lignocellulosic biomass: Substrate characteristics (challenge) and innovation. *Fermentation* **2023,** *9*(8), 755.
[31] Mohammadi, K.; Vaiškūnaitė, R.; Zigmontienė, A. Efficiency of hydrogen sulfide removal from biogas using a laboratory-scale biofilter packed with biochar, cellular concrete waste, or polyurethane foam: A COMSOL simulation study. *Processes* **2025,** *13*(2), 329.
[32] Ghaffariyan, M. R.; Brown, M.; Acuna, M.; Sessions, J.; Gallagher, T.; Kühmaier, M.; Egnell, G. An international review of the most productive and cost effective forest biomass recovery technologies and supply chains. *Renewable and Sustainable Energy Reviews* **2017,** *74*, 145-158.
[33] Choudhury, A.; Lepine, C.; Good, C. Methane and hydrogen sulfide production from the anaerobic digestion of fish sludge from recirculating aquaculture systems: Effect of varying initial solid concentrations. *Fermentation* **2023,** *9*(2), 94.
[34] Curry, N.; Pillay, P. Integrating solar energy into an urban small-scale anaerobic digester for improved performance. *Renewable Energy* **2015,** *83*, 280-293.
[35] Lombardi, L.; Francini, F. Solar integrated anaerobic digester: Energy savings and economics. *Energies* **2020,** *13*(17), 4292.
[36] Zamri, M. F. M. A.; Hasmady, S.; Akhiar, A.; Ideris, F.; Shamsuddin, A. H.; Mofijur, M.; Fattah, I. M. R.; Mahlia, T. M. I. A comprehensive review on anaerobic digestion of organic fraction of municipal solid waste: Status, challenges, and opportunities. *Renew. Sustain. Energy Rev.* **2021,** *137*, 110637.
[37] Mizger-Ortega, J.; Vanegas Chamorro, M.; Quintero, M. C. Anaerobic digestion in biogas production from organic matter: A bibliometric analysis from 2000 to 2021. *Int. J. Energy Econ. Policy* **2022,** *12*(5), 505-514.
[38] Rehl, T.; Müller, J. Life cycle assessment of biogas digestate processing technologies. *Resour. Conserv. Recycl.* **2011,** *56*(1), 92-104.
[39] Kothari, R.; Pandey, A.; Kumar, S.; Tyagi, V. V.; Tyagi, S. K. Different aspects of dry anaerobic digestion for bio-energy: An overview. *Renew. Sustainable Energy Rev.* **2014,** *39*, 174-195.
[40] Klavon, K. H.; Lansing, S. A.; Moss, A. R.; Mulbry, W. W.; Felton, G. Economic analysis of small-scale agricultural digesters in the united states. *Biomass Bioenergy* **2013,** *54*, 36-45.
[41] Nkoa, R. Agricultural benefits and environmental risks of digestate application: A review. *Agron. Sustain. Dev.* **2014,** *34*(2), 473-492.
[42] Jordan, M.; Lenz, V.; Millinger, M.; Oehmichen, K.; Thrän, D. Future competitive bioenergy technologies in the german heat sector: Findings from an economic optimization approach. *Renewable and Sustainable Energy Reviews* **2019,** *101*, 1-13.
[43] Lin, R.; Zhang, Y.; Zhang, Y.; Li, Y.; Zhang, X.; Wang, Y.; Zhang, Y.; Liu, Y.; Zhang, Y.; Zhang, Y. Inhibitory effects of furan derivatives and phenolic compounds on anaerobic fermentation. *Biotechnol. Adv.* **2015,** *33*(5), 1044-1053.
[44] Nyifi, I. A.; Irtwange, S. V.; Bako, T. Design and construction of a tube storage device for biogas using motorized

compressor. *Int. J. Sci. Qual. Anal.* **2018,** *4(*1), 20-26.
[45] Mata-Álvarez, J.; Dosta, J.; Romero-Güiza, M. S.; Fonoll, X.; Peces, M.; Astals, S. A critical review on anaerobic co-digestion achievements between 2010 and 2013. *Renewable and Sustainable Energy Reviews* **2014,** *36*, 412-427.
[46] Morales-Polo, C.; Cledera-Castro, M. D. M.; Moratilla Soria, B. Y. Reviewing the anaerobic digestion of food waste: From waste generation and anaerobic process to its perspectives. *Appl. Sci.* **2018,** *8*(10), 1804.
[47] Hanum, F.; Kamahara, H.; Atsuta, Y.; Yamada, T.; Daimon, H. Treatment of sewage sludge using anaerobic digestion in malaysia: Current state and challenges. *Front. Energy Res.* **2019,** *7*, 19.
[48] Batstone, D. J.; Puyol, D.; Flores-Alsina, X.; Rodríguez, J. Mathematical modelling of anaerobic digestion processes: applications and future needs. *Reviews in Environmental Science and Bio/Technology* **2015,** *14*(4), 595-613.
[49] Shallo, L.; Ayele, M.; Sime, G. Determinants of biogas technology adoption in southern ethiopia. *Energy Sustainability Soc.* **2020,** *10*, 1.
[50] Ritchie, H.; Rosado, P.; Roser, M. CO_2 and greenhouse gas emissions. *Our World in Data.* [Online] **2023**. https://ourworldindata.org/co2-and-greenhouse-gas-emissions (accessed Sep 15, 2025).
[51] McIlroy, S. J.; Saunders, A. M.; Albertsen, M.; Nierychlo, M.; McIlroy, B.; Hansen, A. A.; Karst, S. M.; Lund Nielsen, J.; Nielsen, P. H. MiDAS: The field guide to the microbes of activated sludge. *Database* **2015,** *2015,* bav062.
[52] Wall, D. M.; O'Shea, R.; Murphy, J. D. *Biogas Systems in Industry: An Analysis of Sectoral Usage, Sustainability, Logistics, and Technology Development*. IEA Bioenergy: Austria, 2025. https://www.ieabioenergy.com/wp-content/uploads/2025/06/IEA-Bioenergy_Task-37_Biogas-Systems-in-Industry_022025.pdf (accessed Sep 15, 2025).
[53] World Bank. *Climate-Smart Agriculture: A Call to Action* [Online]. https://documents1.worldbank.org/curated/en/794281468155721244/pdf/889080WP0v10RE0Smart0Development0Ma.pdf (accessed Sep 15, 2025).
[54] World Health Organization. *Burden of Disease from Household Air Pollution for 2016* [Online]. https://cdn.who.int/media/docs/default-source/air-quality-and-health/hap_bod_results_may2018_final.pdf?sfvrsn=d499316c_3 (accessed Sep 15, 2025).
[55] U.S. Energy Information Administration. *International Energy Outlook 2023* [Online]. https://www.eia.gov/outlooks/ieo/ (accessed Sep 15, 2025).
[56] Tchobanoglous, G.; Stensel, H. D.; Tsuchihashi, R.; Burton, F. *Wastewater Engineering Treatment and Resource Recovery*; McGraw-Hill Education: New York, 2014.
[57] *Fermentation of Organic Materials-Characterization of the Substrate, Sampling, Collection of Material Data, Fermentation Tests*; DI 4630; Verein Deutscher Ingenieure: Düsseldorf, 2016.
[58] Holman, J. P. *Heat Transfer*, 10th ed.; McGraw-Hill Education: New York, 2009.
[59] Megyesy, E. *Pressure Vessel Handbook*. Pressure Vessel Publishing, INC, 1977.
[60] Owabor, C. N.; Ono, U. M.; Isuekevbo, A. Enhanced sorption of naphthalene onto a modified clay adsorbent: Effect of acid, base and salt modifications of clay on sorption kinetics. *Adv. Chem. Eng. Sci.* **2012,** *2*(3), 201-208.
[61] Eliaz, N. Corrosion of metallic biomaterials: A review. *Materials* **2019,** *12*, 407.
[62] Karion, A.; Ghosh, S.; López-Coto, I.; Mueller, K.; Gourdji, S.; Pitt, J.; Whetstone, J. Methane emissions show recent decline but strong seasonality in two US northeastern cities. *Environ. Sci. Technol.* **2023,** *57*, 19565-19574.
[63] Angelidaki, I.; Alves, M.; Bolzonella, D.; Borzacconi, L.; Campos, J. L.; Guwy, A. J.; Kalyuzhnyi, S.; Jenicek, P.; Van Lier, J. B. Defining the biomethane potential (BMP) of solid organic wastes and energy crops: A proposed protocol for batch assays. *Water Sci. Technol.* **2009,** *59*(5), 927-934.
[64] Deublein, D.; Steinhauser, A. *Biogas from Waste and Renewable Resources: An Introduction*; John Wiley & Sons: USA, 2011.
[65] Esposito, G.; Frunzo, L.; Giordano, A.; Liotta, F.; Panico, A.; Pirozzi, F. Anaerobic Co-digestion of organic wastes. *Rev. Environ. Sci. Biotechnol.* **2012,** *11*(4), 325-341.
[66] Møller, H. B.; Sommer, S. G.; Ahring, B. K. Methane productivity of manure, straw, and solid fractions of manure. *Biomass Bioenergy* **2004,** *26*(5), 485-495.
[67] Raposo, F.; Fernández-Cegrí, V.; De la Rubia, M. A.; Borja, R.; Béline, F.; Cavinato, C.; Demirer, G.; Fernández, B.; Polanco, M.; Frigon, J.-C.; et al. Biochemical methane potential (BMP) of solid organic substrates: Evaluation of anaerobic biodegradability using data from an international interlaboratory study. *J. Chem. Technol. Biotechnol.* **2011,** *86*(8), 1088-1098.
[68] Alves, M. M.; Pereira, M. A.; Sousa, D. Z.; Cavaleiro, A. J.; Picavet, M.; Smidt, H.; Stams, A. J. M. Waste lipids

to energy: How to optimize methane production from long chain fatty acids (LCFA). *Microb. Biotechnol.* **2009,** *2*(5), 538-550.
[69] Chen, Y.; Cheng, J. J.; Creamer, K. S. Inhibition of anaerobic digestion process: A review. *Bioresour. Technol.* **2008,** *99*(10), 4044-4064.
[70] Cantrell, K. B.; Hunt, P. G.; Uchimiya, M.; Novak, J. M.; Ro, K. S. Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. *Bioresource Technology* **2012,** *107*, 419-428.
[71] Wang, X.; Lu, X.; Li, F.; Yang, G. Effects of temperature and carbon-nitrogen (C/N) ratio on the performance of anaerobic co-digestion of dairy manure, chicken manure and rice straw: Focusing on ammonia inhibition. *Plos One* **2014,** *9*(5), e97265.
[72] El-Mashad, H. M.; Zhang, R. Biogas production from Co-figestion of dairy manure and food waste. *Bioresour. Technol.* **2010,** *101*(11), 4021-4028.
[73] Sun, J.; Mao, X.; Shaghaleh, H.; Chang, T.; Wang, R.; Zhai, S.; Hamoud, Y. A. Analytic method for optimizing the allocation of manure nutrients based on the assessment of land carrying capacity: A case study from a typical agricultural region in China. *Agronomy* **2023,** *13*(4), 1064.
[74] Mata-Alvarez, J.; Dosta, J.; Romero-Güiza, M. S.; Fonoll, X.; Peces, M.; Astals, S. A critical review on anaerobic Co-digestion: Which mixtures maximize synergy? *Renew. Sustain. Energy Rev.* **2014,** *36*, 412-427.
[75] El-Mashad, H. M.; Zhang, R. Biogas production from co-digestion of dairy manure and food waste. *Bioresour. Technol.* **2010,** *101*(11), 4021-4028.
[76] Mao, C.; Feng, Y.; Wang, X.; Ren, G. Review on research achievements of biogas from anaerobic digestion. *Renew. Sustain. Energy Rev.* **2015,** *45*, 540-555.
[77] MacCarty, N.; Still, D.; Ogle, D. Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. *Energy for Sustainable Development* **2010,** *14*(3), 161-171.
[78] Li, Y.; Alaimo, C. P.; Kim, M.; Kado, N. Y.; Peppers, J.; Xue, J.; Wan, C.; Green, P. G.; Zhang, R.; Jenkins, B. M.; Vogel, C. F. A.; Wuertz, S.; Young, T. M. Composition and toxicity of biogas produced from different feedstocks in california. *Environ. Sci. Technol.* **2019,** *53*, 11569-11579.
[79] Hafner, S. D.; De Laclos, H. F.; Koch, K.; Holliger, C. Improving inter-laboratory reproducibility in measurement of biochemical methane potential (BMP). *Water* **2020,** *12*(6), 1752.
[80] Bergland, W. H.; Dinamarca, C.; Toradzadegan, M.; Nordgård, A. S. R.; Bakke, I.; Bakke, R. High rate manure supernatant digestion. *Water Research* **2015,** *76*, 1-9.
[81] Araujo, M. N.; Vargas, S. R.; Soares, L. A.; Trindade, L. F.; Fuess, L. T.; Adorno, M. A. T. Rapid method for determination of biogas composition by gas chromatography coupled to a thermal conductivity detector (GC-TCD). *Int. J. Environ. Anal. Chem.* **2024,** *104*(20), 1-18.
[82] Gerardi, M. H. *The Microbiology of Anaerobic Digesters*; John Wiley & Sons: USA, 2003.
[83] Batstone, D. J.; Keller, J.; Angelidaki, I.; Kalyuzhnyi, S. V.; Pavlostathis, S. G.; Rozzi, A.; Vavilin, V. A. The IWA anaerobic digestion model no 1 (ADM1). *Water Science and Technology* **2002,** *45*(10), 65-73.
[84] El-Mashad, H. M.; Zeeman, G.; Van Loon, W. K. P.; Bot, G. P. A.; Lettinga, G. Effect of temperature and temperature fluctuation on thermophilic anaerobic digestion of cattle manure. *Bioresour. Technol.* **2004,** *95*(2), 191-201.
[85] Appels, L.; Baeyens, J.; Degrève, J.; Dewil, R. Principles and potential of the anaerobic digestion of waste-activated sludge. *Prog. Energy Combust. Sci.* **2008,** *34*(6), 755-781.
[86] Labatut, R. A.; Angenent, L. T.; Scott, N. R. Biochemical methane potential and biodegradability of complex organic substrates. *Bioresour. Technol.* **2011,** *102*(3), 2255-2264.
[87] Ahn, K. H.; Park, K. Y.; Maeng, S. K.; Hwang, J. H.; Lee, J. W.; Song, K. G.; Choi, S. Ozonation of wastewater sludge for reduction and recycling. *Water Science and Technology* **2002,** *46*(10), 71-77.
[88] Li, T.; Yang, Y. A novel inorganic/organic composite membrane tailored by various organic silane coupling agents for use in direct methanol fuel cells. *Journal of Power Sources* **2009,** *187*(2), 332-340.
[89] Bond, T.; Templeton, M. R. History and future of domestic biogas plants in the developing world. *Energy Sustain. Dev.* **2011,** *15*(4), 347-354.
[90] Hemmati, R.; Saboori, H.; Jirdehi, M. A. Multistage generation expansion planning incorporating large scale energy storage systems and environmental pollution. *Renewable Energy* **2016,** *97*, 636-645.
[91] Mapantsela, Y.; Mukumba, P.; Obileke, K.; Lethole, N. Portable biogas digester: A review. *Gases 2024, 4*(3), 205-223.
[92] Alkhalidi, A.; Khawaja, M. K.; Amer, K. A.; Nawafleh, A. S.; Al-Safadi, M. A. Portable biogas digesters for domestic use in jordanian villages. *Recycling* **2019,** *4*, 21.

Appendix A. Safety guidelines for cylinder digesters

1. Perform leak tests with soapy water before operation.
2. Install pressure-relief valves and flame arrestors.
3. Regularly inspect for corrosion, especially internal rusting.
4. Use H_2S scrubbers (steel wool or iron oxide).
5. Train users on safe ignition, ventilation, and monitoring.