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Design, Fabrication and Evaluation of a Mini-Biogas Plant with Automatic Pressure Relief Control for Power Generation

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ABSTRACT: The growing demand for decentralised, sustainable power in Nigeria, combined with the poor management of organic waste in rural and peri-urban areas, motivates the development of small-scale, waste-to-energy technologies. This paper reports the design, fabrication and performance evaluation of a mini-biogas plant that converts cow dung and kitchen waste into electricity through anaerobic digestion, gas conditioning and a modified petrol generator, while a fully passive, electronics-free automatic pressure relief system based on an adjustable water seal protects the digester from over-pressurisation. The 1000 L high-density polyethylene (HDPE) digester was filled with 70% cow dung and 30% kitchen waste in the ratio of 1:1 of dung to water and kept under observation for 5 weeks of retention time.The pH of digester was maintained in the desired range of 6.8 to 7.5 from Week 2 onwards whereas the average digestion temperature ranged from 28.1 °C to 30.8 °C. Average biogas production was 0.92 m³/day (design target 0.5-1.5 m³/day), with a peak of 1.18 m³/day. Gas conditioning raised methane content from 58.4% in the raw biogas to 67.2% after CO_2 scrubbing, within the 60-70% target band. The water-seal pressure relief system activated within 3-4% of its calculated set point at all three tested submerged depths (8, 10 and 12 cm) and re-sealed within 4-6 seconds, confirming that safe, automatic pressure regulation can be achieved without sensors, controllers or external power. These results demonstrate that a low-cost, locally fabricated mini-biogas system with a passive safety mechanism is a technically viable route to decentralised electricity generation and organic-waste management in resource-limited settings.

KEYWORDS: Biogas, Anaerobic Digestion, Mini Biogas Plant, Pressure Relief System, Power Generation.

1. INTRODUCTION

Global energy consumption has risen sharply in recent decades as a result of industrialisation and population growth, and many developing countries, including Nigeria, continue to face long-standing electricity supply and waste management problems, particularly in rural and peri-urban areas (Uyar & Javani, 2022). Fossil fuels remain the dominant energy source despite being polluting, non-renewable and increasingly costly, while heavy reliance on them for power generation has contributed to environmental degradation, greenhouse-gas emissions and frequent power outages (Saleem, 2022; Oladosu et al., 2024). At the same time, household, farm and market organic waste continues to accumulate as a health and environmental hazard, so that inadequate energy supply and inefficient waste disposal together create a strong case for a decentralised, environmentally friendly energy system such as biogas (Uyar & Javani, 2022; P. A. Okoro et al., 2024; Nelson, 2021).

Biogas is generated through anaerobic digestion (AD), a microbial process that converts organic matter such as livestock dung, food waste and agricultural residues into a combustible methane-carbon dioxide mixture in four sequential stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis (Obileke et al., 2025). Typical biogas contains 50-70% methane, 30-40% carbon dioxide and small traces of hydrogen sulphide, nitrogen and water vapour, with the methane fraction giving the gas its combustible, energy-yielding property (Jameel et al., 2024).

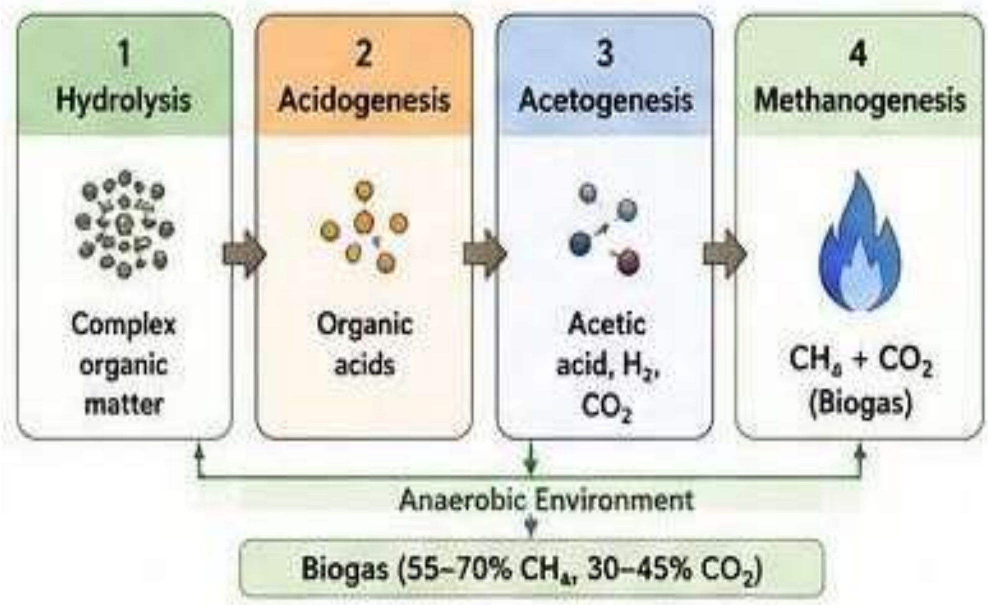

Figure 1: Four stages of the anaerobic digestion process.

Despite this potential, the adoption of small-scale or mini-biogas systems in Nigeria has been limited by technical inefficiencies, weak safety provisions and a general absence of automation. Most existing digesters rely on manual regulation of internal gas pressure, an approach that is inherently unreliable and raises the risk of over-pressure events, gas leakage or rupture of the digester, exposing both operators and equipment to serious hazards (Abah et al., 2025). The absence of automatic pressure-relief mechanisms constrains confidence in, and the scalability of, biogas technology at the household and community level, a problem compounded by limited local technical capacity and dependence on imported components in many existing designs (Shonhiwa et al., 2025).

This study therefore set out to design, fabricate and evaluate a mini-biogas plant that integrates a simple, low-cost automatic pressure-relief control system with a complete gas conditioning and power-generation train. The specific objectives were to: (i) design a functional mini-biogas digester using locally available organic waste; (ii) design and integrate an automatic pressure-relief control system; (iii) convert the biogas produced to power via a small generator; and (iv) evaluate the performance of the constructed system against its design targets.

2. LITERATURE REVIEW

A substantial body of recent work has investigated small-scale biogas systems for rural and off-grid applications, but consistently identifies a gap between biochemical/production optimisation and the integration of automation and safety features. Oluwaseun and Titiladunayo (Oluwaseun & Titiladunayo, 2025) fabricated a mild-steel co-digester for cow dung and elephant grass and, despite favourable substrate properties, recorded low gas yield, which they attributed to poor pressure accumulation and the absence of automated pressure control, explicitly recommending automatic pressure-relief research of the kind undertaken here. Abdurrakhman et al. (Abdurrakhman et al., 2024) demonstrated that a PID-controlled solenoid valve, tuned by particle swarm optimisation, could hold digester pressure deviation below 2%, confirming that automated control markedly improves pressure stability, although their bench-scale system was not validated under field/environmental conditions.

Other studies have targeted microcontroller-based monitoring: an ESP32-based system combining pH and gas-pressure sensing kept methane production stable when digester pH was held between 6.5 and 7.5 and gas was vented automatically at 1.1 bar (Aini et al., 2025), while Bamiyo Dirisu et al. (Bamiyo Dirisu et al., 2023) characterised gas yield and retention time in a 0.25 m³ galvanized-steel digester fed cow dung and fruit peel without any automation, providing useful minimum design benchmarks. Reviews of small-scale anaerobic digestion technology broadly agree that such systems can reliably convert organic waste into usable energy, but that the absence of automated monitoring and pressure-safety provisions continues to limit consistency of gas production and overall operational confidence (Scarlat et al., 2020; Khalil et al., 2022). Similarly, reviews of portable digesters (Khalil et al., 2022) and of biogas-plant sensor technologies (Kumar et al., 2022) report that cost and complexity of existing automation solutions remain prohibitive for rural, low-income deployment, while a review of household gas-storage options (Lindkvist et al., 2021) found flexible storage systems attractive for small plants but noted that pressure-control integration with durable storage remains an open need.

A number of experimental studies have examined feedstock and digestion performance without addressing pressure safety at all, including work on cow-dung-only digestion (Eze et al., 2021; Bamiyo et al., 2021), food-waste digestion (Zhang et al., 2020), co-digestion of agricultural and animal waste (Singh et al., 2023; Ofoefule et al., 2022), and household organic waste digestion (C. Okoro et al., 2022), underscoring a recurring gap: production-side optimisation is well studied, but few designs combine it with a built-in, low-cost pressure-safety mechanism. Studies of biogas purification, such as iron-media hydrogen-sulphide removal (Ryckebosch et al., 2022), and of biogas-fuelled internal combustion engines (Yadav et al., 2022), further show that downstream gas quality and end-use conversion have been investigated largely in isolation from digester-side automation and safety. On the theoretical side, the kinetics and modelling literature on anaerobic digestion (Batstone et al., 2021; Angelidaki et al., 2020) provides the biochemical and control-theoretic basis (including the ideal-gas relationship between pressure, volume and temperature within a closed digester, and feedback control approaches such as the PID law) that underpins pressure-relief system design, but this theory has seen limited translation into low-cost, field-deployable safety mechanisms for small-scale digesters.

Taken together, the literature indicates that while small-scale and automated biogas systems show clear technical promise, most reported designs either optimise gas production without addressing automated pressure safety, or introduce electronic pressure control at a cost and complexity ill-suited to rural deployment. Few studies report field data on long-term durability, and few combine digestion, conditioning, automatic pressure relief and power generation into a single evaluated process train. This is the gap that the present study addresses through a purely passive, water-seal-based pressure-relief mechanism integrated into a complete biogas-to-power system.

3. MATERIALS AND METHODS

The mini-biogas plant comprised three linked process stages: (i) anaerobic digestion of cow dung and kitchen waste to produce raw biogas; (ii) conditioning of the raw gas (moisture removal, hydrogen-sulphide filtration and CO_2 scrubbing) together with automatic regulation of digester pressure via a water-seal relief mechanism; and (iii) conversion of the conditioned gas to electricity using a carburettor-converted petrol generator.

3.1 Materials and Equipment

Materials were selected for local availability, cost-effectiveness, corrosion resistance and suitability for the low operating pressures of biogas. The digester was a 1000 L HDPE water tank; 4-inch PVC pipe (Class C) was used for the slurry inlet/outlet, and a 1/2-inch LPG-rated hose and HDPE pipe formed the gas piping, controlled by 1/2-inch brass ball valves. The moisture trap was a transparent PVC/PET bottle assembly; the H_2S filter (desulfurizer) was a PVC chamber packed with steel-wool (iron-sponge) media; the CO_2 scrubber was a PVC water-scrubbing column; gas was stored in a reinforced flexible biogas bag/HDPE drum of 300-500 L; the automatic pressure-relief system used a bucket/PVC chamber fitted with an adjustable water seal; a stainless-steel/brass mesh flame arrester and a brass regulating valve preceded a 650-1000 W petrol generator that was carburettor-converted to run on biogas, rated at 230 V AC, 50 Hz.

3.2 Design Calculations

3.2.1 Feedstock and digester sizing

Cow dung and kitchen waste were combined in a 70:30 ratio by weight to balance the high buffering capacity and microbial seed of dung with the high volatile-solids content of kitchen waste. The feedstock was diluted with water at 1:1 (dung-equivalent solids to water) to give a pumpable slurry with 7-10% total solids. Of the 1000 L digester volume, about 800 L formed the effective working (liquid) volume, with the remainder serving as gas headspace. Hydraulic retention time (HRT) was estimated as:

HRT (days) = Working Volume (L) / Daily Slurry Feed Rate (L/day)

At a daily feed rate of 15-25 kg/day, this gave an HRT of approximately 20-53 days, within the 20-40 day design target for mesophilic digestion of cattle dung and food waste in the 25-38 °C tropical ambient range.

3.2.2 Biogas yield estimation

Expected biogas volume was estimated by the specific gas yield (SGY) method, V(biogas) = M(feedstock) × SGY, using literature yields of 0.023-0.040 m^3/kg for fresh cow dung and 0.080-0.150 m^3/kg for kitchen/food waste. For the 70:30 feedstock blend at 7.5-12.5 kg combined raw feedstock per day, the estimated production ranged from 0.30 to 0.91 m^3/day, against a design operating target of 0.5-1.5 m^3/day; the gas storage bag was sized at 300-500 L to buffer at least half a day of peak production.

3.2.3 Automatic pressure relief (water-seal) design

The pressure-relief mechanism operates on a water-seal principle: relief pressure is set by the depth of a vent pipe submerged below the water level in the relief chamber, following the hydrostatic relationship $P = \rho g h$, where P is relief pressure (Pa), ρ is water density (1000 kg/m^3), g is acceleration due to gravity (9.81 m/s^2) and h is submerged depth (m). Table 1 lists the calculated relief pressures used to develop the adjustable setting guide; a submerged depth of 8-12 cm (0.8-1.2 kPa) was selected as the optimum operating range for the HDPE digester and PVC piping (design operating pressure 0.5-1.5 kPa), sufficient to move gas through the conditioning train while remaining well within the safe pressure envelope of the system. When digester pressure exceeds the set threshold, gas displaces the sealing water and vents to a safe location; the seal re-forms automatically once pressure falls, without any manual or electronic intervention.

Table 1: Water-seal pressure relief setting guide

Submerged Depth (cm)	Approx. Pressure (mbar)	Approx. Pressure (kPa)
5	5	0.50
8	8	0.80
10	10	1.0
12	12	1.2
15	15	1.5

3.2.4 *CO_2 scrubber sizing*

The CO_2 scrubber was designed as a bubble-column water scrubber, in which raw biogas is bubbled from the bottom of a water-filled PVC column, with CO_2 absorbed and the gas stream cooled as it rises. Three scrubber configurations were compared (Table 2); a single-stage improved bubble scrubber was selected as the best compromise between gas-quality improvement and system complexity/cost, giving an expected methane content of 60-70% at the scrubber outlet.

Table 2: CO_2 removal performance of water-scrubber configurations

Scrubber Design	CO_2 Reduction (%)	Resulting Methane (%)
Simple bubble (1 stage)	10 - 20	55 - 65
Improved bubble (1 stage)	20 - 30	60 - 70
Two-stage scrubber	30 - 40	65 - 75

Table 3: Summary of key design parameters

Parameter	Value
Digester volume (total)	1000 L
Working volume	~800 L
Gas storage capacity	300 - 500 L
Daily feed (slurry)	15 - 25 kg
Feed ratio (dung : water)	1 : 1
Feedstock ratio (dung : kitchen waste)	70 : 30
Hydraulic retention time	20 - 40 days
Expected biogas production	0.5 - 1.5 m³/day
Methane content (after scrubbing)	55 - 70%
Operating pressure	0.5 - 1.5 kPa
Gas temperature (optimal)	25 - 38°C
Power output	300 - 700 W (intermittent)
Total solids content	7 - 10%
Digester pH range	6.8 - 7.5

3.3 System Description

The complete process train links twelve functional units, from feedstock collection through slurry mixing, the digester, gas conditioning (moisture trap, H_2S filter, CO_2 scrubber), gas storage, the automatic water-seal pressure-relief system, the flame arrester and gas control valve, to the biogas generator.

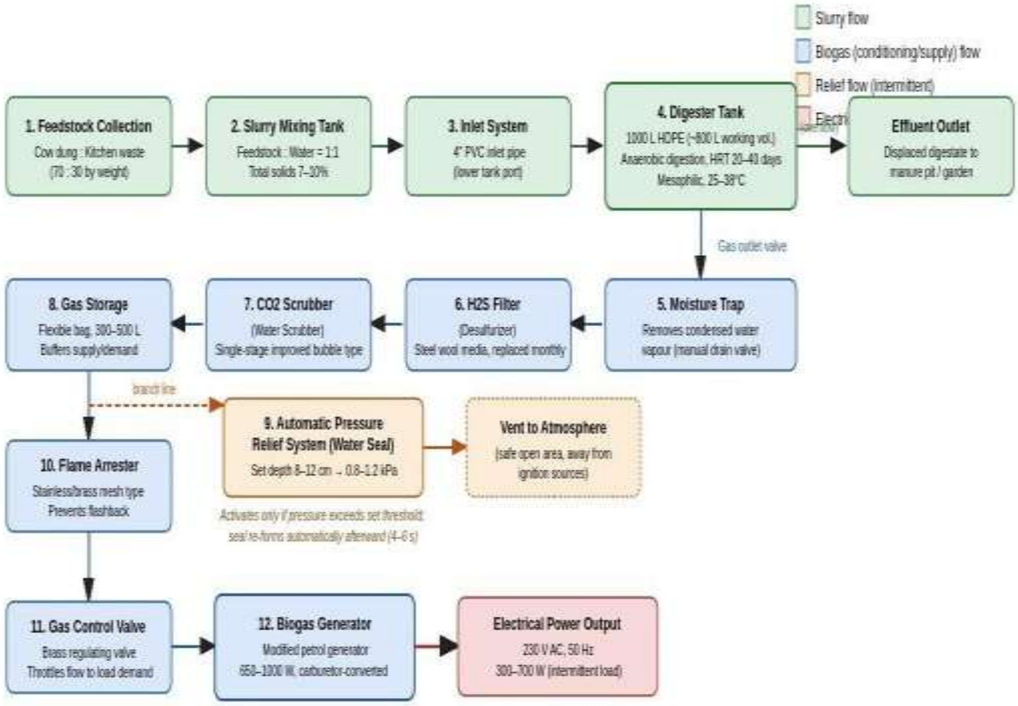

Figure 2: Overall system process flowchart.

3.4 Fabrication and Assembly

The plant was fabricated progressively, beginning with the feedstock-handling and digestion system, followed by gas conditioning and storage, pressure control, and finally power generation. The slurry mixing tank was fitted with a stirring rod and a solvent-welded 4-inch PVC outlet connected to the digester inlet. The 1000 L HDPE digester was installed outdoors on a stable, ventilated base, with inlet and overflow/effluent ports cut according to the slurry-displacement principle and a 1/2-inch brass gas-outlet valve fitted at the top; all joints were pressure- and leak-tested with water before slurry was introduced. The moisture trap, H_2S filter and CO_2 scrubber were fabricated as in-line PVC assemblies and connected sequentially downstream of the digester gas outlet. The pressure-relief water seal was built from a bucket/PVC chamber with the vent pipe set to a depth of 5-15 cm below the water surface (per Table 1) and its vent outlet directed upward to a safe, open area away from ignition sources. A flame arrester and gas control valve were installed ahead of the generator, and an existing 650-1000 W petrol generator was retrofitted with a biogas/air mixer connected via LPG-rated hose, with the entire fuel line leak-tested using soap solution prior to ignition trials.

3.5 Performance Evaluation Procedure

System integrity was verified by soap-solution leak testing of every joint, valve and chamber seal. The digester was then charged daily at the design feed rate (15-25 kg/day, 1:1 dung-to-water ratio) and monitored over the hydraulic retention period, with ambient/slurry temperature and pH logged daily. Daily biogas output was estimated from the inflation rate of the flexible storage bag, cross-checked against its rated capacity, while gas quality (methane content) was assessed via the water-scrubber CO_2-removal reference values, a portable gas analyser where available, and qualitative flame-colour observation at the generator intake. System pressure was monitored with a manometer on the storage line, and the automatic relief response was verified by deliberately restricting downstream flow to confirm venting at the set threshold (0.8-1.2 kPa) and re-sealing afterward. Finally, the biogas generator was operated under varying load, with voltage, frequency and run duration recorded using a multimeter/clamp meter.

4. RESULTS AND DISCUSSION

4.1 Commissioning and Leak Testing

All major joints, valves and chamber seals passed soap-solution leak testing on commissioning; the gas storage bag and line required one resealing after an initial leak was detected and corrected, after which the system passed. This confirms that the fabrication and jointing methods (solvent-welded PVC, Teflon-taped threaded brass fittings) produced a gas-tight process train suitable for feeding.

4.2 Digestion Monitoring: pH and Temperature

Digester pH rose steadily from 6.82 in Week 1 to a peak of 7.15 in Week 4, stabilising at 7.12 in Week 5 (Figure 7), remaining within the 6.8-7.5 design band from Week 2 onward. This trend is consistent with a typical digester start-up, in which an initial, slightly acidic phase dominated by volatile-fatty-acid-forming acidogenic bacteria gives way to a balanced methanogenic population as digestion stabilises. Average digestion temperature (Figure 8) rose from 28.1 °C in Week 1 to a peak of 30.8 °C in Week 4, remaining within the 25-38 °C optimal mesophilic range but toward its lower-middle end, which is likely to account for gas production settling near the centre, rather than the top, of its design range.

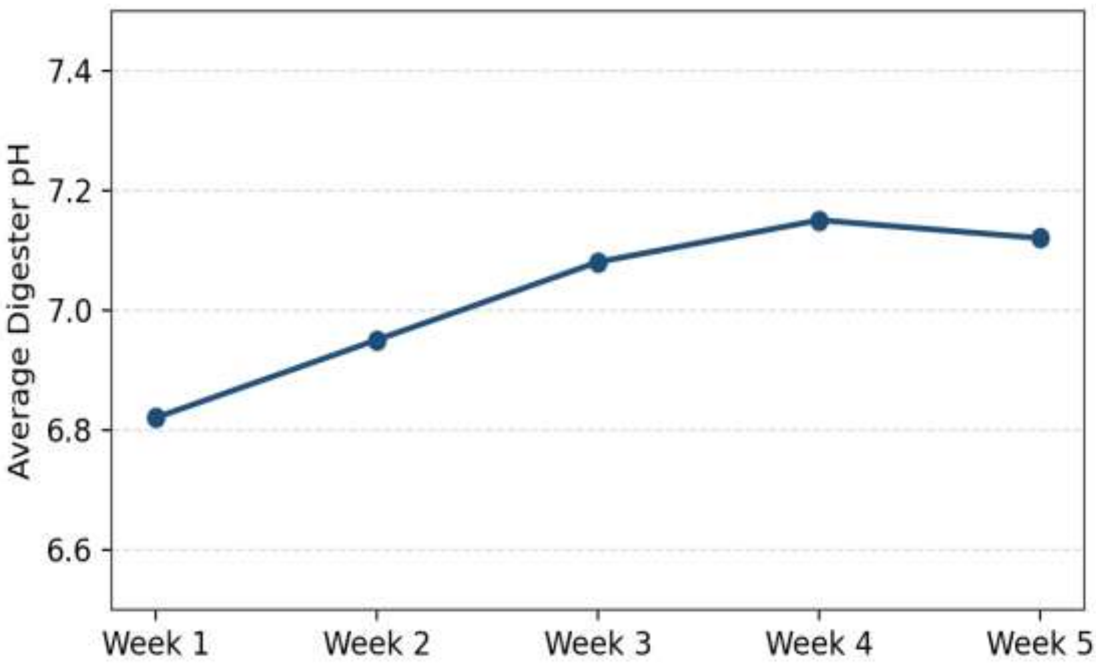

Figure 3: Average digester pH over the five-week monitoring period.

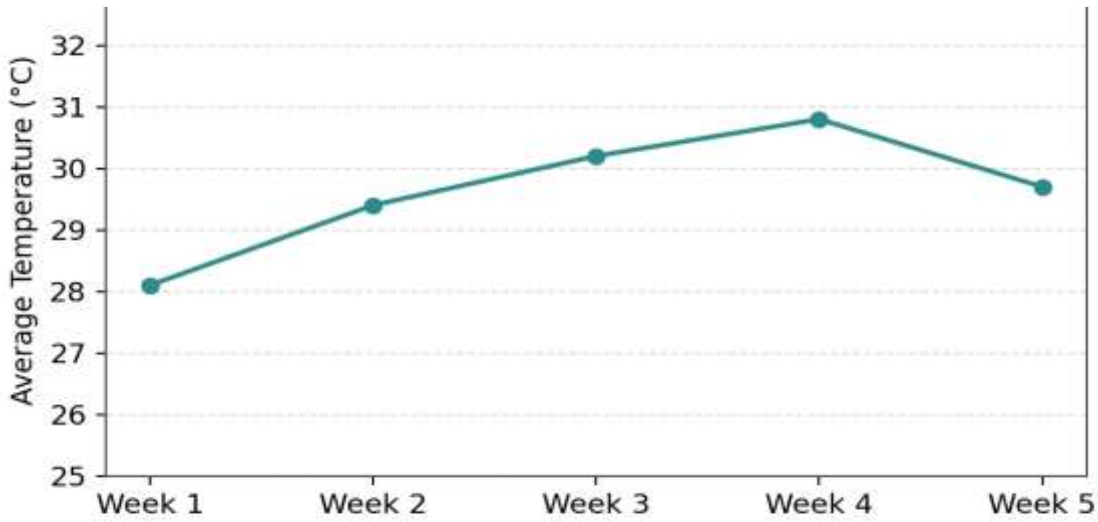

Figure 4: Average digester temperature over the five-week monitoring period.

4.3 Biogas Production

Gas was first observed on Day 12, coinciding with the "active microbial growth" phase noted in Week 2 monitoring, and consistent with the digester being within its design hydraulic retention window (20-40 days). Average daily biogas production over the monitoring period was 0.92 m^3/day, within the 0.5-1.5 m^3/day design target, with a recorded peak of 1.18 m^3/day and a typical storage-bag fill time of 11.5 hours (Table 4). At this production rate, the 300-500 L storage bag fills in roughly 24 hours, meaning gas must be drawn off (via the generator) at least once a day, a requirement directly linked to the pressure-relief sizing discussed in Section 4.5.

Table 4: Biogas production summary

Parameter	Design Target	Measured Result
Average daily biogas production	0.5 - 1.5 m^3/day	0.92 m^3/day
Day gas production first observed	Within HRT (20 - 40 days)	Day 12
Peak single-day production recorded	-	1.18 m^3/day
Storage bag fill time (typical day)	-	11.5 hours

4.4 Gas Quality After Conditioning

Raw biogas methane content was 58.4%, within the expected 55-65% range for unconditioned gas from this feedstock. Methane content was essentially unchanged after H_2S filtration (58.1%), as expected since desulfurisation targets hydrogen sulphide rather than methane or CO_2. After CO_2 scrubbing, methane content rose to 67.2% (Figure 9), within the 60-70% target band for a single-stage improved bubble scrubber and toward the upper end of that range, suggesting that water level and gas-bubble contact time were well matched to the actual gas flow rate. A steady blue flame was observed at the generator intake throughout, consistent with a high-60s methane mixture rather than the yellow, sooty flame associated with CO_2-diluted gas.

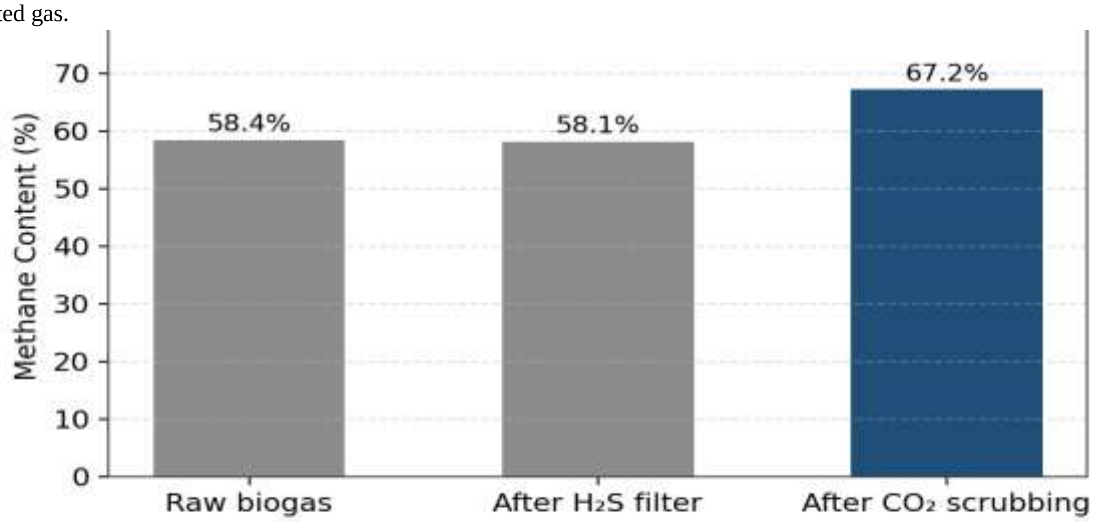

Figure 5: Methane content of the biogas before and after each conditioning stage.

Table 5: Gas quality before and after conditioning

Stage	Design Target (CH_4 %)	Measured Result
Raw biogas (before scrubbing)	55 - 65%	58.4%
After H_2S filtration	No significant CH_4 change	58.1%
After CO_2 scrubbing (final)	60 - 70%	67.2%
Flame colour/stability observed	Steady blue flame	Stable blue flame observed

4.5 Automatic Pressure Relief System Performance

The water-seal pressure-relief mechanism was tested at submerged depths of 8, 10 and 12 cm. Observed relief pressures of 0.83, 1.04 and 1.24 kPa closely tracked the calculated values of 0.80, 1.0 and 1.2 kPa at each depth (Figure 10, Table 6), a consistent 3-4% deviation attributable to minor losses not captured by the idealised hydrostatic model (for example, small pressure losses in the vent pipe/fittings, surface tension at the point of bubble release, or a small manometer offset). The water seal re-formed within 4-6 seconds of activation at all three depths, with re-seal time increasing slightly with depth, as expected since a greater volume of displaced water must return to re-establish a deeper seal. This close agreement between calculated and observed relief pressure, combined with the roughly 24-hour storage-bag fill time reported in Section 4.3, demonstrates that the pressure-relief system is correctly sized to prevent digester over-pressurisation during the several-hour periods each day when gas generation exceeds off-take, achieving the project's central safety objective without any manual or electronic intervention.

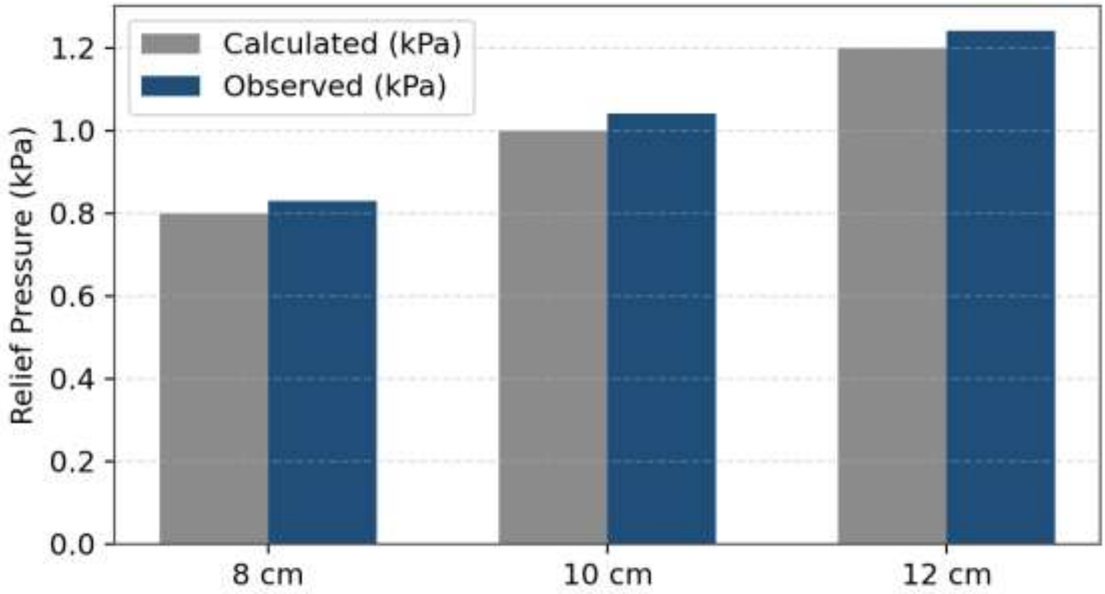

Figure 6: Calculated versus observed pressure relief performance at three submerged depths.

Table 6: Pressure relief system test results

Submerged Depth (cm)	Calculated Pressure (kPa)	Observed Relief Pressure (kPa)	Relief Activated? (Y/N)	Reseal Time (s)
8	0.80	0.83	Yes	4
10	1.0	1.04	Yes	5
12	1.2	1.24	Yes	6

4.6 Power Generation Under Load

The biogas-fuelled generator was operated across the load range from no-load to approximately 700 W (full load) using conditioned gas from storage. Output voltage fell from 232 V at no load to 221 V at full load (Figure 11), and frequency fell from 50.2 Hz to 49.4 Hz (Figure 12) — both variations consistent with a small engine-generator lacking an electronic governor, and acceptable for resistive domestic loads. Run duration on a single filled storage bag fell from 115 minutes at no load to 59 minutes at full load, reflecting the higher fuel consumption rate at higher loads. Critically, the generator did not stall at the design full-load condition of 700 W, experiencing only a slight voltage drop, confirming that the gas train delivered adequate fuel quality and quantity for practical use.

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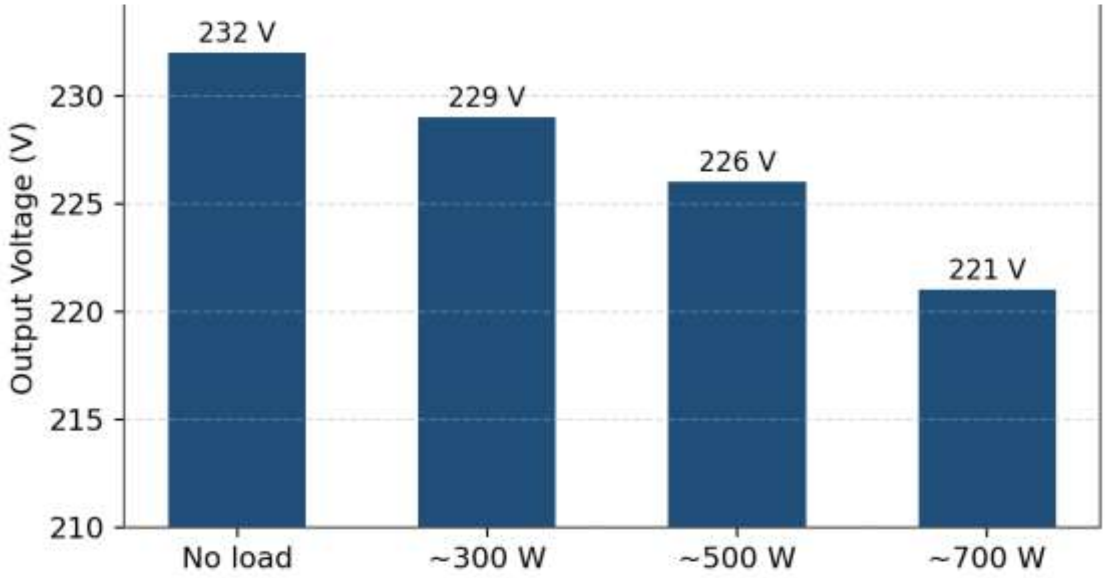

Figure 7: Generator output voltage under increasing load.

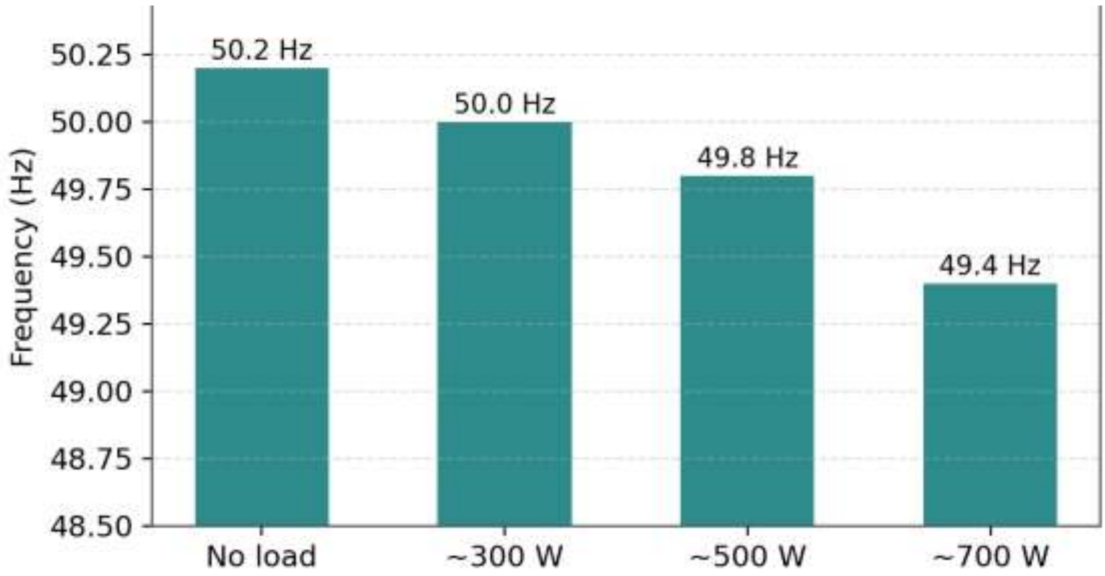

Figure 8: Generator output frequency under increasing load.

Table 7: Generator performance under load

Load (W)	Voltage (V)	Frequency (Hz)	Run Duration (min)	Observation
No load	232	50.2	115	Stable
~300	229	50.0	102	Stable operation
~500	226	49.8	81	Moderate fuel consumption
~700 (full load)	221	49.4	59	Slight voltage drop

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study designed, fabricated and evaluated a mini-biogas plant with an automatic, fully passive pressure-relief control system for power generation. Over a five-week monitoring period, the digester achieved stable operating conditions, with pH settling within the 6.8-7.5 design band from Week 2 and temperature remaining within the 25-38 °C mesophilic range. Average biogas production of 0.92 m³/day fell within the 0.5-1.5 m³/day design target, and conditioning raised methane content from 58.4% to 67.2%, within the 60-70% target band. Most significantly, the water-seal automatic pressure-relief system tracked its calculated set points within 3-4% at all tested depths and re-sealed within 4-6 seconds, confirming that reliable, automatic digester pressure regulation is achievable without electronic sensors, controllers or moving parts. The biogas-fuelled generator sustained the full 300-700 W design load range with only minor voltage and frequency droop. Taken together, these results confirm that usable electricity can be generated from household organic waste using a low-cost, locally fabricated mini-biogas system, and that the electricity-free water-seal pressure-relief mechanism is the design's most distinguishing and readily replicable safety feature.

5.2 Recommendations

1. Install a basic motorised or hand-crank stirring/feeding mechanism to improve slurry consistency and reduce manual-feeding variability.
2. Fit a low-cost gas flow meter on the storage line to replace the storage-bag-inflation proxy with a direct volumetric measurement.
3. Evaluate a two-stage water scrubber where a higher methane content (65-75%) is required for longer engine life or higher generator efficiency.
4. Explore low-cost passive insulation or solar-assisted heating to keep digester temperature closer to the upper mesophilic range (35-38 °C).
5. Investigate alternative desulfurisation media to steel wool to reduce H_2S filter maintenance frequency.
6. Extend performance evaluation to five or more weeks, or across seasons (3-6 months), to assess consistency under varying ambient conditions.
7. Implement digital data logging for pH and temperature to eliminate manual-transcription errors and enable finer-resolution trend analysis.
8. Add low-cost instrumentation (for example, a manometer with data logger) on the relief line for continuous, rather than manual, monitoring of relief events.
9. Assess larger digester volumes together with cost-per-kWh comparisons against grid electricity and solar PV for scale-up beyond the household level.
10. Study co-digestion with other locally available organic wastes, such as abattoir or agricultural residues, to diversify feedstock supply and potentially raise gas yield.

5.3 Contribution to Knowledge

This study contributes a demonstrated, low-cost, fully passive automatic pressure-relief mechanism based on an adjustable water seal that regulates biogas system pressure without electronic sensors, controllers or external power, shown to track its calculated set points within 3-4% across all tested depths. It further presents a complete, integrated household-scale biogas-to-power process train — from feedstock collection through gas conditioning to electricity generation — built from locally available, low-cost materials and shown to sustain a full 300-700 W load range in practice, together with a quantified, reproducible sizing methodology linking feedstock ratio, digester volume, retention time, expected gas yield and pressure-relief settings that was validated against measured results falling within or close to every predicted range.

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