

VALORISATION OF KITCHEN AND ANIMAL WASTE THROUGH A PORTABLE ANAEROBIC-DIGESTION UNIT: DESIGN, FABRICATION, AND EXPERIMENTAL EVALUATION OF BIOGAS YIELD

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Abstract

Untreated kitchen and animal waste remains a major source of unpleasant odours, pathogen transmission, and greenhouse-gas emissions in rapidly urbanising South Asian cities. At the same time, seasonal fluctuations in Pakistan's natural-gas supply highlight the need for affordable and decentralized renewable-energy alternatives. This study presents the design, fabrication, and bench-to-pilot-scale evaluation of a low-cost, movable anaerobic digestion system for converting household kitchen and animal waste into combustible biogas. The system consisted of a 208-L polymer digester equipped with a mechanical shredder, a three-stage gas purification unit for desulfurisation, carbon-dioxide removal, and moisture reduction, a flexible-membrane gas-storage reservoir, and an Arduino-based gas-leak detection system. Seven controlled bottle- and drum-scale experiments were conducted to investigate the effects of collection-vessel elasticity, feedstock composition, particle size, ambient exposure, digester filling level, and feedstock loading on biogas production. These experiments were followed by a 12-day pilot-scale trial using approximately 13–60 kg of mixed vegetable and kitchen waste. Gas production commenced after a three-day lag phase in all experimental trials and subsequently increased approximately monotonically. Greater feedstock loading, smaller particle size, and warmer, sun-exposed conditions resulted in higher gas production. During the pilot trial, the complete system continuously generated combustible biogas over 12 days, with the storage tube reaching a diameter of approximately 23 inches, corresponding to an estimated storage volume of 67 L. Subsequent combustion tests demonstrated successful flame ignition, although flame stability varied. Overall, the findings demonstrate that a low-cost household-scale anaerobic digester constructed from readily available materials can effectively convert mixed organic waste into combustible biogas. The proposed system offers a practical decentralized approach to renewable cooking-fuel generation and organic-waste

management for urban and peri-urban households, particularly in regions experiencing unreliable natural-gas supplies

1. INTRODUCTION AND RELATED WORK

Pakistan's major cities experience chronic natural-gas shortages, while an estimated large share of municipal solid waste generated daily is organic in nature and is routinely dumped on streets or in open landfills rather than treated. Uncollected organic waste decomposes aerobically, releasing methane and carbon dioxide, harbouring disease vectors, and contributing to waterborne illnesses such as typhoid and cholera. At the same time, dwindling reserves of oil and coal have renewed interest in decentralised renewable-energy technologies - wind, solar, hydro, and biogas - of which biogas is distinctive in simultaneously treating waste, generating a combustible fuel, and yielding a nutrient-rich digestate suitable as fertiliser.

Anaerobic digestion (AD) converts biodegradable carbon, protein, and lipid substrates into biogas - typically 55-60% methane (CH_4), 35-40% carbon dioxide (CO_2), and minor fractions of water vapour, hydrogen sulphide, ammonia, nitrogen, oxygen, and hydrogen (Fig. 1) - via a three-stage microbial pathway. Hydrolysis first breaks down complex polymers into soluble monomers using extracellular enzymes; acidogenesis then converts these monomers into volatile fatty acids, alcohols, hydrogen, and carbon dioxide; and methanogenesis, carried out by strictly anaerobic archaea, finally converts acetate, hydrogen, and CO_2 into methane. Because methanogens are highly sensitive to oxygen ingress, pH, and temperature, digester sealing and thermal management are first-order design constraints for any AD system, portable or otherwise.

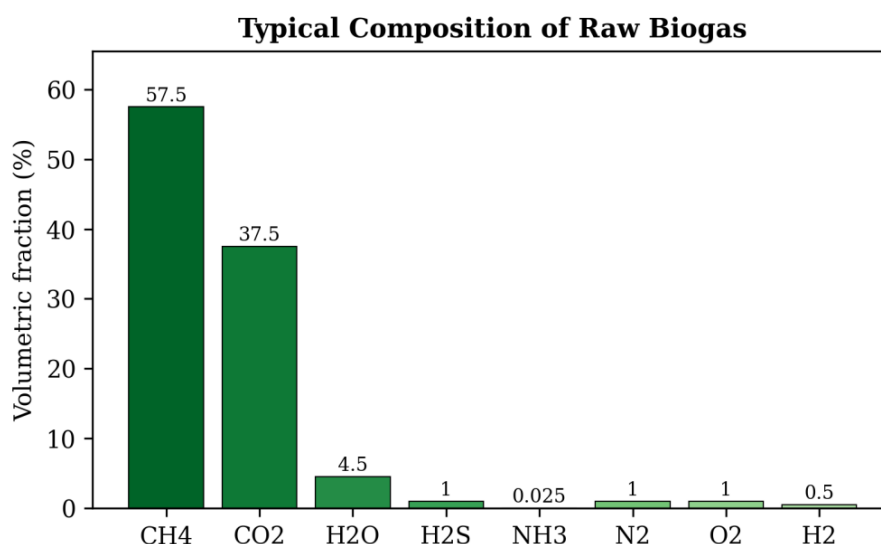


Fig. 1. Typical volumetric composition of raw biogas (values are midpoints of literature ranges).

A substantial body of prior work has examined how feedstock choice and operating conditions govern AD performance. Reported studies indicate that mixing intensity and duration, biomass co-digestion, and nanomaterial or engineered-biochar additives can each measurably enhance methane yield, and that gas-

chromatography-based laboratory assays remain a standard tool for characterising digester output. Comparative feedstock studies report that fruit and vegetable residues - for example pineapple, orange, spinach, and pumpkin waste - generate substantially more biogas than cow dung alone, and that starchy or sugary kitchen waste (spoiled

produce, stale rice, wheat flour) can outperform traditional cow-dung/sewage feedstocks while shortening the multi-month retention times typical of legacy rural digesters. Cassava biomass and other agro-industrial residues have similarly been highlighted as under-exploited feedstocks for regions with limited access to municipal waste streams. Reported daily biogas yields from small kitchen-waste digesters are on the order of 10 litres per kilogram of feedstock, and household- or hostel-scale installations have been demonstrated as both technically and economically viable, particularly in urban settings where kitchen waste is abundant and centralised collection is impractical.

Despite this evidence base, most published designs are either laboratory bench digesters not intended for field deployment or large fixed-dome/floating-drum installations unsuited to individual households. There remains limited experimental documentation of small, movable, household-scale units that combine feedstock preparation (shredding), digestion, in-line gas purification, and safe storage in a single self-contained assembly - and even less documentation of how basic design variables (feedstock form, fill level, and ambient exposure) affect gas output in such a unit under real rooftop conditions. The present study addresses this gap. It reports the design and fabrication of a portable, household-scale biogas unit built from low-cost commodity components, and a structured sequence of screening and pilot experiments quantifying how collection-vessel material, feedstock composition, particle size,

thermal exposure, and digester loading affect gas generation, culminating in a full-system 12-day trial with gas-quantity estimation and safety instrumentation.

2. Materials and Methods

2.1 Feedstock and Reagents

Feedstock consisted of mixed kitchen waste - vegetable peels (potato, banana, carrot, mango, onion, bitter gourd, melon, ridge gourd), corn leaves, cabbage leaves, papaya peel, okra, apple gourd, fenugreek, tomatoes, lettuce, eggplant, capsicum, arwi (taro), cauliflower, leftover cooked food, tea grains, wheat flour and corn-starch slurry, and rice/noodle starch water - together with process water. No external inoculum, buffer, or temperature control was applied beyond ambient rooftop or shaded-terrace exposure, consistent with the target household-deployment scenario.

2.2 System Design and Fabrication

The complete unit (Fig. 6) comprises a mobile steel-frame structure (6 x 4 x 5 ft, mounted on four caster wheels for portability and roof/terrace placement), a 208 L high-density-plastic digester drum, a 3-4 L twin-blade mechanical shredder used to liquefy feedstock prior to loading (reducing blockage risk and accelerating digestion relative to coarse chopping), a three-stage gas-purification train, a flexible tyre-tube gas-storage reservoir (16 in nominal diameter), and an Arduino-based gas-leak detection circuit.

Table 1 summarises the principal component dimensions.

Table 1. Principal specifications of the portable biogas system.

Component	Parameter	Value
Support structure	Length x Breadth x Height	6 ft x 4 ft x 5 ft
Anaerobic digester (drum)	Capacity / Length / Diameter	208 L / 2.91 ft / 2 ft
Waste shredder	Capacity	3-4 L
Purification filters (x3)	Desulfuriser / CO ₂ scrubber / Moisture remover	1.5 L each
Gas storage reservoir	Tube diameter	16 in (nominal, uninflated)

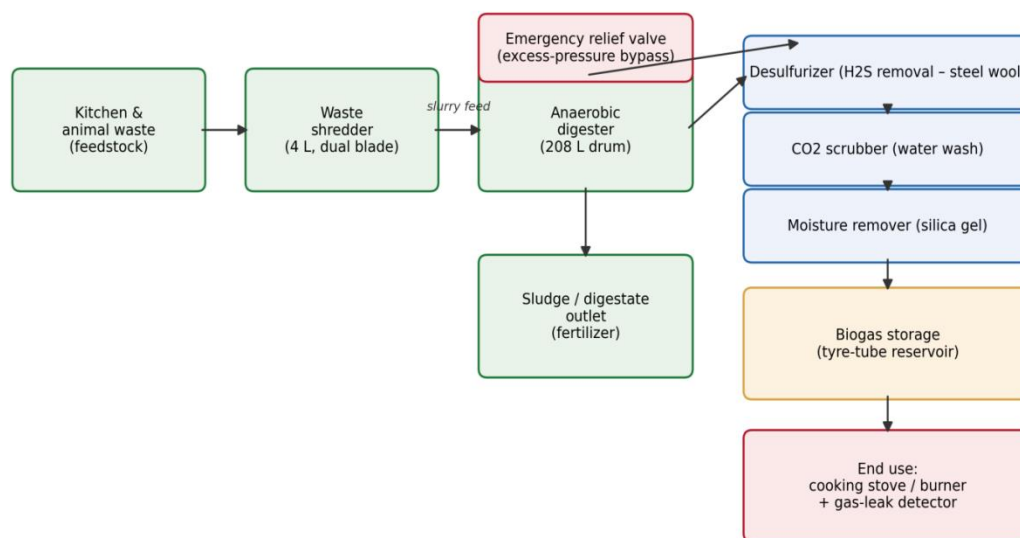


Fig. 6. Process-flow schematic of the portable animal-/kitchen-waste biogas unit.

The digester has a single 1.5 in inlet (fed by the shredder) positioned above the vessel mid-height, a 2 in base outlet for periodic sludge/fertiliser removal, and two 0.25 in gas outlets at the crown: a primary line to the purification train and a secondary emergency-relief line direct to the desulfuriser to protect against over-pressurisation. Purified gas passes sequentially through a steel-wool desulfuriser (H₂S removal), a water-wash CO₂ scrubber (replaced when the wash water turns milky), and a silica-gel moisture remover, before being routed to the storage reservoir and, from there, to a cooking burner. An Arduino microcontroller with a gas sensor and indicator circuit provides continuous leak monitoring at the unit.

2.3 Gas-Quantity Estimation

Because the unit was not fitted with a calibrated flow meter, gas generation was tracked indirectly, following common low-cost digester-screening practice, via the physical expansion of an elastic collection vessel - a balloon in bottle-scale trials and a toroidal tyre-tube reservoir in drum- and pilot-scale trials - whose diameter was recorded daily with a measuring tape. For the pilot-scale reservoir, the stored gas volume was subsequently

estimated from the measured inner and outer tube radii ($r = 4.21$ in, $R = 11.79$ in) using the torus-volume relation $V = (\pi r^2)(2\pi R)$, giving an estimated stored volume of 2.38 ft^3 (67.4 L) at the plateau tube diameter of 23 in; combined with a nominal biogas density of 1.15 kg/m^3 , this corresponds to an estimated stored mass of approximately 77 g and, at an observed 45-minute burn/consumption time, an approximate flow rate of $2.86 \times 10^{-5} \text{ kg/s}$ at the burner.

3. Experimental Design

Seven trials were conducted in sequence, progressing from small-scale factor screening to full-system validation. Each bottle-scale screening trial (Experiments 1-5) used triplicate 6 L bottles fitted with a sealed gas off-take line and an elastic balloon reservoir, loaded with chopped feedstock and left undisturbed on an accessible rooftop for 7 days, with balloon diameter recorded daily. Experiments 6 and 7 scaled up to 20 L and 208 L vessels, respectively, using a flexible tube reservoir and (for Experiment 7) the complete fabricated unit described in Section 2.2. Table 2 summarises the design variable examined in each trial.

Exp.	Design variable examined	Vessel scale	Duration
1	Collection-balloon material/elasticity (good, average, low grade)	6 L bottle (x3)	7 days
2	Feedstock/waste type (3 distinct mixes)	6 L bottle (x3)	7 days
3	Feedstock particle size (block, sliced, finely chopped)	6 L bottle (x3)	7 days
4	Ambient exposure / temperature (roof, shaded terrace, indoor)	6 L bottle (x3)	7 days
5	Digester fill level (full, half, low charge)	6 L bottle (x3)	7 days
6A/6B	Bench-scale ignition trial; 6B added a starch amendment	20 L drum	7 days
7	Full-system pilot trial (complete fabricated unit)	208 L digester	12 days

4. Results

4.1 Bottle-Scale Screening Trials

Across all five bottle-scale trials, gas evolution followed a consistent pattern: no measurable balloon expansion during days 1-3 (a

hydrolysis/acclimation lag phase), followed by a marked increase from day 4 onward that continued, with a declining rate, through day 7 (Fig. 2).

Bottle-Scale Screening Trials (n = 3 replicate bottles per trial)

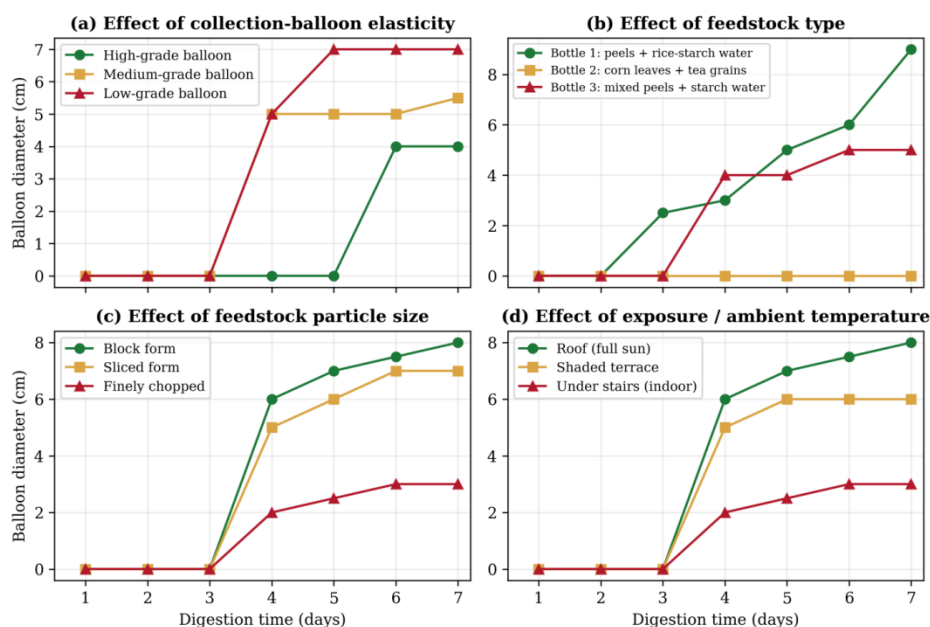


Fig. 2. Bottle-scale screening trials: (a) effect of collection-balloon elasticity; (b) effect of feedstock type; (c) effect of feedstock particle size; (d) effect of ambient exposure/temperature. Balloon diameter is used as a proxy for cumulative gas volume.

Balloon-material trials (Experiment 1, Fig. 2a) showed the greatest expansion in the lowest-grade,

most elastic balloon (7 cm by day 7), confirming that reservoir compliance - not only gas generation - governs the observed balloon-diameter metric and must be controlled when comparing feedstocks. Feedstock-type trials (Experiment 2, Fig. 2b) showed the largest and most sustained expansion in the bottle containing rice-starch water together with vegetable peels and rice-husk/wheat residue (9 cm by day 7), while the bottle containing only corn leaves, tea grains, and noodle-starch water produced no measurable gas, indicating that starch-rich co-substrates markedly enhance gas generation relative to fibrous, low-starch material alone.

Particle-size trials (Experiment 3, Fig. 2c) showed that block-form and sliced feedstock produced substantially more gas (8 cm and 7 cm, respectively, by day 7) than finely chopped material (3 cm), the reverse of what is typically expected from surface-area arguments; this is discussed further in Section 5. Exposure trials (Experiment 4, Fig. 2d) showed the greatest gas volume for rooftop (full-sun) placement (8 cm), intermediate volume for the shaded terrace (6 cm), and the lowest volume indoors under the stairs (3 cm), consistent with a positive temperature dependence of microbial digestion rate.

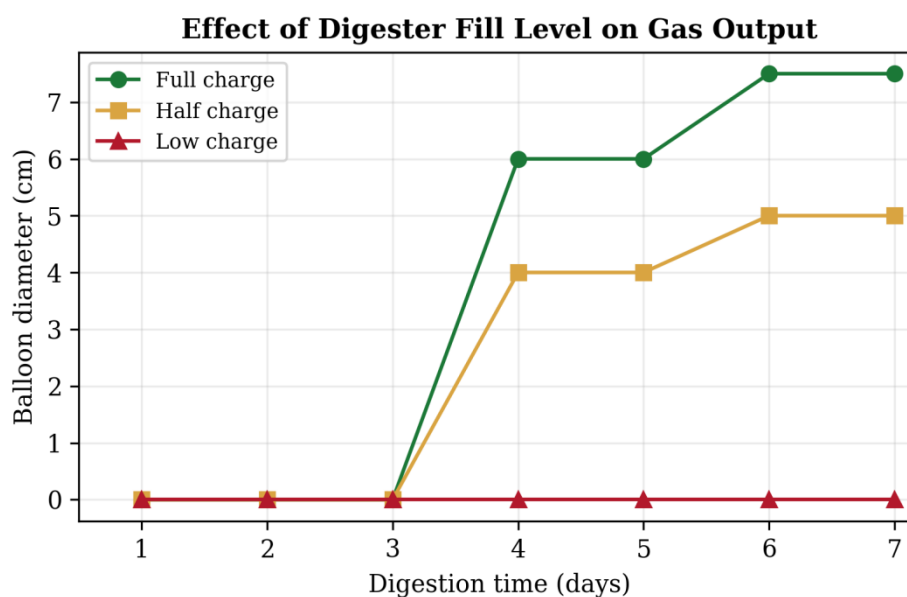


Fig. 3. Effect of digester fill level (Experiment 5) on balloon expansion over 7 days.

Fill-level trials (Experiment 5, Fig. 3) showed that a fully charged bottle produced the greatest gas volume (7.5 cm by day 7), a half-charged bottle produced roughly two-thirds as much (5 cm), and

a low-charge bottle produced no measurable gas over the 7-day window, confirming that feedstock loading is a first-order driver of short-term gas output at fixed digestion time.

4.2 Bench- and Pilot-Scale Trials

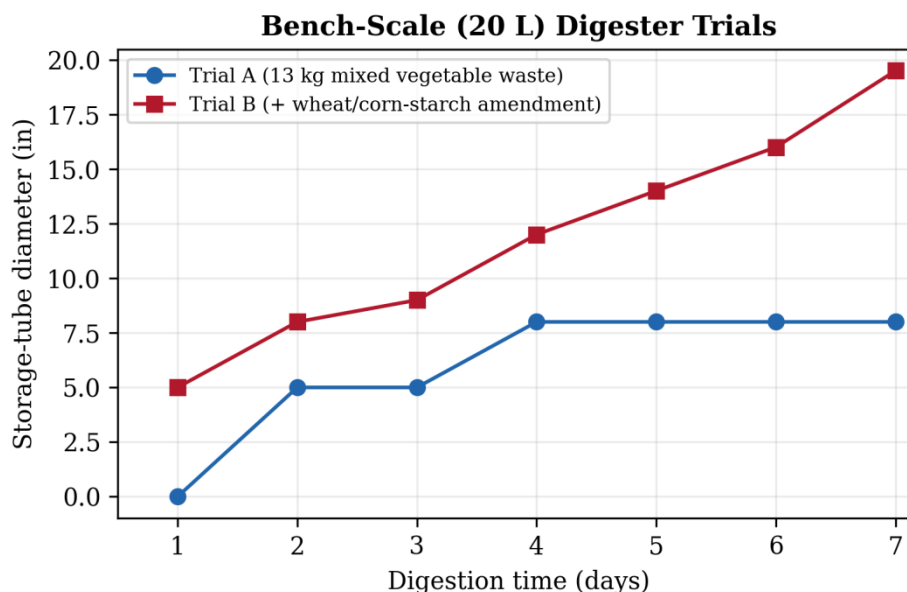


Fig. 4. Bench-scale (20 L) trials: storage-tube diameter for a 13 kg mixed-vegetable-waste charge (Trial A) versus the same charge with a wheat-flour/corn-starch amendment (Trial B).

In the 20 L bench trials (Experiment 6, Fig. 4), the unamended 13 kg mixed-vegetable-waste charge (Trial A) reached a plateau tube diameter of 8 in by day 4 and did not ignite on testing, attributed to an insufficiently developed methanogenic population. Adding a wheat-flour/corn-starch amendment (Trial B) more than doubled the peak

tube diameter to 19.5 in by day 7, with the gas igniting, albeit with an unstable flame, demonstrating that a starch-rich co-substrate can meaningfully accelerate and intensify gas generation at this scale, consistent with the Experiment 2 screening result.

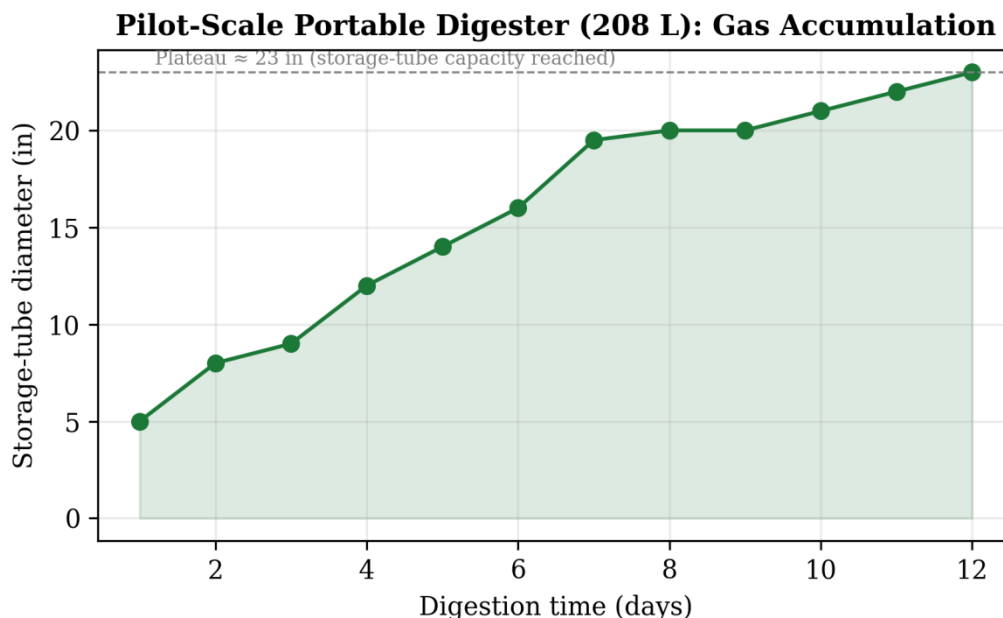


Fig. 5. Full-system pilot trial (Experiment 7): storage-tube diameter over 12 days for the complete 208 L portable digester.

The complete 208 L pilot unit (Experiment 7, Fig. 5), loaded with approximately 60 kg of mixed kitchen waste and process water, showed continuous gas accumulation over the full 12-day observation period, with tube diameter increasing from 5 in on day 1 to 23 in by day 12, at which point the reservoir approached its physical storage capacity. Applying the torus-volume estimate of Section 2.3 to the plateau diameter gives an estimated stored gas volume of approximately 67 L (2.38 ft^3) and an estimated stored mass of approximately 77 g; at the observed 45-minute burner consumption time this corresponds to an estimated flow rate of $2.86 \times 10^{-5} \text{ kg/s}$. Combustion testing confirmed that the gas produced by the full system ignited and sustained a usable flame.

5. Discussion

The results are broadly consistent with established anaerobic-digestion theory and with the literature reviewed in Section 1. The uniform 3-day lag phase observed across all trials reflects the time required for hydrolytic and acidogenic populations to establish before methanogenesis becomes

significant, and is in line with the multi-stage AD pathway described above. The strong positive effect of feedstock loading (Experiment 5) and of starch-rich co-substrates (Experiments 2 and 6) supports prior reports that starchy/sugary kitchen waste can outperform low-energy inputs such as cow dung alone, and that co-digestion with an easily degradable carbon source accelerates gas evolution. The clear temperature/exposure effect (Experiment 4) is consistent with the known sensitivity of mesophilic methanogens to ambient temperature and supports rooftop or other sun-exposed placement as a practical, no-cost design choice for household-scale units in Pakistan's climate.

The particle-size result (Experiment 3) - block and sliced feedstock outperforming finely chopped material - runs counter to the common expectation that smaller particles, with greater surface area, digest faster. A plausible explanation is that finely chopped material in a static, unstirred bottle digester compacted and reduced local porosity and mass transfer, or promoted localised over-acidification, an artefact that would be expected to diminish or reverse in the shredder-

liquefied full-scale system (Section 2.2), which avoids solid blockage by liquefying feedstock before loading; this discrepancy between bottle-scale and system-scale feedstock preparation is an important caveat when generalising the bottle-trial results to the fabricated unit and merits direct verification in future work (Section 7).

At the system level, the successful 12-day continuous gas accumulation and confirmed ignition in Experiment 7 demonstrate that the integrated shredder-digester-purification-storage design is functionally viable for household deployment. The unstable flame observed in the unamended bench trial, contrasted with more stable ignition after starch amendment and in the fully loaded pilot unit, reinforces that adequate feedstock loading and a readily degradable carbon fraction are practically necessary - not merely beneficial - for reliable end-use combustion in a small, uninoculated, ambient-temperature digester of this type.

6. Conclusions

- A portable, household-scale anaerobic digester integrating a mechanical shredder, a 208 L digestion drum, a three-stage gas-purification train, a flexible storage reservoir, and an electronic leak detector was successfully designed, fabricated, and field-tested.
- Across all screening trials, gas evolution began after a consistent ~3-day lag phase and thereafter increased with digestion time, feedstock loading, ambient temperature/sun exposure, and the inclusion of starch-rich co-substrates.
- The full-scale pilot unit produced combustible biogas continuously over 12 days, reaching an estimated stored volume of ~67 L and successfully igniting, confirming the technical viability of the design for household cooking-fuel applications.
- The unit offers a low-cost, decentralised route to simultaneous organic-waste treatment, renewable cooking-fuel generation, and fertiliser recovery, with particular relevance to gas-deficient urban and peri-urban areas of Pakistan and comparable settings.

7. Limitations and Future Work

- Gas quantity was estimated indirectly from reservoir expansion rather than measured with a calibrated flow meter or gas chromatograph; balloon/tube elasticity was shown (Experiment 1) to itself influence the metric, and future work should incorporate direct volumetric or GC-based methane-content measurement.
- Trials were not temperature-controlled or replicated across seasons; performance under Karachi's full annual temperature range, and under a controlled mesophilic or thermophilic set-point, remains to be characterised.
- The counter-intuitive particle-size result (Section 5) was observed only in static bottle-scale trials and should be re-examined directly in the shredder-fed full-scale digester, where feedstock is liquefied rather than left in solid form.
- Long-term (multi-month) durability, digestate/fertiliser quality, H₂S-scrubber service life, and cost-per-litre-of-gas were not quantified in this study and are recommended targets for follow-on work.
- As proposed by the original design team, coupling the unit with a small photovoltaic array (a solar-biogas hybrid) could offset the observed temperature sensitivity and extend reliable operation into cooler or shaded conditions.

REFERENCES

- Kunatsa and X. Xia, "A review on anaerobic digestion with focus on the role of biomass codigestion, modelling and optimization on biogas production and enhancement," Energy, 2022.B.
- Singh, Z. Szamosi, and Z. Simenfalvi, "Impact of mixing intensity and duration on biogas production in an anaerobic digester," 2022.
- M. K. Devi, S. Manikandan, M. Oviyapriya, and M. Selvaraj, "Recent advances in biogas production using agro-industrial waste: A comprehensive review and outlook of techno-economic analysis," 2022.
- N. Dehghani, M. Tabatabaei, M. Aghbashlo, and H. Kazemi Shariat Panahi, "A state-of-the art review on the application of nanomaterials for enhancing biogas production," 2019.

- S. Chamarthi, P. V. Bhale, N. Srinivasa Reddy, and Ch. Chandra Mouli, "Laboratory scale experiments for biogas production using gas chromatography analysis," *IOSR Journal of Engineering*, vol. 3.
- T. V. Okudoh, "The potential of cassava biomass and applicable technologies for sustainable biogas production in South Africa: A review," *Renewable and Sustainable Energy Reviews*, vol. 39.
- Javed, M. A., Saeed, M., & Zeb, I. (2026). Automated vs Manual Hematology Techniques: Diagnostic Accuracy, Efficiency, and Clinical Utility in Tertiary Care Hospitals: <https://doi.org/10.5281/zenodo.19659917>. *Pakistan Journal of Medical & Cardiological Review*, 5(1), 2771-2778.
- Nazim Nazir. (2023). Artificial intelligence-driven predictive safety instrumented systems for critical energy infrastructure: A framework for next-generation functional safety. *International Journal of Communication Networks and Information Security*, Volume 15 ,(Issue-12), [pages 18]. DOI-<https://ijcnis.org/index.php/ijcnis/article/view/9129>
- Ishaq, Zeb., I, Saeed., M, Gurganari., L, Parveen., S.(2026). Evaluation of Hematological Changes in COVID-19 Patients and Their Prognostic Value in Clinical Management. *Pakistan Journal of Medical & Cardiological Review*.556-566
- Aqeel.,A, kamal.,S,K, Ajaz.,M, Naz.,S, Nazeer.,S. (2026). Advanced machine learning approaches for predictive modeling of microbial growth dynamics and shelf life in functional foods. *Genetics and Molecular Research*. Vol 25 (10)S. doi.org/10.4238/ccrx4g97.
- Naz,A., Saleem, S., Faizan,N., Aqeel,A., Khan, J., (2025). Prescribing patterns of antibiotics using who prescribing indicators among pediatrics: A need for antibiotics stewardship program.*European Journal of Clinical Pharmacy*;Volume:7:Issue1.
- Ashraf, A., Sultani, M. A., Atique, M. S., Qureshi, M., & Shayan, T. J. (2026). Exploring Graphene-Enhanced Quantum Materials and Superconducting Heterostructures for Advanced Batteries and Sustainable Fusion Energy Technologies. *Sch Acad J Biosci*, 14(8), 555-581. doi.org/10.36347/sajb.2026.v14i08.004
- Das, B. C., Achol, I. A., Islam, M. S., Sijan, A. R., Kabir, M. R., & Ghosh, S. K. (2026, May). Sustainability-Driven Unsupervised Learning for Municipal Waste Management Archetype Discovery. In *2026 IEEE 6th International Conference on Computing, Power, and Communication Technologies (IC2PCT)* (pp. 510-516). IEEE. <https://doi.org/10.1109/ic2pct68894.2026.11584412>