



Development of Anaerobic Digester for Co-Digestion of Organic Residues for Biogas Production

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Article Info

Article history:

Received: Dec 27, 2025

Revised: Jan 31, 2026

Accepted: Apr 30, 2026

Keywords:

Anaerobic co-digestion,
Pig manure,
Water hyacinth,
Gmelina arborea
sawdust,
Biogas, Methane gas

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ABSTRACT

The growing world demand of sustainable energy and the dire necessity of having efficient methods to manage residues have compounded the attention of anaerobic digestion as a promising residue-to-energy approach. Although it has been conventionally employed to stabilise single feedstock, there is a common limitation to anaerobic digestion in the yield of methane and the stability of the process under heterogeneous organic residues. To mitigate these challenges, this study focused on the design, construction and performance evaluation of a small-scale anaerobic digester suitable for co-digestion. The equipment constructed was a 220-litre cylindrical polyethylene reactor, with a L-shaped gas outlet and a dual compartment purification system to maintain high-quality gas. It was tested by co-digesting pig manure, water hyacinth (*Eichhornia crassipes*) and *Gmelina arborea* sawdust in the ratio 4:2:1. The results showed that the substrate composition (pig dung: water hyacinth: sawdust) balanced the carbon-to-nitrogen ratio and produced high quality biogas after 18 days of retention. The analysis through Gas Chromatography-Mass Spectrometry established the presence of methane and carbon-dioxide concentrations of 65.58 wt% and 28.29 wt%, respectively and trace amounts of other gases. Flammability test on the gas shows a steady bluish flame, indicating sufficient combustive power. This study has proven that co-digestion is a low cost, replicable approach to renewable energy generation and sustainable management of organic residues in resource constrained settings.

INTRODUCTION

The growing concern of the harmful effect of fossil fuel on the environment and the cost of organic residue disposal are the driving force behind the world switching to sustainable energy systems (Xie *et al.*, 2022; UNEP, 2024). A key to this shift has been anaerobic digestion (AD), an efficient biochemical route to converting agricultural, industrial and domestic residues into bio-gas enriched with a high level of methane, and nutrient-dense bio-fertilizers (Baloch *et al.*, 2022; IEA Bioenergy, 2025). These renewable energy sources and agricultural inputs are critical for creating decentralized energy solutions and supporting soil health. By channelling underutilized plant and livestock residues out of landfills and open dumping

sites into AD systems, this technology addresses the dire need for efficient residue management while simultaneously generating sustainable power.

The basic biochemical process of AD involves degradation of organic matter in the complex community of microbes in the absence of molecular oxygen (Ostos *et al.*, 2024; Jourdain and Gu, 2025). The process is appreciated as well due to its contribution to the circular economy not only because of energy generation but also because of its product, the resultant digestate is a high-quality bio-fertilizer that not only makes soil more fertile but also makes the agricultural sector less dependent on chemical alternatives (Mona *et al.*, 2021; Baloch *et al.*, 2022). Furthermore, AD systems are important in the health of people because they enhance

sanitation and regulation of pathogens of uncontrolled organic residue. In the rural and off-grid societies, biogas can be used as a clean alternative to the conventional fuels such as kerosene or firewood, thus helping to decrease indoor air pollution and prevent local deforestation, respectively (Odejobi *et al.*, 2022).

Various organic residue streams, ranging from animal manures and agricultural residues to aquatic weeds and industrial lignocellulosic biomass, are effectively utilized in anaerobic digestion systems (Baloch *et al.*, 2022; Odejobi *et al.*, 2022, Kolajo *et al.*, 2025). The utilization of these materials has tremendous environmental impact by alleviating the emission of methane gases in open dumping sites and curbing the pollution of water bodies caused by runoff from residues that have not been treated (UNEP 2024). For example, the harvest of invasive species, such as water hyacinth, for AD, will not only produce power but also assist in recovering water ecosystems (Ngan *et al.*, 2016). However, the main drawback of mono-digestion, or single substrate use is that each individual residue stream will be more likely to yield a dominant gas profile or be biochemically constrained in some way, e.g., poor nutrient levels or low levels of methane (Nkuna *et al.*, 2022; Kadam *et al.*, 2024).

The traditional form of the anaerobic digestion technology utilized single feedstocks such as sewage sludge or animal manure (Nkuna *et al.*, 2022; Kelif *et al.*, 2024). Nonetheless, mono-digestion is usually limited technologically, such as inappropriate nutrient concentrations and low-yield of methane. As an example, animal manure alone is often insufficient to provide large-scale biogas generation that is economically feasible (Karki *et al.*, 2021; Nkuna *et al.*, 2022). This has seen the emergence of co-digestion which is the concurrent digestion of a primary substrate by one or more secondary organic residues (Nazir *et al.*, 2023;

Kadam *et al.*, 2024). Co-digestion is based on the logic of obtaining better nutrient balance, especially when it comes to getting carbon-to-nitrogen (C/N) ratio, which balances the biochemical process and results in the best gas production (Kadam *et al.*, 2024; Kelif *et al.*, 2024). Through mixing substrates with complimentary characteristics, researchers are able to dilute inhibitory chemicals and keep a stable pH condition of the methanogenic archaea (Ryue *et al.*, 2020; Sun *et al.*, 2025).

In addition to biological stability, co-digestion contributes greatly to the economic profitability of the biogas plants by increasing the rates of energy recovery and possibly generate revenue through residue treatment fees (Callegari *et al.*, 2020). In third world countries, decentralized bio gas systems can create local jobs in construction, maintenance and downstream agricultural enterprises. Although this technology has these benefits, there are still barriers of technical complexity of the current design of digester and absence of affordable and replicable models of biogas technology that are applicable to low-income families (Kelif *et al.*, 2024).

The chemical content and biodegradability heterogeneity of mixed residues can be a significant problem to the existing AD systems, which are most frequently designed to be optimal with only one, homogeneous substrate (Mignogna *et al.*, 2023). The unstable substrate structure and the heterogeneous rate at which they degrade often cause instability in the process or system malfunctions (Sun *et al.*, 2025). This study will fill these gaps by designing and developing an anaerobic digester to jointly digest pig manure, water hyacinth (*Eichhornia crassipes*) and *Gmelina arborea* sawdust. Through the research, the study aims to help in the creation of more robust and efficient technologies of residue-to-energy that may

thrive in situations wherein residue streams are diverse but mostly underutilized.

MATERIALS AND METHODS

Design and Fabrication of the Anaerobic Digester

The biogas digester was designed to be used on the household level with special considerations on construction with minimal costs, easy handling, and longevity. A cylindrical polyethylene reactor with a capacity of 220 litres was used to serve as the main reactor vessel due to its resistant to corrosion and capability to withstand the pressure of gases inside the tank.

Engineering Design Calculations

The physical dimensions of the digester were dictated by the following engineering considerations:

Reactor Geometry: To maintain even distribution of internal pressure and reduce the exposed surface area to retain heat, a cylindrical geometry was considered, with a selected diameter (D) of =0.45 m and total digester volume expressed as:

$V_d = 220L = 0.22 m^3$, the overall height (H) was calculated as:

$$H = \frac{4V}{\pi D^2} = 1.4m$$

Volumetric Loading: A working slurry height (h_s) of 0.90m was held constant to sustain constant methanogenic activity, giving a total of slurry volume of about 143L. This gives a gas headspace height (h_g) of 0.5m for accumulation:

$$H_g = H - h_s = 1.4m - 0.9m = 0.5m$$

Daily Feeding Rate: Based on a 1.5% volumetric loading rate for small-scale reactors, the daily feed volume (V_{feed}) is calculated as:

$$V_{feed} = 0.015 \times 0.22m^3 = 0.0033m^3$$

Component Specifications

To prevent mechanical failure or process inhibition, component dimensions were specified as follows:

Inlet and Outlet Pipes: The feed inlet was designed to use PVC pipe of 50mm in diameter to ensure that fibrous sawdust, water hyacinth residues are not blocked.

Gas Outlet System: L-shaped design: A vertical entry section of 130mm, which sticks into the headspace was used. This design is used as a physical prevention of slurry splashing or entraining moisture in the gas line during peak production.

Gas Purification (Scrubbing Unit)

In the gas line, a special dual-compartment purification system was installed to improve the quality of fuel. The initial chamber has water that eliminates soluble impurities in water and hydrogen sulfide (H_2S). The second chamber contains silica gel and a sponge to absorb any water vapor and fine particulates to leave a clean dry gas to burn efficiently.

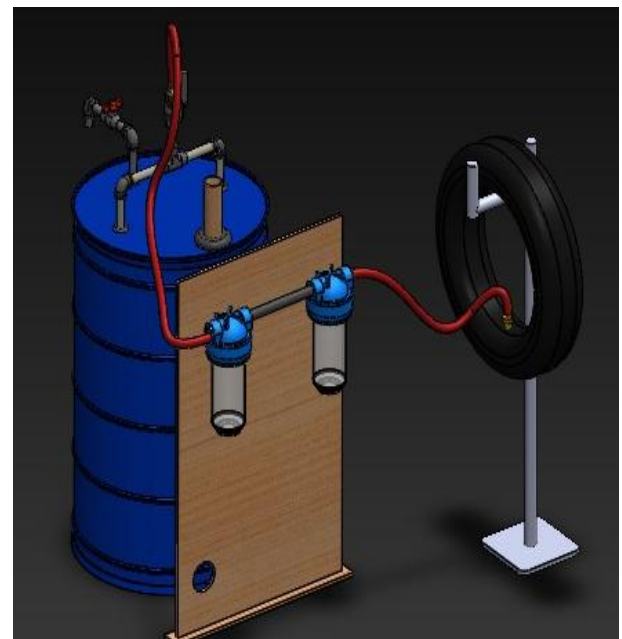


Fig. 1 (Sketch): A Sketch of the Digester Design

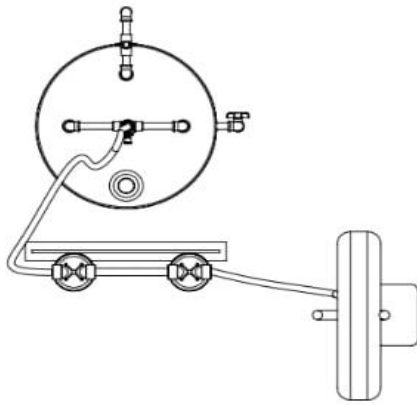


Fig. 2: Orthographic Projection of the digester (Plan view)

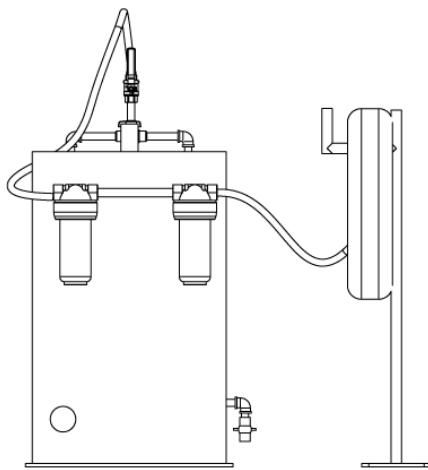


Fig. 3: Orthographic Projection of the digester

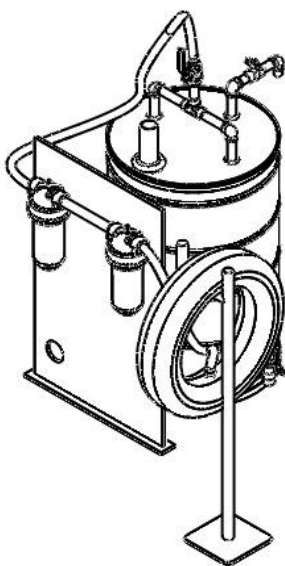


Fig. 4: Isometric view of the digester design

Feedstock Collection and Preparation

The collection of substrates was done around the University of Ibadan campus and local markets. The pig manure was homogenised in order to eliminate unwanted substances such as sand, small stones, and non-organic contaminants. Water hyacinth was harvested from the University dam. The freshly harvested plants were cut into 2-5 cm to enhance microbial accessibility. The *Gmelina arborea* sawdust was collected, air dried and sieved to remove shavings and obtain a homogenous particle size of <1.0mm. This specific particle size was selected to maximize the surface area available for microbial hydrolysis while maintaining the structural stability of the slurry. The standard sieve size used was 1.0mm sieve.

The feedstocks were combined in the proportion of 4:2:1 (pig dung: water hyacinth: sawdust). This specific ratio was adopted based on the work of Ona *et al.* (2022), who optimized biogas production through the co-digestion of sawdust and piggery dung, and Ngan *et al.* (2016), who demonstrated that mixing water hyacinth with animal manure in similar ratios significantly improves methane yield by balancing the carbon-to-nitrogen (C/N) ratio. The mixture was then blended with water to obtain a homogeneous slurry. The digester was hermetically closed and it was subjected to ambient conditions. The production of gas was detected after an 18-day retention period.

Experimental Setup and Mixing Ratios

The study experimental design was based on the optimization of the biochemical environment of methanogenic archaea by blending of key substrates. A volume-based mixing ratio of 4:2:1 (pig dung: water hyacinth: sawdust) was taken to overcome the natural constraints of the mono-digestion. This particular proportion was selected to give a synergistic ratio between the high nitrogen content and microbial richness of pig manure, readily

biodegradable carbohydrates of water hyacinth and the high carbon content of the *Gmelina arborea* sawdust. The combination of these three feedstocks was expected to respond to a good ratio of carbon to nitrogen (C/N), which is necessary to eliminate the inhibition of ammonia, while maintaining a constant source of energy to support the metabolic activities of the microorganisms. The use of volume-based ratios, rather than mass-based measurements, was a deliberate methodological choice necessitated by the heterogeneous nature of the substrates and the practical constraints of field and laboratory conditions. This method guaranteed the uniformity and repeatability of the experiment throughout the loading stage. The preparation stage included the addition of clean water to the mixed substrates gradually and stirring the mixture constantly. This was repeated until a consistent, semi-liquid slurry was obtained and this was essential in ensuring that the mixture passed through the inlet pipe (50 mm diameter) smoothly and also to avoid blockage on the inside. The physical arrangement was to fill the prepared slurry in the 220-litre cylindrical reactor until it had taken about 2/3 of the total volume. The loading rate was calculated to have a free headspace of 0.50 m where the generated biogas could accumulate. After loading, the L-shaped gas outlet and the feeding funnel, as well as the rest of the joints and components, were hermetically sealed using industrial-grade adhesive to ensure that the conditions were completely oxygen-free to ensure the process of methanogenesis. The whole system was run at ambient mesophilic conditions, and the digestion process was monitored daily for 18 days until stable biogas production was confirmed.

Analytical Methods and Gas Characterisation

Gas Chromatography-Mass Spectrometry (GC-MS)

To determine the precise chemical composition of the generated biogas, samples were harvested from

the digester outlet using airtight gas sampling bags to ensure purity and prevent external contamination. A Varian 3800 /4000 gas chromatograph mass spectrometer (GC-MS) was used to analyse the samples. The instrumental setup was Agilent DB5ms capillary column, which had a length diameter of 30.0mm x 0.25mm. Nitrogen which was of high purity was the carrier gas and this was kept at a fixed flow rate of 1.51 ml/min. The GC column oven analytical temperature program was set to start with an initial temperature of 70°C and reach a maximum of 250°C and increase steadily with a constant rate of 10°C/min. Finally, the retention times and spectral data were used to confirm the presence of a particular identified chemical compound.

Performance Validation Tests

The qualitative burning properties and the quantitative thermal efficiencies of the generated biogas were determined by conducting a set of standardised tests. The first test was a flammability test in which a standard biogas burner was used to observe and record the colour, stability and intensity of the flame to ensure sufficient methanogenesis and efficient combustion (Manesh *et al.*, 2020).

Thereafter, a water boiling test was conducted as a practical thermal analysis to ascertain the heating capacity of the system; this entailed finding out the exact time it took to elevate the temperature of 2 litres of water to a noisy boiling temperature say of about 100°C under normal conditions. This test was modelled after the standardised Water Boiling Test (WBT) protocol frequently used in biomass and biogas cookstove evaluations to determine thermal efficiency and performance of fuel.

RESULTS AND DISCUSSION

Characterisation of the Fabricated Digester

The construction of the 220-litre digester successfully maintained the required anaerobic

conditions throughout the retention period. The use of polyethylene provided high durability and corrosion resistance against the acidic intermediates produced during the early stages of digestion. The L-shaped gas outlet design proved effective, as no slurry intrusion or moisture blockage was observed in the gas line during the peak production phase.



Fig. 5: The fabricated Reactor



Fig. 6: The Fabricated Anaerobic Digester

Substrate Characterisation and Synergy

The complementary chemical properties of the residues were used in selecting the residues. Although there was no determination of specific laboratory values of the samples, reference values of the used residues are given in Table 3.1 to justify the mixing ratio.

Table 3.1: Physicochemical Properties of the Raw Residues

Residue	Moisture Content (%)	Total Solids (%)	Volatile Solids (% of TS)	C/N Ratio	References
Pig Manure	>70%	15-25%	70-80%	15-20	Silva <i>et al.</i> (2025); Cai <i>et al.</i> (2021)
Water Hyacinth	90-95%	5-10%	70-80%	20-30	Ngan <i>et al.</i> (2016); Oduor <i>et al.</i> (2022)
Gmelina Sawdust	Low (Air-dried)	85-90%	85-90%	High	Adenaiya (2021); Ona <i>et al.</i> (2022)

The digestion process and yield of methane were greatly affected by the physicochemical properties of the chosen residues (Table 3.1). Although Gmelina arborea sawdust and water hyacinth were very important sources of carbon, the moisture and lignocellulosic nature of these sources required co-digestion with pig manure (which is rich in nitrogen). The substrate blend was optimally mixed by introducing a volume based ratio of 4:2:1, which created a synergetic balance with the aim of

achieving a carbon to nitrogen (C/N) ratio of 20:1 to 30:1. This ratio played a crucial role in reducing ammonia inhibition by the pig manure and enough energy to support the metabolic processes of the methanogenic archaea.

Biogas Composition and Chemical Analysis

The Gas Chromatography-Mass Spectrometry (GC-MS) analysis provided a high-resolution profile of

the produced biogas, identifying twelve distinct compounds.

Methane (CH₄) and Carbon Dioxide (CO₂)

Concentrations

The main energy carrier was methane, which was determined as 65.58 wt%. This concentration is significant as it exceeds the 60% threshold typically required for efficient domestic combustion (Kadam *et al.*, 2024; Kabeyi and Olanrewaju, 2022). The second most common gas was carbon dioxide 29wt%. The high level of methane production reflects the synergy effects of co-digestion of various feedstock. Pig manure was important as it contributed to a strong microbial consortium and a high buffering capacity due to the presence of the ammonium compounds that enabled the system to

effectively oppose pH decline during the initial acidogenic phases of digestion (Xie *et al.*, 2022; Lourenço *et al.*, 2025).

In addition, water hyacinth contributed an easily biodegradable carbohydrates that increased the early stage of hydrolysis which often becomes the rate limiting reaction in the anaerobic metabolism (Ngan *et al.*, 2016; Onthong *et al.*, 2023). Finally, *Gmelina arborea* sawdust was a key carbon source, which was able to offset the nitrogen-rich pig manure to achieve the highest balance of carbon to nitrogen (C/N) ratio which would promote the metabolic activity of the methanogenic archaea and maximize the production of gases (Ona *et al.*, 2022; Nkuna *et al.*, 2022).

Table 3.2: Results of the Analysis

Peak #	Compound Detected	Mol. Formula	Molecular Wt.	Peak Area %	Comp (% wt)
1	Hydrogen	H ₂	2	6.14	0.19
2	Water vapor	H ₂ O	18	2.63	0.12
3	Ammonia	NH ₃	20	6.58	0.08
4	Nitrogen	N ₂	28	8.77	4.03
5	Methane	CH ₄	16	18.86	65.58
6	Carbon monoxide	CO	28	1.75	0.54
7	Oxygen	O ₂	32	14.91	0.69
8	Carbon dioxide	CO ₂	44	17.54	28.29
9	Hydrogen sulfide	H ₂ S	34	12.28	0.07
10	Ethane	C ₂ H ₆	30	5.26	0.13
11	Dimethyl sulfide	C ₂ H ₆ S	64	4.39	0.21
12	Sulphur Oxide	SO ₂	64	0.88	0.03

The analysis of small gaseous compounds provides important information about the metabolic stability of the biochemical pathways of the digester. An example is the fact that 0.19 wt% of hydrogen was detected which indicates that it was utilized effectively by the hydrogenotrophic methanogens (Sun *et al.*, 2025; Xie *et al.*, 2022) and indicates the

existence of a strong syntrophic bond between the different microbial populations (Ostos *et al.*, 2024; Jourdain and Gu, 2025). The most prevalent non-digestive gas of 4.03 wt% was probably carried in as a result of minor air intrusion during feedstock loading or gas sampling; though this feedstock results in minor dilution of the calorific value of the

biogas, the presence of nitrogen is acceptable and safe at moderate values. Moreover, 0.08 wt% ammonia concentration at the end of the reaction proves that the substrate mixture was effective in preventing the ammonia inhibition that often occurs during the mono-digestion of nitrogen-rich animal

manures. Finally, the trace level of hydrogen sulphide (H_2S) at 0.07 wt% indicates not only the low-sulphur content of the selected feedstocks but also confirms the practical effectiveness of the dual-compartment water filter in purifying the end-product gas (Abubakar, 2022; Ajieh *et al.*, 2020).

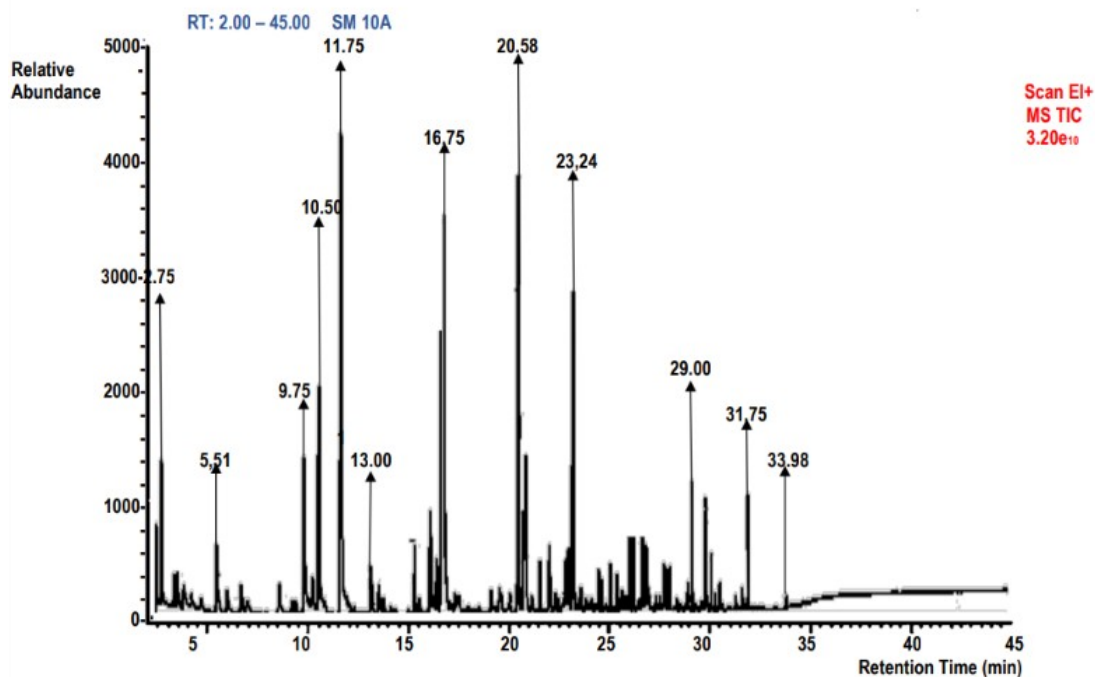


Fig. 7: Gas Chromatograph of the Biogas produced

Performance and Thermal Validation

Flammability test

Upon ignition, the biogas produced a steady, bluish flame. The absence of yellow or sooty tips indicates complete combustion and high methane purity (Manesh *et al.*, 2020; Odejobi *et al.*, 2022). The stability of the flame, without flickering or blow-off, confirms that the 0.50 m gas headspace provided sufficient pressure for consistent delivery.

Thermal Efficiency: Water Boiling Test

A standardized water boiling test was carried out to determine the thermal efficiency as well as the practical heating performance of the produced gas. In this evaluation, the water reached its boiling point of approximately $100^{\circ}C$ in exactly 12 minutes which proves that the level of methane

concentration was high enough to provide us with thermal energy that could be used (Manesh *et al.*, 2020; Ajieh *et al.*, 2020). The results, recorded in ambient environmental conditions, without the fluctuation of flames, properly confirm the effectiveness of the system in the operational adaptation to the real-life domestic cooking conditions (Odejobi *et al.*, 2022; Kabeyi & Olanrewaju, 2022).

Economic Evaluation and Affordability

One of the key aspects of the creation of the fabricated system is its affordability in resource-limited environments. The overall fabrication price was less than traditional metallic or fixed-dome concrete digesters by using locally available, recycled and inexpensive materials.

Table 3.3: Bill of Engineering Measurement and Evaluation

S/N	Description of material	Quantity	Unit	Cost (Naira)
1	220-L cylindrical polyethylene drum	1	No.	30,000
2	ϕ50mm PVC pipe	1	Length	2500
3	ϕ20mm PVC pipe	1	Length	2,500
4	ϕ63mm PVC pipe	1	Length	5,500
5	ϕ32mm PVC pipe	1	Length	3,000
6	Dual-compartment scrubbing unit	1	Set	16,000
7	ϕ8mm flexible rubber gas hose	1	No.	2,000
8.	Used tyre tube	1	N0.	20,000
9	Adhesives and sealants	2	Tins	6,000
10	Filter Media (Silica gel/Sponge)	1	Pack	7,000
Total Fabrication Cost				94,500

CONCLUSION

An anaerobic digester suitable for co-digestion of organic residues was designed and constructed. Anaerobic co-digestion of pig manure, water hyacinth and sawdust 220-L biodigester yielded a high-quality biogas containing a methane concentration of about 66%. The experiment validates that co-digestion is a more stable process that facilitates fuel performance as opposed to

mono-digestion. This system is affordable and can be deployed in the rural and small-scale use in residue management and renewable energy production. It has been shown that transforming invasive aquatic weeds (water hyacinth) and timber industry residue (sawdust) into energy is a feasible approach toward circular resource management. Such decentralized approach will decrease the use of fossil fuels and create a cleaner substitute to firewood, which can reduce indoor air pollution in the rural environment.

Conflict of Interest: None

Ethical Approval: None

Funding: None

CRedit Author Statement: Tolulope E. Kolajo: Conceptualisation, Design, Supervision, Analysis, Writing-Review and Editing; Olayinka P. Makinde: Design, Construction, Experimentation, Writing-Original Draft.

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