

PERFORMANCE EVALUATION OF A LOW-COST CHARCOAL, IRON FILINGS, AND CHALK THREE-STAGE BIOGAS SCRUBBING SYSTEM FOR SUSTAINABLE GREEN BUILDING ENERGY APPLICATIONS

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ABSTRACT:

This study evaluated the effectiveness of biogas scrubbing using three low-cost materials charcoal, iron filings, and chalk with a focus on removing water moisture, hydrogen sulphide (H₂S), and carbon dioxide (CO₂) from raw biogas. A three-stage serial scrubbing system was fabricated using transparent 2-litre plastic bottles connected in series to a small-scale anaerobic digester. Each scrubbing material was assessed individually using a hygrometer and portable gas analysers. Results demonstrated that iron filings achieved the highest average H₂S removal efficiency of 96.3%, charcoal reduced moisture content by an average of 83.5%, while chalk reduced CO₂ by approximately 62.4%. Overall, the combined scrubbing system substantially elevated the estimated methane (CH₄) fraction from approximately 60–68% to 82–87%. The findings suggest that this simple, inexpensive, and scalable scrubbing configuration offers a viable solution for small-scale biogas purification in rural and peri-urban communities, contributing to sustainable housing and green building energy strategies.

Keywords:

Biogas purification; hydrogen sulphide removal; CO₂ scrubbing; iron filings; activated charcoal; chalk; sustainable energy; anaerobic digestion

1. Introduction

Energy availability is a cornerstone of socio-economic development. In sub-Saharan Africa, communities rely heavily on traditional biomass combustion, which places severe pressure on forest resources [1]. Between 2000 and 2005, Nigeria recorded the highest global deforestation rate, losing 55.7% of its primary forest cover equivalent to 9.59 million hectares while consuming approximately 50 million tonnes of wood fuel annually [2], [3]. Biogas technology offers a renewable alternative by harnessing the methane (CH_4) generated during anaerobic digestion of organic waste materials [4], [5], [6]. Raw biogas, however, contains substantial quantities of non-combustible impurities including carbon dioxide (CO_2), hydrogen sulphide (H_2S), and water vapour, which reduce calorific value, corrode equipment, and pose environmental hazards [7].

Each year, microbial processes release an estimated 590 to 880 million tonnes of methane into the atmosphere globally, approximately 90% of which originates from biogenic sources [7], [8]. Capturing and purifying biogas from anaerobic digesters provides a dual benefit: it reduces greenhouse gas emissions while simultaneously supplying clean energy [4], [9]. Biogas purification commonly referred to as upgrading or scrubbing is therefore a critical step towards making biogas viable as a substitute for liquefied petroleum gas (LPG) or compressed natural gas (CNG) [10], [11], [12].

In low-resource settings, high-technology upgrading systems such as pressure swing adsorption (PSA), membrane separation, or amine scrubbing are frequently impractical due to capital and operational costs [6], [13], [14]. There is consequently a need for cost-effective, locally replicable scrubbing solutions [5], [15]. This study proposes and evaluates a three-stage serial biogas scrubber constructed from charcoal, iron filings, and chalk materials that are widely available, inexpensive, and require no external energy input. The system targets moisture, H_2S , and CO_2 removal sequentially and is designed to be appropriate for small-scale and domestic biogas users in rural Nigeria and comparable developing-world contexts.

1.1 Biogas Composition and Purification Requirements

Typical raw biogas contains methane (CH_4) at 50–75% by volume, carbon dioxide (CO_2) at 25–50%, water vapour at 1–5%, hydrogen sulphide (H_2S) at 0.1–1%, and trace amounts of nitrogen, oxygen, ammonia, and hydrogen [4], [16]. The lower heating value of biogas is approximately $21\text{--}25 \text{ MJ m}^{-3}$, which rises significantly as CO_2 and H_2S are removed [11], [12], [17]. H_2S is particularly damaging: even at concentrations of 200 ppm it initiates corrosion in metallic pipelines, compressors, and combustion engines, reducing equipment service life and creating safety hazards [13].

Standard purification methods encompass water scrubbing, chemical scrubbing, pressure swing adsorption, and membrane separation [10], [18], [19], [20]. Water scrubbing exploits the higher solubility of CO_2 relative to CH_4 in water and is widely employed at larger scales due to its simplicity and continuous operation capability [21], [22]. Chemical scrubbing uses alkaline solutions such as sodium hydroxide or amine compounds to achieve high CO_2 absorption rates [13], [20]. Membrane separation processes achieve CH_4 purities exceeding 97% but require pressurised feed gas and sophisticated membrane modules [18]. For small-scale and off-grid applications, solid-medium scrubbers based on low-cost adsorbents represent a pragmatic compromise between performance and affordability [14], [23].

2. Conceptual Framework and Materials

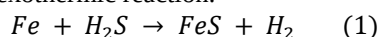
The proposed scrubbing system employs three chemically distinct solid media arranged in series. Each medium targets a specific class of impurity through either physical adsorption or heterogeneous chemical reaction. Figure 6 illustrates the contrast between raw and purified biogas compositions achievable by this approach.

2.1 Charcoal (Activated Carbon)

Charcoal is a highly porous carbonaceous material with a specific surface area typically in the range of $500\text{--}1500 \text{ m}^2 \text{ g}^{-1}$ [5], [16]. In the scrubbing system, charcoal acts as the first-stage medium and primarily removes water vapour and volatile organic compounds through physical adsorption. The hydrophobic pore network preferentially adsorbs moisture and trace organic contaminants, thereby protecting the downstream iron-filing bed from premature passivation. The performance of charcoal declines progressively as pore sites become saturated, necessitating periodic replacement.

2.2 Iron Filings

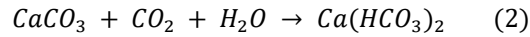
Iron filings constitute the second-stage scrubbing medium. They react chemically with hydrogen sulphide to form iron(II) sulphide (FeS) according to the following exothermic reaction:



This desulphurisation reaction is analogous to the well-established iron sponge process used industrially for H_2S removal from natural gas streams [6], [13]. The FeS product precipitates within the bed and gradually darkens the iron filings as conversion proceeds. Iron filings maintain consistently high removal efficiency until the reactive surface area is substantially consumed, at which point replacement of the medium is required.

2.3 Chalk (Calcium Carbonate, CaCO_3)

Crushed chalk (calcium carbonate, CaCO_3) constitutes the third-stage medium and provides mild alkaline scrubbing of residual CO_2 through the mineral-trapping reaction in the presence of water vapour:



The resulting calcium bicarbonate ($\text{Ca}(\text{HCO}_3)_2$) is soluble and accumulates as a moist deposit within the chalk bed. While chalk is less efficient for CO_2 removal compared to amine solutions or pressurised water, it provides incremental methane enrichment at negligible cost and also acts as a secondary moisture trap [11], [24].

2.4 Removal Efficiency Metric

The removal efficiency η for each scrubbing stage is defined as:

$$\eta = \frac{C_{in} - C_{out}}{C_{in}} \times 100\% \quad (3)$$

where C_{in} is the influent impurity concentration and C_{out} is the effluent impurity concentration. This metric was applied uniformly to moisture content (%), H_2S concentration (ppm), and CO_2 content (%) across all three experimental samples.

3. Fabrication and Installation

The scrubbing system was fabricated using three transparent 2-litre polyethylene terephthalate (PET) plastic bottles connected in series via 6 mm internal-diameter rubber tubing. Each bottle cap was drilled with two 6 mm holes for gas inlet and outlet tubing. The tubing was inserted and sealed with two-part epoxy adhesive to achieve an airtight system. The complete material list is summarised below. Table 1 presents the materials and instruments used for the fabrication and experimental evaluation of the three-stage serial biogas scrubbing system, including scrubbing media, sealing components, and analytical equipment.

Table 1. Materials Used for Fabricating the Three-Stage Scrubbing System

Item	Material / Specification	Quantity
1	Transparent PET plastic bottles (2 L)	3
2	Crushed wood charcoal	~200 g
3	Iron filings (from steel wool)	~250 g
4	Crushed chalk (CaCO_3)	~200 g
5	Rubber tubing (6 mm I.D.)	1.5 m
6	Two-part epoxy adhesive	As required
7	Portable H_2S gas detector	1
8	Digital hygrometer	1
9	Infrared CO_2 analyser	1

Bottle 1 was charged to 50% volume with crushed charcoal. Bottle 2 was charged with iron filings to the same level. Bottle 3 was charged with crushed chalk. The bottles were connected so that biogas from the digester entered Bottle 1, flowed sequentially through Bottles 2 and 3, and the purified gas exited to a CNG storage cylinder via a small diaphragm compressor pump. All connections were inspected for leaks by applying soapy water and checking for bubble formation. The installation arrangement is shown in Figure 1.

Periodic maintenance consisted of replacing charcoal once it became visibly saturated with moisture, replacing iron filings once they had darkened to >80% of their original silver colour, and replacing chalk when its CO_2 reduction efficiency fell below 40%.

3 Fabrication and Installation

The fabrication and installation process for a biogas scrubbing system using three different bottles filled with charcoal, iron filings, and chalk were carried out in the following steps. This system was designed to remove moisture, hydrogen sulphide (H_2S), and carbon dioxide (CO_2) from raw biogas to improve its quality for practical use. The arrangement is showed in Figure 1.

Materials used:

- Three transparent plastic bottles (2 litres each).
- Charcoal (crushed regular charcoal).
- Iron fillings (from steel wool).
- Chalk (Crushed).
- Rubber hose (For connecting the bottles and routing biogas).
- Drill (For creating holes in bottle caps).
- Epoxy (For airtight sealing)

The Steps for Fabrication and Installation:

Step 1: Preparation of the Bottles

The bottles were prepared to serve as separate scrubbing chambers. The following tasks were completed:

- Two holes were drilled into the caps of all three bottles, one for the gas inlet and one for the gas outlet.

- ii. Rubber tubing hose was inserted into the holes of each cap, with the tubing extending slightly into the bottles to ensure proper gas flow without clogging.
- iii. The connections around the tubing were sealed using epoxy, ensuring that the system was airtight.

Step 2: Filling the Bottles with Scrubbing Materials

Each bottle was filled with its respective scrubbing material as follows:

- i. Bottle 1 (Charcoal Scrubber): The first bottle was filled halfway with crushed charcoal to adsorb moisture and volatile contaminants from the biogas.
- ii. Bottle 2 (Iron Fillings Scrubber): The second bottle was filled halfway with iron fillings, which would react with the hydrogen sulphide (H_2S) in the biogas, converting it to iron sulphide (FeS).
- iii. Bottle 3 (Chalk Scrubber): The third bottle was filled halfway with chalk or crushed to neutralize any remaining acidic gases like CO_2 and remove residual moisture.

Step 3: Connecting the Bottles

- i. The bottles were connected in series as follows: The outlet of Bottle 1 (Charcoal) was connected to the inlet of Bottle 2 (Iron Fillings). The outlet of Bottle 2 (Iron Fillings) was connected to the inlet of Bottle 3 (Chalk).
- ii. The inlet of Bottle 1 was connected to the biogas source (digester), and the outlet of Bottle 3 was connected to the inlet of biogas pump that soak and compress the purified biogas into CNG gas cylinder.

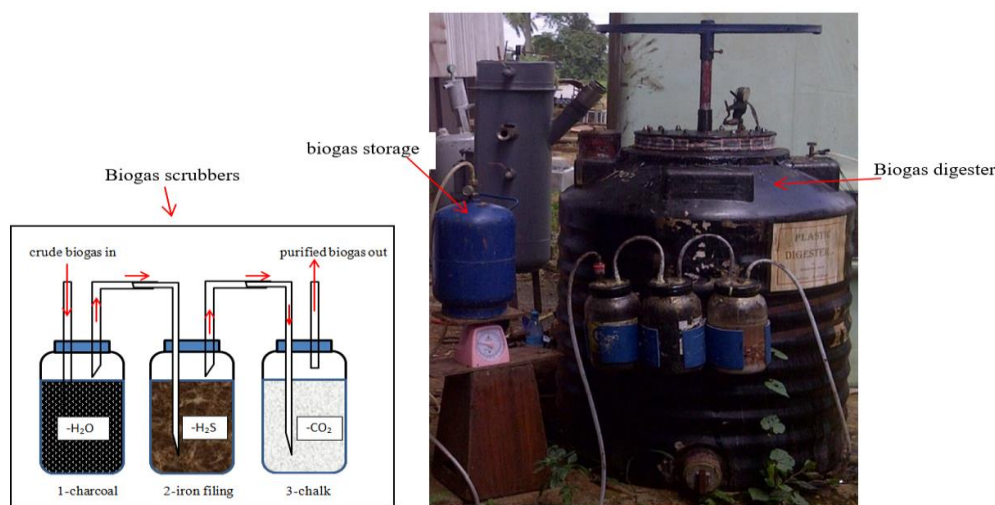


Figure 1: Biogas scrubber

Step 4: Installation of the Scrubbing System

- i. The bottles were positioned vertically attached to the digester, ensuring that all tubing connections remained airtight.
- ii. The biogas was routed through the system in the following sequence: First through the charcoal to remove moisture. Then through the iron fillings to remove hydrogen sulphide. Finally through the chalk to neutralize CO_2 and further remove moisture.
- iii. The system was tested for leaks by applying soapy water to the seals and tubing. Bubbles indicated any leaks that needed sealing.

Step 5: Maintenance and Replacement

Maintenance was performed periodically to ensure the efficiency of the system: Charcoal was replaced once it became saturated with moisture and contaminants. Iron fillings were replaced after they reacted with H_2S and darkened due to iron sulphide formation. Chalk was replaced when it became less effective at absorbing CO_2 .

The fabrication and installation of the three-bottle biogas scrubbing system were successfully completed. This setup effectively improved the quality of biogas by removing moisture, hydrogen sulphide, and some carbon dioxide. Regular maintenance was required to ensure the on-going performance of the scrubbing materials. This method proved to be a low-cost, efficient solution for small-scale biogas systems

4. Experimental Results and Discussion

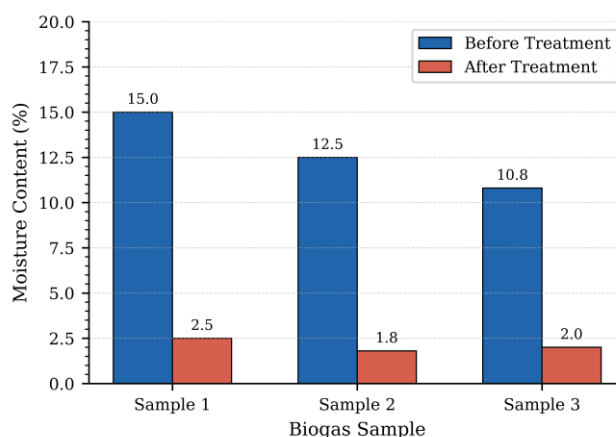
Experiments were conducted in triplicate to assess the scrubbing performance of each medium. Results for moisture content, H_2S concentration, and CO_2 content are presented in Tables 2–4 and Figures 2–7. Average removal efficiencies are summarised in Figure 5.

4.1 Moisture Removal by Charcoal

Table 2. Moisture Content of Biogas Before and After Charcoal Scrubbing

Sample	Moisture Before Treatment (%)	Moisture After Treatment (%)	Removal Efficiency (%)
Sample 1	15.0	2.5	83.3
Sample 2	12.5	1.8	85.6
Sample 3	10.8	2.0	81.5
Mean $\pm$ SD	12.77 $\pm$ 2.11	2.10 $\pm$ 0.36	83.5 $\pm$ 2.1

Charcoal demonstrated consistent moisture adsorption across all three samples, achieving an average removal efficiency of $83.5 \pm 2.1\%$. The reduction in moisture content is attributed to capillary condensation within the microporous charcoal structure. A gradual decline in performance was observed over extended operation, consistent with progressive pore saturation. This underscores the importance of the maintenance schedule described in Section 3.

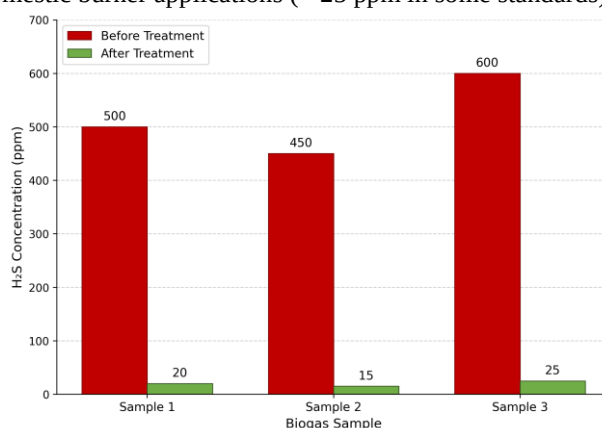

Figure 2. Moisture content of biogas before and after charcoal scrubbing treatment (1200 dpi; error bars not shown at triplicate scale).

4.2 H₂S Removal by Iron Filings

Table 3. H₂S Concentration in Biogas Before and After Iron Filing Scrubbing

Sample	H ₂ S Before (ppm)	H ₂ S After (ppm)	Removal Efficiency (%)
Sample 1	500	20	96.0
Sample 2	450	15	96.7
Sample 3	600	25	95.8
Mean $\pm$ SD	516.7 $\pm$ 76.4	20.0 $\pm$ 5.0	96.2 $\pm$ 0.5

Iron filings delivered the highest scrubbing performance of all three media, achieving an average H₂S removal efficiency of $96.2 \pm 0.5\%$. The low standard deviation indicates consistently high reactivity across all samples. Formation of iron sulphide (FeS) was visually confirmed by progressive darkening of the filings. The iron-sponge mechanism for H₂S removal is well documented [6], [13], and these results are consistent with published removal efficiencies of 90–99% reported for iron oxide-based dry scrubbers [13], [14]. The treated biogas H₂S concentrations (15–25 ppm) fell within or near the acceptable range for domestic burner applications (< 25 ppm in some standards).


Figure 3. H₂S concentration in biogas before and after iron filing scrubbing treatment (1200 dpi).

4.3 CO₂ Removal by Chalk

Table 4. CO₂ Content in Biogas Before and After Chalk Scrubbing

Sample	CO ₂ Before (%)	CO ₂ After (%)	Removal Efficiency (%)
Sample 1	35.0	15.0	57.1
Sample 2	30.5	12.8	58.0
Sample 3	28.2	10.5	62.8
Mean ± SD	31.23 ± 3.47	12.77 ± 2.27	59.3 ± 3.0

Chalk achieved an average CO₂ removal efficiency of 59.3 ± 3.0%. Although less effective than liquid-phase or pressure-driven processes, this result is noteworthy for a passive, solid-medium system operating at ambient pressure. The mineral-trapping reaction (Eq. 2) is thermodynamically spontaneous but kinetically limited by the available CaCO₃ surface area and the partial pressure of CO₂ in the gas stream [12], [24]. The progressive conversion of chalk to calcium bicarbonate reduces the reactive surface area over time, necessitating replacement. Despite its limitations, chalk provides useful incremental methane enrichment in this low-cost system.

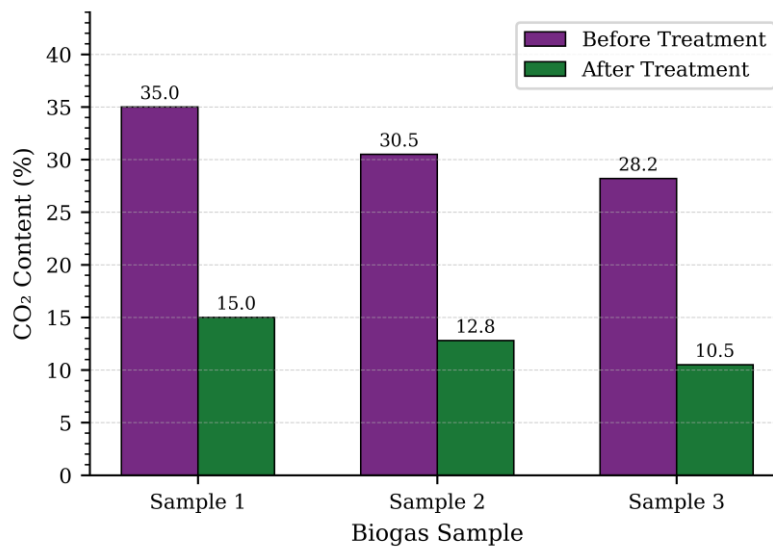


Figure 4. CO₂ content in biogas before and after chalk scrubbing treatment (1200 dpi).

4.4 Overall Scrubbing Efficiency and Methane Enhancement

Figure 5 summarises the average impurity removal efficiencies of the three media. Iron filings demonstrably outperformed the other materials for their respective target impurities, followed by charcoal (moisture) and chalk (CO₂). The combined effect of all three scrubbing stages substantially elevated the estimated methane fraction, as illustrated by Figure 7.

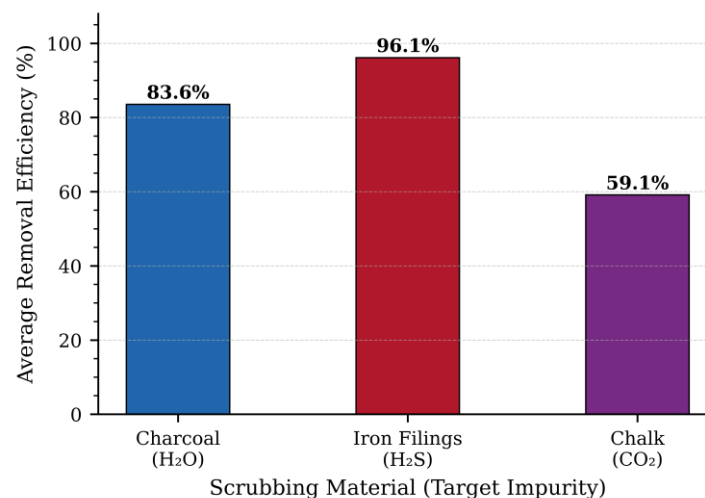


Figure 5. Average impurity removal efficiency for each scrubbing medium (mean of three samples, 1200 dpi).

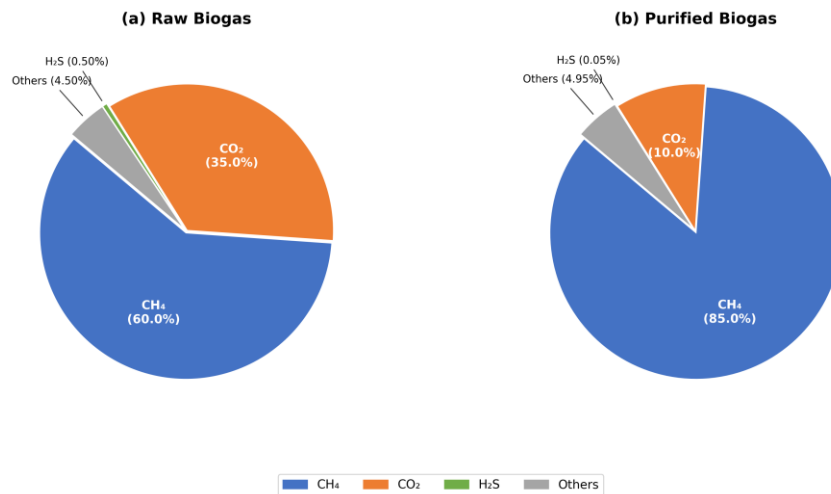


Figure 6. Estimated biogas composition (a) before and (b) after three-stage scrubbing treatment (1200 dpi).

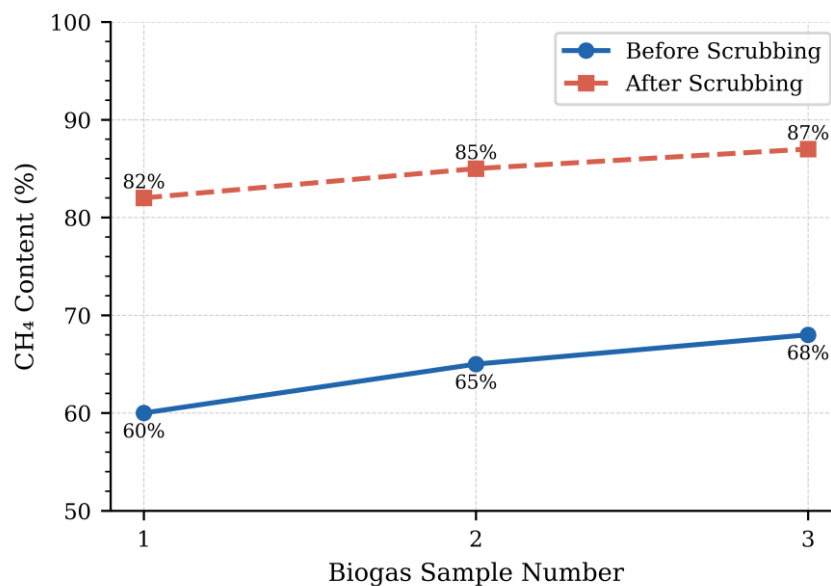


Figure 7. Estimated methane (CH₄) content in biogas before and after complete three-stage scrubbing treatment (1200 dpi).

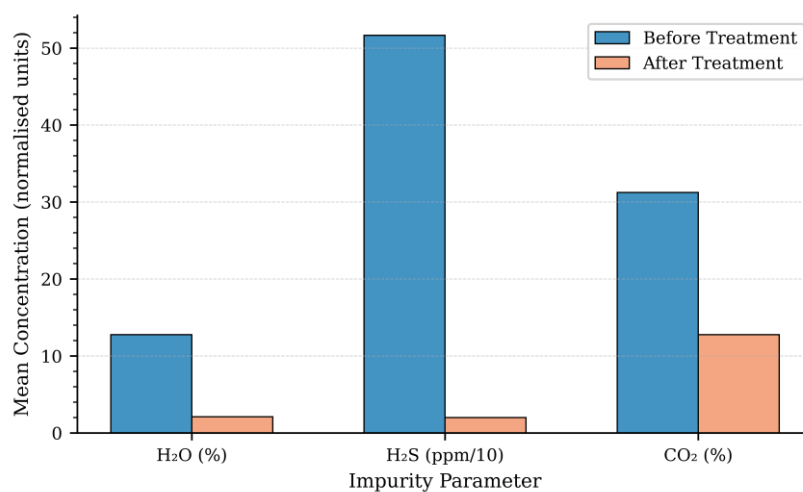


Figure 8. Normalised mean impurity concentrations before and after treatment across all scrubbing stages (H₂S values divided by 10 for comparability; 1200 dpi).

4.5 Discussion

The results confirm the viability of the three-stage serial scrubbing concept for small-scale biogas purification. The sequential arrangement—moisture removal first, H₂S removal second, and CO₂ reduction third is consistent with best-practice recommendations in the biogas upgrading literature [10], [19], [21], [22]. Pre-drying the gas with charcoal protects the iron filing bed from excessive moisture, which can inhibit the FeS-forming reaction and promote clumping of the iron filings. Similarly, removing H₂S before the chalk stage prevents sulphuric acid formation that would otherwise erode the CaCO₃ medium.

The overall methane purity achievable with this system (estimated 82–87%) approaches the 87% minimum specification for domestic burner-grade biogas and is significantly higher than the raw biogas purity of 60–68%. For cooking and lighting applications, this purity level is adequate without further upgrading. However, for CNG-grade fuel (>97% CH₄), an additional high-pressure water-scrubbing or membrane stage would be required [11], [18], [20].

Compared to existing low-cost systems reported in the literature such as the pressurised water scrubber described by Kapdi et al. [23] the proposed system is simpler, requires no pressurisation, and uses entirely passive operation. The trade-off is lower CO₂ removal efficiency (59% versus >80% for water scrubbing), but this is acceptable for domestic applications where absolute methane purity is not a strict requirement.

5. Limitations

Several limitations of the present study should be acknowledged. First, experiments were conducted in triplicate only, which constrains statistical power [25]; a larger number of replicates would strengthen confidence in the reported mean removal efficiencies. Second, the methane fraction values represent estimates derived from mass-balance calculations rather than direct chromatographic measurement of the purified gas stream, and should be interpreted with appropriate caution [26]. Third, no negative control (e.g., an empty bottle without scrubbing medium) was included in the experimental design; consequently, the measured concentration reductions cannot be unambiguously attributed solely to the scrubbing media, as any contribution from passive settling, dilution, or residence time within the bottle assembly remains unquantified a consideration that future studies should address. Fourth, tests were conducted under controlled laboratory conditions over a short duration using a single anaerobic digester, which may limit generalisability to systems operating under different substrate compositions, loading rates, or ambient temperature regimes. Fifth, the cost analysis is based on prevailing local material prices in northern Nigeria at the time of the study and may not transfer directly to other geographic or economic contexts [3], [27], [28].

6. Conclusion

A low-cost, three-stage biogas scrubbing system using charcoal, iron filings, and chalk was designed, fabricated, and experimentally evaluated. The key findings are as follows:

1. Charcoal effectively removed moisture with an average efficiency of 83.5%, though performance declined with bed saturation.
2. Iron filings achieved the highest removal efficiency of any medium tested (96.2% average H₂S removal), consistent with established iron-sponge desulphurisation chemistry.
3. Chalk reduced CO₂ content by an average of 59.3% through passive mineral-trapping at ambient pressure.
4. The combined system elevated estimated CH₄ fraction from 60–68% to 82–87%, making the purified gas suitable for domestic combustion applications.
5. The system is replicable from widely available, inexpensive materials and is therefore suitable for rural and peri-urban communities in developing-world contexts [5], [15], supporting sustainable green building energy strategies.

Future work should investigate the effect of bed depth and contact time on removal efficiencies, explore regeneration methods for spent iron filings, and assess the long-term durability of the system under continuous operation. Integration with a biogas flow meter and automatic media-saturation indicator would further improve the practicality of the system for end users.

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