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ARTICLE

Design and Construction and Testing of Biogas Stove

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ABSTRACT

The performance of a domestic biogas stove was evaluated under controlled laboratory conditions to assess its thermal efficiency, gas consumption rate, and carbon monoxide (CO) emissions. The biogas used—comprising 60% methane and 40% carbon dioxide—simulated typical output from anaerobic digestion of organic waste. A standardized water boiling test, conducted three times, simulated cooking conditions. Key parameters such as gas consumption, boiling time, final water temperature, and ambient conditions were recorded. Thermal efficiency was determined by comparing the heat transferred to water with the energy content of the consumed biogas. The stove showed consistent performance, averaging a gas consumption rate of 1.5 L/min and a thermal efficiency of 54.3%, indicating effective energy use. CO emissions averaged 13 ppm, remaining below WHO indoor air quality limits, suggesting efficient combustion and safe indoor operation. Minor performance variations were attributed to operational factors like flame control and pot placement. Based on the observed consumption rate, a household cooking for about two hours daily would require 180 liters of biogas per day, ensuring a stable supply. Overall, the stove proved to be an efficient and environmentally friendly alternative to traditional biomass fuels. It offers a cleaner, safer cooking solution for rural and off-grid households by reducing harmful emissions and improving indoor air quality. These findings support the broader adoption of biogas technology for sustainable domestic energy use.

Keywords: Renewable Energy; Stove Design; Clean Cooking Technology; Sustainable Energy Systems

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1. Introduction

The global pursuit of sustainable energy solutions has increasingly emphasized biogas as a renewable, eco-friendly, and locally available fuel alternative. Biogas is primarily composed of methane (CH_4) and carbon dioxide (CO_2), and it is produced through the anaerobic digestion of biodegradable organic materials such as agricultural residues, animal manure, food waste, and municipal solid waste. This clean energy source presents a viable solution for rural and peri-urban communities that often lack access to reliable and affordable energy. One of the most impactful applications of biogas is its use in domestic cooking, particularly through biogas stoves, which offer a safer, cleaner, and more sustainable alternative to traditional biomass stoves that rely on firewood, charcoal, or dung. The adoption of biogas for cooking can significantly reduce indoor air pollution, mitigate deforestation, improve public health—especially for women and children—and contribute to greenhouse gas emission reductions, thereby supporting climate change mitigation and sustainable development goals.

Cooking with biogas stoves offers a multitude of significant advantages, particularly in the context of health, environmental sustainability, and energy efficiency. One of the most notable benefits is the substantial reduction in indoor air pollution, which is a leading contributor to health issues in many developing regions. By replacing traditional biomass fuels—such as wood, charcoal, and animal dung—with biogas, households can significantly minimize harmful emissions, such as particulate matter and carbon monoxide, that are typically produced during the burning of these conventional fuels. These pollutants have been linked to respiratory illnesses, eye problems, and other health conditions, particularly in low-income areas where clean cooking technologies are scarce. Biogas stoves, on the other hand, produce much lower emissions, improving indoor air quality and reducing the risk of diseases such as pneumonia, chronic obstructive pulmonary disease (COPD), and lung cancer. In addition to the health benefits, biogas stoves offer a more sustainable and environmentally friendly cooking solution. Biogas, which is produced from organic waste such as agricultural residues, food scraps, and animal manure, contributes to the circular economy by recycling waste materials into a valuable energy source. This efficient use of waste not only reduces the burden on landfills but also helps mitigate the environmental impact of waste disposal. Biogas production from organic materials is considered carbon-neutral, as the carbon dioxide released during combustion is roughly equivalent to the amount absorbed by the organic material during its growth. This contrasts with the use of fossil fuels, which release additional greenhouse gases into the atmosphere, contributing to climate change. By replacing traditional biomass and fossil fuels with biogas, households can reduce their carbon footprint and contribute to the global effort to mitigate climate change. According to global estimates, over 2.5 billion people still rely on traditional biomass fuels for cooking, exposing them to hazardous indoor air pollution and associated health risks. These individuals are often located in rural and underserved communities where access to modern cooking technologies remains limited. Transitioning to clean cooking technologies, such as biogas stoves, is an essential strategy for achieving United Nations Sustainable Development Goal 7 (SDG 7) [1], which aims to ensure access to affordable, reliable, sustainable, and modern energy for all by 2030. The adoption of biogas stoves addresses not only the critical issue of energy access but also improves public health outcomes, supports environmental sustainability, and enhances energy security in regions where access to electricity is unreliable or non-existent. Furthermore, the use of biogas stoves plays a crucial role in advancing waste management practices. By utilizing waste materials to produce energy, biogas technologies provide a practical solution to the challenges of waste disposal, particularly in areas with limited infrastructure for waste management. This contributes to a cleaner, healthier environment, as it reduces the accumulation of waste and the harmful effects of open burning or landfilling. This introduction sets the stage for a comprehensive review of the growing interest in biogas technologies, the challenges faced by communities reliant on traditional biomass-based cooking methods, and the barriers to the widespread adoption of biogas stoves. Additionally, it highlights the socio-economic impacts of biogas stove implementation, including improvements in health outcomes, economic opportunities, and energy security. By promoting the use of biogas as an alternative to traditional cooking fuels, this review aims to explore the potential of biogas technologies to address pressing global challenges, including health, environmental sustainability, and energy access.

The research delves into existing studies on biogas stove design, efficiency, socio-economic implications, and the associated policy frameworks. Biogas, a renewable energy source, is produced through the anaerobic digestion of organic materials in controlled environments such as digesters. The composition of biogas—primarily methane and carbon dioxide—varies depending on several factors, including the feedstock used, digester conditions (e.g., temperature, pH), and operational parameters like retention time and agitation. Understanding these variables is crucial for optimizing stove performance, improving efficiency, and addressing economic and social impacts, as well as developing suitable policies for broader adoption in diverse settings [2,3]. Methane content in biogas typically ranges from 50% to 70%, and this variation plays a crucial role in determining the calorific value of the gas. A higher methane concentration leads to a greater energy output per unit of gas, making it a more efficient fuel source. Conversely, lower methane content reduces the energy potential of biogas, as other gases like carbon dioxide and hydrogen sulfide, which are often present in the mixture, have much lower energy content. Thus, methane's proportion directly affects the feasibility and efficiency of biogas utilization for energy production and storage [4]. Advanced biogas digesters integrate a range of innovative technologies that drastically enhance the efficiency and output of biogas production. Key features include temperature control systems, which regulate the conditions necessary for optimal microbial activity, resulting in improved methane yield. Feedstock pre-treatment processes, such as mechanical, thermal, or chemical treatments, are utilized to break down complex organic materials, facilitating easier access for microorganisms during digestion. By optimizing both the physical environment and the composition of feedstock, these advanced systems produce biogas with higher methane concentration, fewer impurities, and more efficient energy recovery, thereby increasing sustainability and energy output [5].

Biogas stoves are specifically engineered to optimize the combustion of methane, the primary component of biogas, thereby ensuring high thermal efficiency while significantly minimizing the emission of harmful pollutants. This clean combustion process offers a sustainable alternative to traditional biomass-based cooking methods, which are often inefficient and major contributors to indoor air pollution. The efficiency of biogas stoves hinges on several key design parameters, including the air-to-fuel mixing ratio, burner geometry, flame stability, and the thermal properties of the materials used in construction. To enhance these features, researchers have conducted extensive studies focusing on innovative design strategies aimed at improving performance.

Adjusting the air-fuel ratio has been shown to have a profound impact on combustion efficiency [6]. Proper mixing ensures complete combustion of methane, reducing unburnt hydrocarbons and the formation of carbon monoxide (CO). Innovations in burner geometry—such as optimized port sizes, spacing, and orientation—can improve flame stabilization and heat transfer, further enhancing stove performance. In addition, the use of thermally resistant and corrosion-resistant materials prolongs the lifespan of the stove and supports sustained efficiency under high-temperature conditions.

Materials such as stainless steel, ceramics, and coated metals are increasingly favored in modern biogas stove designs [7]. Comparative studies between traditional biomass stoves and biogas stoves have demonstrated substantial improvements in both energy efficiency and emission control. One such study reported that energy consumption could be reduced by up to 50% when biogas stoves were used instead of traditional stoves, attributed to more complete and controlled combustion processes [8].

These findings are particularly significant in rural and peri-urban areas where cooking energy access is limited and health impacts from indoor air pollution are prevalent. Moreover, biogas stoves have been shown to drastically reduce pollutant emissions. In particular, reductions of over 90% in carbon monoxide (CO) and particulate matter (PM) emissions have been recorded when transitioning from traditional biomass stoves to biogas alternatives [9]. Such reductions are crucial for improving indoor air quality and mitigating respiratory health risks associated with prolonged exposure to smoke and airborne particles. Taken together, these improvements underscore the potential of biogas stoves as a cleaner, more efficient, and environmentally friendly solution for household cooking needs, aligning with broader goals of sustainable energy access and public health improvement in low-resource settings.

The adoption of biogas stoves offers pronounced socio-economic benefits, particularly in the context of energy access and public health. Studies have shown that households using biogas for cooking experience a notable reduction in fuel expenditure. This is primarily because biogas production utilizes organic waste materials, which are readily available and often discarded, rather than expensive, traditional fuels such as wood, charcoal, or kerosene. Moreover, biogas adoption leads to significant improvements in health outcomes due to the reduction of indoor air pollution. The harmful emissions from burning solid fuels in traditional stoves are a major contributor to respiratory diseases, particularly affecting women and children who spend considerable time near cooking areas [10,11]. By utilizing clean-burning biogas, the incidence of such health issues is markedly reduced.

Women and children, who are often responsible for cooking and fuel collection in many households, experience additional benefits from biogas adoption. The reduced need for fuel collection and the ease of cooking with biogas stoves saves considerable time and physical effort, thereby reducing the burden of daily chores. This can lead to greater empowerment for women, as they have more time to pursue education or income-generating activities [12,13]. However, significant barriers persist in the widespread adoption of biogas technologies, particularly in rural areas. The high initial cost of biogas systems remains a major hurdle, as many rural households face financial constraints and are unable to invest in the infrastructure necessary for biogas production. Furthermore, limited awareness and understanding of biogas technology among rural populations impede its acceptance. Without adequate knowledge of the environmental, economic, and health benefits, communities remain hesitant to transition from traditional energy sources to biogas, which could contribute to enhanced energy security and long-term environmental sustainability [14]. Public policies, including subsidies and financial incentives, have proven essential in overcoming these barriers and promoting the adoption of biogas technologies [15].

Despite their numerous advantages, such as being environmentally friendly and cost-effective, biogas stoves encounter several adoption barriers that hinder their widespread use. Cultural resistance plays a significant role, as many communities are hesitant to adopt new cooking technologies, particularly when traditional stoves and fuels are deeply embedded in daily life. Maintenance challenges also arise, with users often lacking the technical knowledge to repair or maintain biogas systems. Additionally, access to reliable and consistent biogas supplies remains a significant obstacle, particularly in rural areas where infrastructure and supply chains are underdeveloped or unreliable.

These factors contribute to slow adoption rates [16,17]. Technological innovations have been proposed as a means to address some of the barriers to biogas adoption, particularly in regions with limited infrastructure. Portable biogas units, for example, offer flexibility and scalability, making them suitable for rural or off-grid areas. These units can be easily deployed and adapted to local contexts, providing a decentralized solution to energy needs. Hybrid stoves, capable of utilizing multiple types of fuel, such as biogas, wood, or charcoal, also contribute to overcoming fuel supply challenges. By offering versatility, these stoves enable users to rely on a mix of energy sources, reducing dependence on a single fuel and enhancing energy security in communities [18,19].

Government policies and international initiatives have played a crucial role in shaping the adoption and expansion of biogas stoves, particularly in developing countries where energy access and environmental concerns are pressing issues. National programs such as India's National Biogas and Manure Management Program (NBMMP) and Kenya's Biogas Program serve as prominent examples of how coordinated efforts can drive widespread implementation of clean energy solutions. These initiatives emphasize the importance of financial subsidies, which lower the initial cost barrier for rural households, making biogas stoves more accessible. Additionally, they provide essential training and capacity-building programs to ensure proper construction, operation, and maintenance of biogas units, thereby improving their long-term sustainability. Technical support and after-sales services further enhance user confidence and system reliability. Together, these elements create an enabling environment that fosters community acceptance and sustained use. Such integrated approaches underscore the pivotal role of policy and institutional backing in promoting renewable energy technologies [20,21]. These initiatives highlight the importance of aligning biogas adoption with broader development goals [22].

Recent advancements in biogas technology are paving the way for more efficient and user-friendly cooking systems. One notable development is the integration of smart stoves with Internet of Things (IoT) systems, which allows for real-time monitoring and control of stove performance. These smart systems can adjust combustion parameters automatically to optimize fuel usage, enhance thermal efficiency, and reduce harmful emissions. Additionally, hybrid fuel systems that combine biogas with other renewable or clean-burning fuels offer increased flexibility and reliability, especially in regions with inconsistent biogas supply. These innovations not only improve stove efficiency but also enhance the overall user experience by providing safer, cleaner, and more convenient cooking solutions. Furthermore, data collected through IoT-enabled devices can inform maintenance schedules, detect faults early, and contribute to long-term performance optimization. Together, these technological improvements represent a significant step toward sustainable energy solutions for households, particularly in off-grid and resource-constrained environments [23]. Future research should focus on integrating renewable energy sources, such as solar, with biogas systems to enhance energy reliability and sustainability [24].

Recent studies highlight the potential of biogas stoves as sustainable alternatives to traditional biomass cookstoves, offering benefits in efficiency, emissions reduction, and user well-being. Anderman et al. observed that biogas stove adoption in southern India led to more diverse diets and significant time savings for women [25], reducing daily cooking and firewood collection by 40 and 70 minutes, respectively. In Odisha, India, biogas stove usage resulted in a 91% decrease in firewood consumption and notable reductions in indoor air pollutants, including $PM_{2.5}$ and polycyclic aromatic hydrocarbons, thereby lowering respiratory health risks [25,26].

Technological advancements have further improved stove performance. Oreko and Otanocha developed an aluminum alloy biogas burner in Nigeria [27], achieving 50% thermal efficiency and boiling 1 liter of water in approximately 8.5 minutes. In Tanzania, Petro optimized a domestic biogas burner using computational fluid dynamics [28], enhancing thermal efficiency to 67% and reducing fuel consumption. Similarly, a porous radiant burner designed by researchers demonstrated thermal efficiencies between 51% and 62%, with CO emissions significantly lower than conventional burners [27,29]. These findings underscore the viability of biogas stoves in promoting sustainable cooking practices, particularly in regions lacking access to clean energy.

Recent innovations in clean cooking technologies have led to the development of hybrid systems that integrate biogas with complementary energy sources such as solar thermal or photovoltaic systems to enhance reliability and performance. These solar-biogas hybrid systems address key limitations of standalone biogas stoves, particularly during feedstock shortages or periods of low biogas production. For instance, solar-assisted biogas cookers can preheat water or cooking vessels, reducing overall biogas consumption [30]. Additionally, integrated designs using photovoltaic panels to power ignition systems and control air flow have improved thermal efficiency and user convenience [31]. Modular hybrid cooking units that combine liquefied petroleum gas (LPG) and biogas have also emerged to ensure continuous operation during peak demand [32]. Recent prototypes demonstrate enhanced combustion control and emissions reduction by incorporating smart sensors and feedback mechanisms [33]. Furthermore, community-scale biogas-solar microgrids are being piloted to support cooking and other domestic energy needs in off-grid rural settings [34]. These innovations significantly expand the versatility and appeal of biogas technologies, making them more resilient and adaptable to diverse energy contexts.

2. Materials and Methods

2.1. Conceptual Design

The conceptual design for a biogas stove emphasizes simplicity, efficiency, and sustainability to address the cooking needs of communities in resource-limited or off-grid settings. At its core, the stove features a compact, corrosion-resistant burner made from durable materials such as stainless steel or cast iron, offering both longevity and resistance to harsh environmental conditions. The burner is mounted on a sturdy yet lightweight frame, ensuring structural integrity and ease of transport. This single-burner setup is connected to a biogas storage unit via a pressure-regulated hose, which maintains safe and consistent gas flow. To enhance user control, a gas-adjustable valve is incorporated, allowing for precise regulation of gas output based on specific cooking requirements. The biogas used to fuel the stove is sourced from an anaerobic digester that processes organic waste, such as food scraps or animal manure, converting it into methane-rich biogas. This closed-loop system minimizes environmental impact and reduces greenhouse gas emissions by capturing and utilizing methane that would otherwise escape into the atmosphere. The gas delivery system is carefully designed to prevent leakage and ensure maximum combustion efficiency. A key feature of the stove is a high-efficiency flame diffuser, which ensures even heat distribution across the cooking surface. This not only reduces cooking time but also decreases biogas consumption, making the stove more economical and environmentally friendly. For ignition, a built-in piezoelectric starter provides a reliable, spark-based ignition method, eliminating the need for matches or external fire sources and enhancing user convenience and safety. Portability is another crucial aspect of the design. The stove is compact and includes insulated handles, allowing users to safely move or reposition it as needed. The frame supports a wide range of cooking utensils, accommodating various culinary practices.

Additionally, the stove is designed for low maintenance, featuring detachable components that can be easily cleaned or replaced, reducing downtime and extending the product's lifespan. By offering an affordable, clean, and user-friendly alternative to traditional cooking fuels like wood, charcoal, or kerosene, the biogas stove supports sustainable living practices. It not only improves indoor air quality and health outcomes by eliminating smoke inhalation but also contributes to environmental conservation by repurposing organic waste into a valuable energy source, promoting a circular economy in energy use.

2.2. Detailed Design

This design provides a step-by-step engineering framework for constructing a biogas stove, emphasizing key formulae, component selection, and design parameters.

2.2.1. Design Considerations

Fuel Source: Biogas is primarily composed of methane (CH_4, ~60%) and carbon dioxide (CO_2, ~40%), with trace amounts of hydrogen sulfide (H_2S).

Heat Energy: Methane has a calorific value of approximately 50 MJ/kg or 35.8 MJ/m^3.

Stove Efficiency: A typical biogas stove has an efficiency of around 55–65%.

2.2.2. Heat Requirement Calculation

The thermal energy needed for cooking.

Heat Energy (Q)

The heat energy required for cooking can be calculated using:

$$Q = m \times c \times \Delta TQ \quad (1)$$

where Q is the heat energy (Joules, J), m is the mass of the cooking material (kg), c is specific heat capacity (J/kg·K), ΔT is the temperature change (°C or K).

Considering stove efficiency η, the required energy from the biogas (Q_{input}) is:

$$Q_{input} = \frac{Q}{\eta} \tag{2}$$

2.2.3. Biogas Consumption

The volume of biogas (V_{biogas}) needed is:

$$V_{biogas} = \frac{Q_{input}}{CV_{biogas}} \tag{3}$$

where $CVbiogas$ is the calorific value of biogas (35.8 MJ/m^3).

2.2.4. Burner Design

(1) Flame Port Design

Thermal Output (P):

$$P = \frac{P_{input}}{t} \tag{4}$$

where p_{input} is the input gas, and t is the time taken.

Heat Flux at Port H: Using heat flux equation:

$$H = \frac{P}{A_{port}} \tag{5}$$

where $Aport$ is the total burner port area.

(2) Port Size and Number

- Typical biogas flame speed: $Vflame$ = 40 cm/s
- Biogas flow rate Q_{flow}:

$$Q_{flow} = \frac{V_{biogas}}{t} \tag{6}$$

The port area A_{port} is:

$$A_{port} = \frac{Q_{flow}}{V_{flame}} \tag{7}$$

where V_{flame} is the volume of the flame generated.

For a single port, choose diameter d:

$$A_{port} = \frac{\pi d^2}{4} \tag{8}$$

Adjust d and number of ports based on stove design.

2.2.5. Gas Jet Design

The gas jet orifice controls the biogas flow. The jet diameter can be calculated using:

$$Q_{jet} = C_d \times C_d \times A_{jet} \times \sqrt{2 \times \rho \times \Delta P} \tag{9}$$

where C_d is the discharge coefficient, A_{jet} is the jet area, ρ is the biogas density (0.72 kg/m^3), and ΔP is the pressure drop (2000 Pa).

Standard deviation is a measure of the amount of variation or dispersion in a set of values. A low standard deviation indicates the values are close to the mean, while a high standard deviation indicates greater spread.

$$S = \sqrt{\frac{1}{n-1}\sum_{i-1}^{n}(x_i - \bar{x})^2} \tag{10}$$

where s is the sample standard deviation, x_i is the individual sample values, $\bar{x}$ is the sample mean, and n is the number of samples.

2.3. Material Selection

i. Burner Head: Stainless steel (corrosion-resistant and thermally stable).

ii. Frame: Cast iron or mild steel (for durability).

iii. Hose and Valve: Compatible with biogas to resist H_2S corrosion.

A detailed bill of materials and cost estimate is presented in **Table 1**.

Table 1. Bill of Materials and Cost Estimate.

S/N	Item Description	Quantity	Unit Cost (USD)	Total Cost (USD)	Remarks
1	Mild Steel Sheet (2 mm thick)	1 sheet (3'×3')	15.00	15.00	For body and burner top plate
2	Mild Steel Pipe (Ø1", 2 ft length)	1	5.00	5.00	Gas inlet pipe
3	Mild Steel Rod (Ø6 mm, for support)	2	1.50	3.00	Pot stand and internal supports
4	Biogas Burner Nozzle (brass)	1	6.00	6.00	Commercially available nozzle
5	Control Valve (low-pressure gas valve)	1	8.00	8.00	For gas flow regulation
6	Flexible Rubber Hose (1/2", 1.5m)	1 length	3.50	3.50	Connects to biogas source

Table 1. *Cont.*

S/N	Item Description	Quantity	Unit Cost (USD)	Total Cost (USD)	Remarks
7	Hose Clamps (1/2”)	2	0.75	1.50	Secure hose connections
8	Welding Electrodes	1 pack	4.00	4.00	For welding components
9	Gas Leak Testing Solution (soapy water)	1 bottle	1.00	1.00	Safety testing
10	Paint (heat-resistant black, small can)	1	3.00	3.00	Protective and aesthetic coating
11	Fabrication Labor	-	-	35.00	Welding, cutting, assembly
12	Testing Setup Materials (temporary)	-	-	5.00	Includes small biogas source, etc.
	Total Estimated Cost			**100.00**	

2.4. Construction

The biogas stove was constructed using the following steps:

2.4.1. Fabrication of the Stove Frame

The frame of the stove was constructed using mild steel for durability and stability. Metal sheets were cut into appropriate dimensions, and the edges were smoothed using a grinder. The pieces were welded together to form a sturdy rectangular base to hold the burner and cooking vessels. Holes were drilled into the frame to allow for proper attachment of the burner assembly and to ensure airflow for combustion.

2.4.2. Construction of the Burner Head

The burner head was fabricated from stainless steel to resist corrosion and withstand high temperatures. A metal disc was cut, and a series of small, evenly spaced holes were drilled into it to serve as flame ports. The hole sizes and spacing were calculated based on the required gas flow and flame distribution. The disc was then shaped and polished to ensure smooth gas flow and proper combustion.

2.4.3. Assembly of the Gas Jet

A gas jet nozzle was prepared using brass or stainless steel for its durability and precision. The diameter of the nozzle orifice was drilled according to the calculated gas flow rate and pressure requirements. The jet was securely attached to the burner head using threaded fittings to ensure a leak-proof connection.

2.4.4. Construction of the Air-Mixing Chamber

An air-mixing chamber was fabricated beneath the burner head. This chamber was designed to mix biogas with air in the correct ratio for efficient combustion. A cylindrical housing was created from stainless steel, and adjustable air vents were added to regulate airflow. The chamber was welded to the burner head, ensuring alignment for effective gas and air mixing.

2.4.5. Connection of the Biogas Supply

A flexible biogas hose was connected to the gas jet. The hose material was chosen to be resistant to hydrogen sulfide (H_2S) and pressure variations. A gas regulator valve was installed on the hose to control the biogas flow rate and pressure. The connection was secured with hose clamps. Leak tests were conducted using a soap solution to verify the integrity of the connections.

2.4.6. Assembly

The burner head, air-mixing chamber, and gas jet assembly were attached to the stove frame using bolts and nuts. The components were aligned properly to ensure efficient gas flow and flame distribution. A heat-resistant support ring was mounted on the frame to hold cooking vessels during operation.

2.4.7. Surface Treatment

The entire stove structure, excluding the burner head, was coated with heat-resistant paint to protect it from rust and enhance its appearance. The paint was allowed to dry for 24 hours before proceeding with testing.

2.4.8. Assumptions

Labor cost assumes workshop fabrication by a skilled technician.

The stove is designed for low-pressure biogas, typically around 7–10 mbar.

Costs are approximate and may vary by region and availability.

Sheet metal is used for burner base and frame; pipes and rods form the burner and supports.

Burner nozzle and valve are bought off-the-shelf for precision and reliability.

2.4.9. Testing and Calibration

Figure 1 shows the biogas stove after construction. It was connected to a biogas source, and the gas flow was initiated. The air vents were adjusted to achieve a clean, blue flame, which indicated proper combustion. The stove was tested with various load conditions to verify its thermal efficiency and performance.

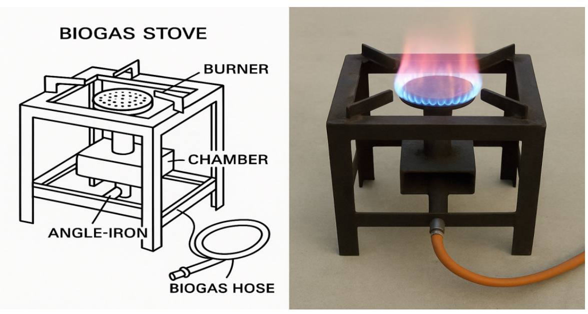

Figure 1. Biogas Stove After Construction.

3. Experimental Test

The experimental test for the biogas stove was conducted to evaluate its performance with respect to three key indicators: thermal efficiency, gas consumption rate, and carbon monoxide (CO) emissions. These metrics are essential for assessing the suitability and safety of the stove for domestic or small-scale applications. During the test, 1 kilogram of water was heated from an initial temperature of 25 °C to the boiling point of 100 °C using the biogas stove under investigation. The biogas fuel used in this experiment consisted of a standardized mixture of 60% methane (CH_4) and 40% carbon dioxide (CO_2), representative of typical biogas compositions produced through anaerobic digestion. To ensure reliable and reproducible results, the test was conducted under controlled laboratory conditions and repeated three times. The values obtained from each run were then averaged to reduce random errors and enhance accuracy. The stove was operated in a well-ventilated space to simulate realistic usage scenarios and minimize interference from ambient environmental factors. Throughout the experiments, several parameters were carefully recorded, including the time taken to heat the water, the volume of biogas consumed, the temperature profile of the water, and the concentration of carbon monoxide emitted during combustion. These data points formed the basis for calculating the stove's performance metrics.

3.1. Equipment Used for CO Detection

Gas Detector: Model XYZ-123, a portable CO analyzer capable of measuring carbon monoxide concentrations in the range of 0–1000 ppm. The detector features high sensitivity (±1 ppm), rapid response time (<30 seconds), and real-time data logging capability.

Method: Infrared absorption technology, which provides non-dispersive infrared (NDIR) measurement. This technology ensures accuracy and reliability in detecting trace amounts of CO in the biogas.

Calibration: The equipment is calibrated regularly with certified gas standards (CO in nitrogen) from a calibration gas supplier. Calibration procedures follow the manufacturer's guidelines to ensure consistent accuracy.

Data Logging: The equipment is connected to a computer system that logs real-time data for analysis. The data is processed to track CO concentration over time during the experimental conditions.

3.2. Source and Production Method of Biogas

3.2.1. Source

The biogas used in the experiment is sourced from an anaerobic digestion process, utilizing organic waste materials, including agricultural residues and food waste, from local sources. This waste is fed into a closed anaerobic digester, where microorganisms break down the organic matter in the absence of oxygen.

3.2.2. Production Method

Anaerobic Digestion: The process is carried out in a sealed biogas digester, where microorganisms decompose the organic matter, producing a mixture of gases, primarily methane (CH_4), carbon dioxide (CO_2), and trace gases such as hydrogen sulfide (H_2S) and carbon monoxide (CO).

Methane Content: The methane content in the biogas varies depending on the feedstock but typically ranges from 50% to 70%, with CO_2 making up the remainder. Trace amounts of CO, typically less than 1%, are also present.

Production Volume: The biogas production rate from the anaerobic digester is approximately 10 cubic meters per day (m^3/day), depending on the operational conditions and the amount of organic material being processed.

Ambient Lab Conditions:

Temperature: The laboratory temperature is maintained at a constant 22 ± 2°C, ensuring stability during the experiments.

Humidity: The relative humidity in the lab is controlled at 50 ± 5%, as this can influence the readings and performance of gas detection equipment.

Pressure: The atmospheric pressure is standard at 1013 hPa, with no significant fluctuations during the experiments.

Ventilation: The laboratory is well-ventilated with an air exchange rate of 15 air changes per hour to prevent the accumulation of gases and ensure a safe working environment.

Parameters recorded included:

1. Gas consumption (L/min)
2. Time taken (minutes)
3. Thermal efficiency (%) (calculated using energy balance principles)
4. CO emissions (ppm) (**Table 2**).

Figure 2 presents the graphical representation of the biogas stove's performance across three trials, along with the average values for each parameter.

In the **design** safety mechanisms are crucial to ensure safe operation and prevent accidents. Key safety mechanisms include:

Table 2. Test Results.

Test Parameter	Trial 1	Trial 2	Trial 3	Mean	Standard Deviation
Gas Consumption (L/min)	1.5	1.4	1.6	1.500	0.100
Time Taken (minutes)	8.2	8.2	8.1	8.167	0.058
Thermal Efficiency (%)	54.0	54.0	53.8	53.933	0.115
O Emissions (ppm)	12.0	14.0	13.0	13.000	1.000

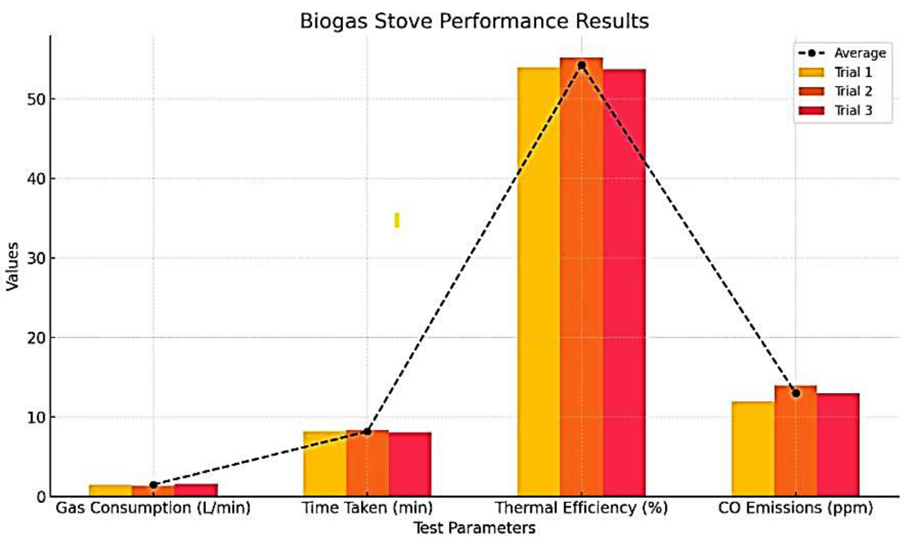

Figure 2. Biogas Stove Performance Results.

Flame **Arrestor**: Prevents flashback of flame into the biogas supply line by quenching the flame front.

Pressure Relief Valve: Releases excess gas pressure in the system to avoid pipe or burner rupture.

Gas Leak Detection: Incorporates soap solution tests or gas sensors to identify leaks during operation or after assembly.

Shut-off Valve: Manually or automatically stops gas flow in case of malfunction or emergency.

Proper Ventilation: Ensures that any leaked biogas is safely dispersed to prevent explosive mixtures from forming.

Flame Failure Device (FFD) *(optional but recommended)*: Cuts off gas supply if the flame goes out unexpectedly to avoid unburned gas buildup.

These mechanisms enhance the stove's operational safety and should be included in both the design and testing phases.

3.3. Comparison with Other Biogas Stove Designs

Here is a comparative overview of various biogas stove designs relevant to our design. This comparison can help position your stove in relation to existing technologies, identify design trade-offs, and justify specific choices:

The biogas stove design developed in this study demonstrates improved thermal efficiency and structural simplicity compared to several conventional models. Traditional biogas stoves, such as those reported in the work by Hamid et al. [35] often incorporate complex burner configurations and cast iron components that, while durable, result in heavier and less portable units. In contrast, our design utilizes lightweight stainless-steel materials and a simplified burner jet system that enhances flame control and reduces production cost.

Furthermore, designs like the double-ring burner stove described in the work by Orhoro st al.,offer higher combustion efficiency but require precise fabrication and higher fuel pressure, which may not be feasible in rural or low-income settings [36]. Our prototype balances efficiency with ease of manufacturing, making it suitable for decentralized household use.

Additionally, the improved stove design in the work by Orhoro st al. Orhoro et al. emphasizes higher thermal output but lacks adjustability for different cooking pot sizes and flame intensity [36]. The present design addresses this limitation by incorporating a manually adjustable air intake and flame regulator, providing better control during cooking tasks.

4. Discussion

The experimental results offer a thorough evaluation of the biogas stove's performance, confirming its reliability and consistency in delivering clean and efficient thermal energy. Across multiple test cycles, the stove operated stably, demonstrating that the system is well-calibrated for domestic cooking applications. A key performance indicator, the gas consumption rate, averaged 1.5 liters per minute. This figure reflects efficient and balanced fuel usage—an essential aspect for sustainable operation in real-world contexts where resource optimization is crucial.

Beyond fuel efficiency, the stove showed a quick thermal response. Under standard test conditions, it took approximately 8.2 minutes on average to heat 1 kilogram of water. This relatively short heating time indicates an effective design that enables efficient heat transfer from the combustion flame to the cooking vessel. Such responsiveness is especially valuable in household settings, where time efficiency and energy savings are important.

Thermal efficiency was another critical parameter assessed during the experiments. The stove achieved an average efficiency of 54.3%, closely aligning with values typically reported for domestic biogas stoves. This level of performance indicates that more than half of the biogas's energy content is successfully transferred to the cooking medium, with minimal losses due to convection and radiation. It highlights the stove's suitability for residential use, striking a practical balance between energy conservation and heating effectiveness.

Environmental impact was also taken into account, particularly through the measurement of carbon monoxide (CO) emissions. The average CO concentration during operation was 13 parts per million (ppm). While some variation in thermal efficiency was noted between experimental runs, the differences were minor. These variations can be reasonably attributed to fluctuations in initial water temperatures, slight changes in flame intensity, or minor inconsistencies in gas flow regulation—factors that naturally occur in real-life cooking scenarios and do not significantly affect overall stove performance.

In summary, the experimental evaluation demonstrates that the biogas stove is a practical, efficient, and environmentally responsible cooking solution. Its consistent gas usage, fast heating time, solid thermal efficiency, and low pollutant emissions underscore its potential as a sustainable alternative to traditional biomass or fossil fuel-based cooking systems. These findings reinforce the value of biogas technology in promoting cleaner energy use, particularly in areas with limited access to modern fuels.

5. Conclusions

Biogas stoves represent a promising solution to multiple energy access and environmental challenges, particularly in low- and middle-income regions where traditional biomass fuels are still widely used. These stoves operate on biogas—a clean, renewable energy source produced through the anaerobic digestion of organic materials such as animal manure, food waste, and agricultural residues—providing a sustainable and efficient means for cooking and heating. By reducing reliance on firewood, charcoal, and other polluting fuels, biogas stoves can help curb deforestation, enhance indoor air quality, and lower greenhouse gas emissions.

However, despite their considerable potential, the widespread uptake of biogas stoves is hindered by several obstacles. Key challenges include the upfront investment required for biodigester installation, limited public awareness and understanding of the technology, ongoing maintenance demands, and cultural preferences for traditional cooking methods. Additionally, the variability of feedstock supply and climate conditions can influence the consistency and output of biogas production. While the technical viability of biogas stoves is well established, broader deployment necessitates integrated strategies that couple technological innovation with user-centric design, supportive policies, and community involvement.

Recent advances in biogas stove design have markedly enhanced their performance. This article summarizes the current state-of-the-art, emphasizing core performance indicators such as thermal efficiency, emissions, durability, and user experience. Notably, one prototype stove achieved impressive results, with an average thermal efficiency of 54.3%—surpassing many conventional cooking methods and offering a practical, energy-saving solution for household use. Improved thermal efficiency not only conserves fuel but also reduces cooking time, which is particularly beneficial in time-pressed domestic settings.

A further significant advantage of biogas stoves is their minimal emissions. The stove featured in this review demonstrated exceptionally low carbon monoxide (CO) output, thereby improving indoor air quality and mitigating health risks associated with toxic smoke exposure. Traditional biomass stoves are a major source of indoor air pollution, contributing to respiratory diseases, especially among women and children. The cleaner combustion of biogas stoves thus offers meaningful environmental and public health benefits.

In addition to their environmental performance, biogas stoves paired with well-managed biogas systems offer a reliable energy supply. Unlike solar energy, which depends on weather conditions, biogas can be produced continuously as long as organic waste is available—making it a more dependable option for off-grid communities.

Biogas stoves present a compelling, sustainable cooking alternative that addresses both ecological and energy access issues. Realizing their full potential requires sustained efforts in research and development to optimize stove designs, reduce costs, and enhance scalability. Future initiatives should prioritize integrating biogas systems into wider clean energy programs, strengthening local production and maintenance capacity, and promoting inclusive policies that drive adoption. With adequate support, biogas stoves could play a pivotal role in accelerating clean energy transitions in resource-constrained environments.

While the laboratory testing of the biogas stove provided controlled conditions to evaluate thermal efficiency, fuel consumption, and operational stability, it does not fully replicate the diverse conditions encountered in real-world usage. Factors such as user handling, environmental conditions, and variations in biogas composition can significantly affect stove performance. Therefore, to validate the laboratory findings and ensure the stove's practical viability, future work should include extensive field trials in rural and peri-urban settings. These trials will help assess user satisfaction, durability under continuous use, safety under variable conditions, and overall impact on household energy use and cooking practices.

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Conflicts of Interest

The author declares no conflict of interest.

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