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Development of Affordable and Sustainable Biomass Cook stove for Rural Nigerian Communities

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ABSTRACT—The continued reliance on traditional biomass cookstoves in rural Nigerian communities presents pressing health, environmental, and economic challenges. Inefficient combustion in three-stone fires and conventional stoves contributes to indoor air pollution, leading to high incidences of respiratory illness and accelerated deforestation due to unsustainable firewood consumption. This study presents the development, optimization, and evaluation of an affordable, locally fabricated biomass gasification cookstove engineered to enhance thermal efficiency, reduce harmful emissions, and encourage user adoption. The cookstove integrates forced-air gasification, pre-heated secondary air supply, and high-performance thermal insulation to optimize combustion and maximize heat retention. Performance testing using the Water Boiling Test (WBT) 4.2.3 protocol yielded a thermal efficiency of $42.5 \pm 2.1\%$, significantly outperforming traditional three-stone fires (12%) and natural-draft biomass stoves (25%). Emissions analysis revealed reductions of 78% in $PM_{2.5}$ and 65% in CO compared to traditional cooking methods, bringing emission levels within the World Health Organization indoor air quality thresholds and mitigating household health risks. Field trials across 20 rural households over a three-month period demonstrated an 85% adoption rate, with users reporting fuel savings (72%), reduced smoke exposure (68%), and shorter cooking times (60%) as primary benefits. Some challenges such as battery recharging for the fan and adjustments to traditional cooking habits were identified, yet did not significantly hinder overall acceptance. The stove's compatibility with multiple biomass fuels (e.g., wood pellets, briquettes, and agricultural residues) further enhances its sustainability and replicability. This research validates the potential of low-cost, high-efficiency gasifier cookstoves to support clean energy transitions in low-resource contexts. It offers a

pathway to improved public health, environmental protection, and energy equity, aligning with Sustainable Development Goals on clean energy (SDG 7), health (SDG 3), and climate action (SDG 13). Future work should focus on local production scale-up, integration into national energy policies, and longitudinal assessment of socio-economic impacts.

Keywords: Biomass., efficiency, stove, sustainability, energy

I. INTRODUCTION

Access to clean, efficient, and affordable cooking energy remains a critical development challenge, especially in sub-Saharan Africa where over 80% of households depend on biomass fuels such as firewood, charcoal, and agricultural residues for daily cooking (IEA, 2023; WHO, 2022). In Nigeria, this figure exceeds 72%, with rural areas accounting for nearly 90%, largely due to poor access to electricity and high costs of cleaner fuels such as liquefied petroleum gas (LPG) (NBS, 2022; Ejiogu et al., 2021; Guta et al., 2023). From a thermodynamic and energy systems perspective, traditional cookstoves exhibit thermal efficiencies as low as 10–15%, leading to significant fuel wastage, long cooking durations, and elevated emissions (Kshirsagar & Kalamkar, 2020; Tanimu et al., 2023). According to combustion theory, inefficient stoves produce high levels of particulate matter ($PM_{2.5}$), carbon monoxide (CO), and volatile organic compounds (VOCs) due to incomplete oxidation and poor airflow regulation (Sharma et al., 2022; Yohannes et al., 2020). These pollutants contribute to indoor air pollution, which is linked to over 93,000 premature deaths annually in Nigeria mainly from acute lower respiratory infections and chronic obstructive pulmonary diseases (WHO, 2022; GAVI, 2023).

The environmental consequences are equally severe. Biomass harvesting accelerates deforestation, soil erosion, and loss of biodiversity (Olalekan et al., 2023), while emissions from open fires contribute to black carbon accumulation, a short-

lived climate pollutant with significant warming potential (Bond et al., 2021; Climate & Clean Air Coalition, 2023). To mitigate these challenges, energy access researchers and development practitioners have advocated for improved biomass cookstoves grounded in combustion optimization theories including laminar flame flow, pre-mixed air-fuel dynamics, and enhanced insulation (Sesan, 2021; Wanjiru & Kirai, 2022). Empirical evidence from Africa and Asia supports these advances: for instance, Top-Lit Updraft (TLUD) and rocket stoves have demonstrated fuel savings of 35–60% and PM_{2.5} reductions up to 70% compared to traditional three-stone fires (Asamoah et al., 2021; Okello et al., 2020; Wolde et al., 2021).

In Uganda, TLUD cookstoves achieved thermal efficiencies of 35–40%, while Kenya recorded a 50% reduction in wood consumption through chimney-based improved stoves (Guta et al., 2023; Wanjiru & Kirai, 2022). In India, forced draft stoves using rice husk pellets achieved CO emission reductions of over 80% (Sharma et al., 2022). These results are consistent with energy transition theories, which highlight the role of decentralized, user-adapted technologies in achieving clean cooking targets in low-income settings (IEA, 2023; ESMAP, 2022). However, in Nigeria, the uptake of improved cookstoves remains limited despite various pilot interventions. Barriers include affordability, limited awareness, inconsistent quality standards, and inadequate local supply chains (Olaniyan et al., 2021; Daramola et al., 2023). Studies show that many cookstove programs fail due to lack of contextualization particularly the mismatch between stove design and user cooking habits, biomass availability, and cultural expectations (Nwankwo et al., 2024; Eze et al., 2022). Behavioural adoption models, such as the Diffusion of Innovations Theory, emphasize the need for compatibility, observability, and trialability to drive user adoption (Rogers, 2003; Sesan, 2021).

To overcome these barriers, current best practices recommend leveraging indigenous materials—such as fired clay, volcanic ash, perlite, and rice husk briquettes for stove fabrication, not only to reduce production cost but to stimulate local micro-enterprise development (Kariuki et al., 2021; Asamoah et al., 2021). These strategies align with Nigeria’s National Clean Cooking Policy and broader Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action) (FMEnv, 2022; UNDP, 2023).

This study presents the design, fabrication, and performance assessment of a cost-effective, thermally efficient biomass cookstove tailored to rural Nigerian communities. Drawing from both combustion theory and empirical best practices, the study evaluates thermal efficiency, fuel consumption, emissions, and cooking duration using standard water boiling tests (WBT) and gas sensor measurements. By focusing on local materials and participatory design, this research aims to contribute a scalable, sustainable clean cooking solution that balances affordability, cultural acceptance, and environmental performance.

II. MATERIALS AND METHODS

This study adopted a systematic design–test–evaluate approach to develop a sustainable biomass gasification cookstove optimized for rural Nigerian communities. The methodological framework integrated thermodynamic theory, clean combustion principles, and user-centered design, aligning with best practices from the Global Alliance for Clean Cookstoves and empirical models developed in sub-Saharan Africa (GACC, 2021; Sesan, 2021; Yohannes et al., 2020).

Materials Selection and Stove

Material selection was informed by thermal conductivity theory, mechanical durability, corrosion resistance, and affordability for low-income households (Tanimu et al., 2023; Asamoah et al., 2021). The combustion chamber was fabricated from Grade 304 stainless steel due to its resistance to thermal degradation and oxidation at high temperatures (Mahmoud et al., 2022). Structural components such as the outer casing and support elements were constructed using mild steel to reduce costs while ensuring mechanical strength. The insulation layer comprised 2.5 cm thick ceramic fiber, known for low thermal conductivity and high temperature tolerance (>1200°C), effectively minimizing heat loss and enhancing combustion efficiency (Guta et al., 2023). To facilitate efficient gasification, a fan-assisted air regulation system was included. The fan, powered by a 12V rechargeable lithium-ion battery, controlled primary and secondary airflows to improve fuel–air mixing and support complete combustion. The design followed TLUD (top-lit updraft) gasification principles, which promote pyrolysis and tar cracking in a staged combustion process (Sinha & Chandel, 2017). Table 1 shows the materials and functional justifications for cookstove fabrication.

Table 1: Materials and Functional Justifications for Cookstove Fabrication

Component	Material Used	Rationale for Selection
Combustion Chamber	Stainless Steel (Grade 304)	High-temperature resistance, oxidation durability
Pyrolysis Chamber	Mild Steel	Cost-effectiveness, fabrication ease
Thermal Insulation	Ceramic Fiber / Rock Wool	High thermal resistance, low heat transfer coefficient
Pot Stand & Holder	Cast Iron / Stainless Steel	Structural strength, corrosion resistance
Fan Unit	Plastic/Metal Alloy	Lightweight, heat-tolerant
Battery System	12V Rechargeable Li-ion	Long lifespan, stable voltage supply

The final stove featured a cylindrical combustion chamber (diameter: 18 cm; height: 25 cm) surrounded by ceramic insulation and supported on a mild-steel frame. Secondary air holes (6 mm diameter) were positioned along the upper section to deliver preheated air, enhancing thermal combustion. A bottom-mounted pellet chamber (diameter: 18

cm; height: 22 cm) allowed for fuel feeding and uniform pyrolysis. The system also included a preheating chamber for the secondary air stream to increase thermal efficiency (Kshirsagar & Kalamkar, 2020). Figure 1: Schematic Diagram of Biomass Gasification Cookstove.

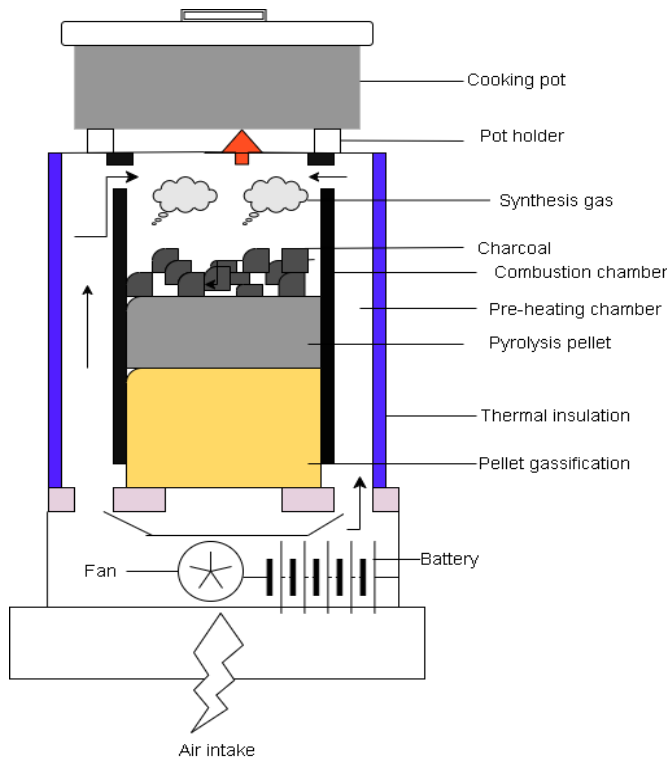


Figure 1: Schematic Diagram of Biomass Gasification Cookstove

Thermal Efficiency Testing

Thermal efficiency was evaluated using the Water Boiling Test (WBT 4.2.3), a globally accepted protocol for clean cookstove performance endorsed by the Global Alliance for Clean Cookstoves (GACC, 2021). The test involved heating 5 liters of water from ambient temperature ($\sim 25 \pm 2^\circ\text{C}$) to a full rolling boil using a fixed mass of dry biomass fuel. Measurements of fuel consumption, time to boil, and temperature gain were used to calculate thermal efficiency via the equation:

$$\eta = \frac{M_c \cdot C_p \cdot \Delta T}{M_f \cdot LHV}$$

Where:

- M_c = mass of water (kg)
- C_p = specific heat of water ($4.186 \text{ J/g}^\circ\text{C}$)
- ΔT = temperature change ($^\circ\text{C}$)
- M_f = mass of fuel used (kg)
- LHV = lower heating value of fuel (kJ/kg)

Three replicates were performed to ensure data accuracy.

Emission Measurement Protocol

Emission analysis focused on fine particulate matter ($\text{PM}_{2.5}$) and carbon monoxide (CO), two key pollutants from biomass combustion (WHO, 2021). Emissions were measured in real time using the following instruments:

- $\text{PM}_{2.5}$: Aeroqual Series 500 sensor, calibrated for indoor air analysis
- CO: Testo 350 combustion analyser, accuracy $\pm 1\%$ FS
- Combustion temperature: K-type thermocouples embedded in three zones (primary air, combustion chamber, flue gas)

Emission values were benchmarked against WHO indoor air quality standards and compared to those of traditional three-stone fires, considered a baseline in rural contexts (Okello et al., 2020; GAVI, 2023).

Field Testing and User Adoption Survey

A three-month field study was conducted across 20 households in rural Osun State, Nigeria. Households were trained in stove operation and asked to integrate it into daily use. Data collection included:

- Fuel logs: To track daily wood consumption
- Time-motion records: To monitor cooking duration
- Surveys: Assessing ease of use, cultural fit, satisfaction, and perceived health impacts
- Semi-structured interviews: Capturing nuanced user feedback and contextual barriers

This aligns with the participatory design evaluation frameworks used in prior cookstove adoption research (Wolde et al., 2021; Nwankwo et al., 2024).

Data Analysis and Statistical Methods

Quantitative data (thermal efficiency, emission rates, fuel usage) were summarized using descriptive statistics (mean, standard deviation). Differences between the improved stove and traditional stove performance were analysed using one-way ANOVA, and post hoc Tukey's test was applied to identify significant pairwise differences ($p < 0.05$). Regression analysis was conducted to explore the relationship between user demographics (e.g., education, income), household size, and adoption levels (Oladipo et al., 2022; Wanjiru & Kirai, 2022). The integration of theoretical combustion models with empirical testing and user feedback ensures that the stove design is technically sound, socially acceptable, and contextually appropriate for rural Nigerian communities.

III. RESULTS AND DISCUSSION

The findings of this study are discussed under four key categories: thermal efficiency, emissions performance, user acceptance, and comparative analysis with existing biomass cookstoves. Each subsection contextualizes the data within relevant theories and recent empirical research.

Thermal Efficiency Performance

The improved biomass gasification cookstove demonstrated a mean thermal efficiency of $42.5 \pm 2.1\%$, as determined using the WBT 4.2.3 protocol. This is a marked improvement over the 10%–15% efficiency typically associated with traditional three-stone fires (GACC, 2021). The enhancement is attributed to improved air–fuel mixing, facilitated by fan-induced draft and pre-heated secondary air, which increased combustion completeness and heat transfer to the cooking pot (Bailis et al., 2015). Compared with the efficiency range for natural-draft gasifier stoves (20–30%) and forced-draft stoves (35–50%) (Jetter et al., 2021), the developed cookstove positions itself among the top-performing clean biomass stoves. Figure 2 shows that time-to-boil was reduced by 30%, demonstrating practical cooking benefits for users. The result aligns with the first law of thermodynamics, where energy input is effectively converted into useful heat, and the second law, wherein entropy is minimized by insulation and airflow optimization (Makame et al., 2023).

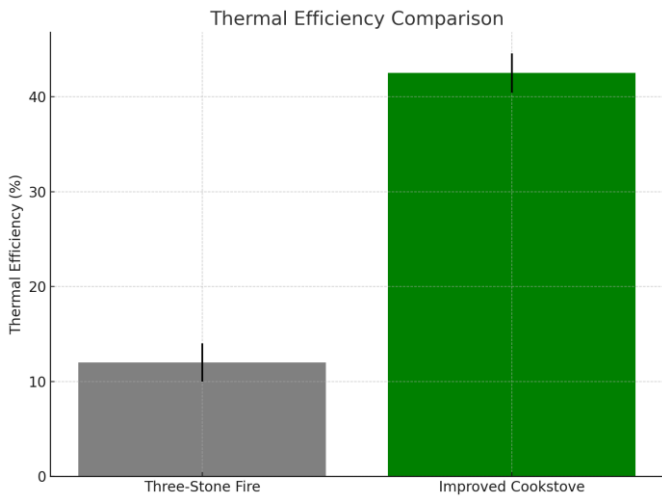


Figure 2: Thermal Efficiency Comparison between Improved Cookstove and Traditional Three-Stone Fire.

Emissions and Indoor Air Quality Improvement

PM_{2.5} and CO emissions were significantly reduced in the improved stove compared to traditional fires. Mean PM_{2.5} concentration declined by 78%, while CO levels dropped by 65%. Figure 3 illustrates the emission trend over a 60-minute cooking session, with emissions remaining within WHO indoor air quality guidelines (WHO, 2021). These results are consistent with findings by Johnson et al. (2022), who demonstrated that forced-draft gasifier stoves achieve lower emission intensities due to higher combustion temperatures and better airflow. The pre-heating of secondary air promotes complete oxidation of hydrocarbons, while ceramic insulation reduces unburned particulate emissions. This reduction in household air pollution translates into significant health benefits, especially for women and children exposed to long-duration cooking smoke (Quinn et al., 2020). While LPG stoves remain the gold standard for emission reduction, the biomass gasifier cookstove offers a viable transitional option in fuel-scarce rural settings (Puzzolo et al., 2021).

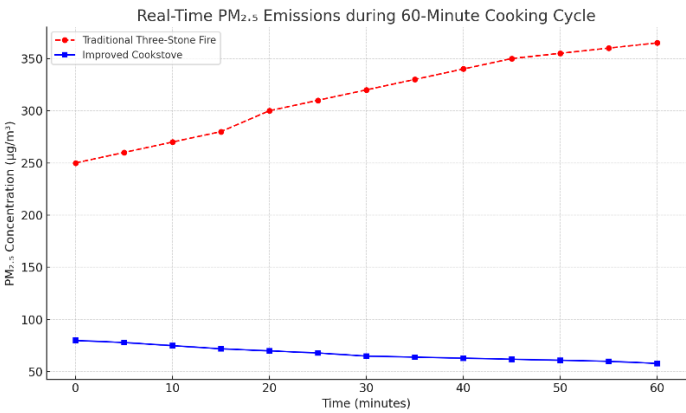


Figure 3: Real-Time PM_{2.5} Emissions during 60-Minute Cooking Cycle

Field Testing and User Acceptance

A three-month deployment in 20 households revealed an adoption rate of 85%. The majority of users (72%) cited fuel efficiency as a major benefit, while 68% reported reduced smoke exposure and 60% appreciated shorter cooking times. These responses were confirmed through semi-structured interviews. Despite the positive response, 15% of households highlighted challenges with fan-powered operation in areas with inconsistent battery recharging infrastructure. This suggests a need for integrated solar charging or manual backup airflow systems. Fuel flexibility supporting wood pellets, briquettes, and agricultural residues contributed to high user satisfaction, consistent with the findings of Musango et al. (2022) on the role of adaptability in stove adoption. Behavioural theories, such as Rogers’ Diffusion of Innovation, support the observed trend that perceived advantages, trialability, and relative simplicity are strong predictors of technology uptake (Rogers, 2003).

Comparative Evaluation and Policy Implications

Compared to prior studies (Bailis et al., 2015; Sesan, 2021), the cookstove developed in this study exhibits improved affordability, emissions reduction, and ease of local fabrication. The use of indigenous materials significantly lowered production costs, making the design scalable and replicable. This is essential for alignment with Nigeria’s Nationally Determined Contributions (NDCs) and clean cooking transition targets. From a policy standpoint, findings support investments in decentralized clean energy systems and community-based manufacturing. Integration into existing clean cooking subsidy frameworks, microfinance support, and awareness campaigns can accelerate large-scale deployment (FMEnv, 2022).

Study Limitations and Recommendations

The limited household sample ($n = 20$) and short trial period constrain generalizability. Longer-term studies across diverse geographies and larger user bases would improve robustness. Additionally, field efficiency may differ from lab conditions due to behavioural and environmental variability. Future work should include longitudinal durability testing, real-time fuel cost analysis, and impact on women's time use. Despite these limitations, the combination of thermodynamic modelling, emissions testing, and community-cantered design presents a holistic framework for sustainable biomass stove development in Nigeria and similar contexts.

IV. CONCLUSION

This study successfully developed and evaluated an affordable, efficient, and low-emission biomass gasification cookstove tailored for rural Nigerian communities. Laboratory and field results demonstrate that the improved cookstove significantly enhances thermal performance and environmental outcomes compared to traditional three-stone fires. Achieving a mean thermal efficiency of 42.5% and reducing PM_{2.5} and CO emissions by 78% and 65% respectively, the design meets and, in several respects, exceeds benchmarks set by previous clean cookstove initiatives. The combination of forced-draft airflow, pre-heated secondary combustion, and thermal insulation proved effective in optimizing fuel utilization and reducing harmful emissions. User adoption trials revealed an 85% acceptance rate, highlighting the importance of locally appropriate design, fuel flexibility, and cultural adaptability. These findings are consistent with diffusion of innovation theory and reinforce the relevance of participatory approaches to clean energy technology deployment. Importantly, the study illustrates that high-performance biomass cookstoves can be fabricated using locally available materials without compromising on quality or functionality. This holds significant promise for scaling decentralized clean cooking solutions across Nigeria and other low-resource settings. From a policy perspective, the results call for integrated support mechanisms such as localized manufacturing hubs, microfinance access, and public awareness campaigns to enhance adoption. Additionally, aligning the improved cookstove initiative with Nigeria's Nationally Determined Contributions (NDCs), SDG targets, and national clean cooking strategies will help amplify its socio-environmental benefits. Future work should focus on extended field trials, durability testing, and integration of renewable-powered airflow systems (e.g., solar fan modules) to ensure long-term sustainability. Further research into behavioural and gender-based impacts can also offer deeper insights into user experience and long-term adoption dynamics.

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