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Development of an Improved Biomass Stove and Performance Evaluation Using Three Types of Briquettes

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ABSTRACT
Background and Objective: Several works on biomass cookstove design have been published under open and controlled conditions; however, fuel efficiency and smoky emissions remained their critical challenges. Proffering solutions to these challenges requires continuous research in development of improved stoves, which remained an active aspect of stove research and development. This study, therefore, contributed additional knowledge to stove research and development through the development of a clay-lining biomass stove. Its performance was evaluated using briquettes produced from untreated, torrefied and fermented sawdust mixed with different combinations of paper binders. **Materials and Methods:** Stove design factors were taken into consideration in design, while fabrication was done using designed parameters. Stove performance evaluation was performed using standard test procedures identified in literature. The stove thermal efficiency was determined using water boiling tests (WBT) and control cooking tests (CCT). **Results:** The developed stove showed good performance with a significant reduction in smokiness. When used in burning briquettes, it shows that heat transfer per unit surface area within the combustion chamber was 3.435 kW/hr, while the stove thermal efficiencies varied between 31.47-39.89% for untreated briquettes, 17.13-38.52% for torrefied briquettes and 23.84-39.89% for fermented briquettes, respectively. The unit cost of production of the biomass stove was NGN7, 300.00 (~US$7). **Conclusion:** The decrease in stove smokiness, favourable specific fuel consumption (0.56-0.68) and thermal efficiency performance, in addition to positioning for a competitive market and favourable production costs, make it acceptable.

KEYWORDS
Biomass stove, briquette, combustion, smokiness, fuel consumption, flame propagation

INTRODUCTION
The 2030 target for the realization of United Nations Sustainable Development Goal 7 predicated on an energy tripod of affordability, reliability and sustainability[1] provided for generation of clean energy from relatively cheap and affordable sources for domestic cooking in households. The desk study review on the production and utilization of woodfuel (firewood and charcoal) in Africa further affirmed that globally, over

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3 billion people had no access to clean fuel, with an estimated 1 billion found in Sub-Saharan Africa[1]. Unfortunately, this population depended largely on wood fuel as an essential base fuel material for its energy supplies.

The global dependence on wood for domestic cooking and industrial energy needs has contributed remarkably to forest depletion at a rate of 2.5 to 3% per year[2]. Unless there is a viable alternative, an estimated 50% of the global population will continue to burn fuelwood on the 3-stone stove technology to meet their domestic cooking, which contributes about 14% of total energy use globally[3]. Nevertheless, given the growing attention focused on climate change, user comfort and improvement in fuel quality continue to drive further developments in stove technology.

There was a paradigm shift from energy growth to research and development on stove technology, with significant advancements conceivable with current engineering designs[3]. There are strong indications of progress in the utilization of firewood and charcoal in domestic cooking, production of biochar for soil amendment and carbon sequestration[4] and other energy needs with considerable increase in energy consumption per capita revolving around stove development[5]. It is inevitable that conventional stoves require modifications to burn a particular fuel to address the issues of low energy efficiency and dangerous gas emissions. An experimental study on hay and switch grass briquette emissions in a domestic wood stove suggests that the biomass can be burned in domestic wood stoves with similar performance and comparable emissions to other woody briquettes[6]. Improved cookstove (ICS) design may be energy efficient, but may not stop deforestation but rather reduce pressure on forests, facilitating sustainable f biomass fuel harvest[3,7,8].

Literature studies on the design of biomass cookstove showed advancements are ongoing to improve fuel efficiency and reduce emissions that are detrimental to the environment and smoke[9]. Concerted efforts towards improvement in cookstove technology development failed to meet up with expectations. Patil *et al.*[10], reviewed the performance of briquette cookstove. Flores *et al.*[11] reported good performances on the gradual introduction and adoption of improved cooking stoves in Honduras for domestic applications. In another study, Panwar[12] reported about 35% stove thermal efficiency from an energy efficient biomass cookstove suitable for burning different fuel wood and briquette with 3-6 ppm and 17-25 ppm CO and CO_2 emissions, respectively. Wang *et al.*[13] reported a thermally efficient and eco-friendly coal-biomass stove successfully demonstrated in Shanxi Province of China, with great potential for improving indoor air quality. Anggraeni *et al.*[14] have reported the ideal conditions and parameters for stove development, however, there is the problem of achieving full combustion through improved air-to-fuel ratios, less heat loss and proper draft in stove designs. An experimental analysis on a modified cook stove fired by bagasse briquette reported a thermal efficiency of 46.11 and 44.29% for cold phase and hot phase, respectively[15].

A comparative study of parabolic dish-type concentrator solar cooker and modified cookstove shows that the modified cookstove performed better in terms of reliability, capacity and duration of cooking, while the solar cooker is more effective in terms of emissions[15]. A continuous feed-type husk biomass cookstove developed by Kole *et al.*[16] was evaluated for clean burning under high altitude conditions in Ethiopia using coffee and rice husks in two different sized pots. The results showed an average thermal efficiency of 29% and 7.7 min boiling time for coffee husk and 28 and 8.4 min for rice husk, respectively[16]. The experiment reported an average specific fuel consumption of 98 over 115 g/L reported for improved biomass cook stove[16]. The total selling price of the husk biomass cook stove developed amounts to 6.72 USD[16].

Biomass-fired stoves have been developed as replacements for high-cost electric heaters in briquette production process[17,18]. The stove, fired with rice husk briquette heats the die barrel with satisfactory performance, saving an estimated 6 kW of electric heater. There is, therefore, an urgent need for the current efforts towards cookstove technological innovations to gain more relevance in Research and

Development (R and D) to proffer solutions beneficial to teeming global population. This study, therefore, reported the development of a biomass stove highlighting design considerations, calculations and construction and the performance evaluation firing with briquettes as fuel.

MATERIALS AND METHODS

Study area and duration of experiment: The development and experimentation were performed at the engineering workshop and thermodynamics laboratory of the Federal College of Agriculture Ishiagu, Nigeria, respectively. The duration spans 6 months, between June, 2021 and December, 2021.

Biomass stove design considerations and calculations: The major objectives of the development of the stove are to produce workable combustion equipment that has economic feasibility for the local burning of briquettes. Stove design considerations include:

- **Stove performance factors:** Performance factors such as thermal and combustion efficiencies will be enhanced by ensuring maximum heat transfer and selection of lightweight material (sheet metal) for construction
- **Smoke emission:** The design should considerably limit smoke emissions and eliminate risks associated with conventional stoves. Critical factors responsible for stove emissions include diversities of different models of wood-burning devices in use with varying draft characteristics, variable altitudes, variable fuelwood seasoning and storage conditions and wide variations in burn rate, burning time, damper setting and kindling approach

Stove fuel efficiency factors: The consumption of fuel in a stove is affected by the following factors considered during the design processes for specific applications. Some of these key elements considered in fuel consumption determination include:

- **Fuel type and characteristics:** Inherent biomass physical properties such as particle moisture, density, ash content, etc. and preparation procedure could affect the combustion characteristics, hence consumption rate. For instance, some fuels contain more energy per unit mass than others do; a common example is LPG and wood
- **Stove heat-transfer efficiency:** Heat transfer efficiency is the quantity of energy absorbed in a combustion process by the cooking pot compared to the quantity of energy released. Heat/gases transfer to the pot during fuel combustion is an important feature in stove design. Improved heat transfer mechanisms should be engaged to reduce fuel consumption. Notable heat transfer mechanisms to improve heat transfer efficiency include improvement in convection heat transfer and the stationary surface of the cooking pot or maximizing the velocity of combustion gases and pot surface area in contact with these gases

Reduced heat loss: Heat loss during cooking was due to size of combustion chamber, heat conductor material and heat insulation material. With clay lining, heat loss in the stove combustion chamber is expected to be considerably reduced.

Cost and other considerations: The developed stove will be low-cost and affordable for domestic applications. Other considerations include appropriate stove size, desirable thermal efficiency and other parameters estimated by computation.

End user factors: End user factors such as smokiness, cleanliness, attractiveness and aesthetics during cooking.

Stove description: The device (Fig. 1a) designed and constructed at the metal and fabrication workshop, Federal College of Agriculture Ishiagu, Ebonyi State has two compartments: An ash collection section and

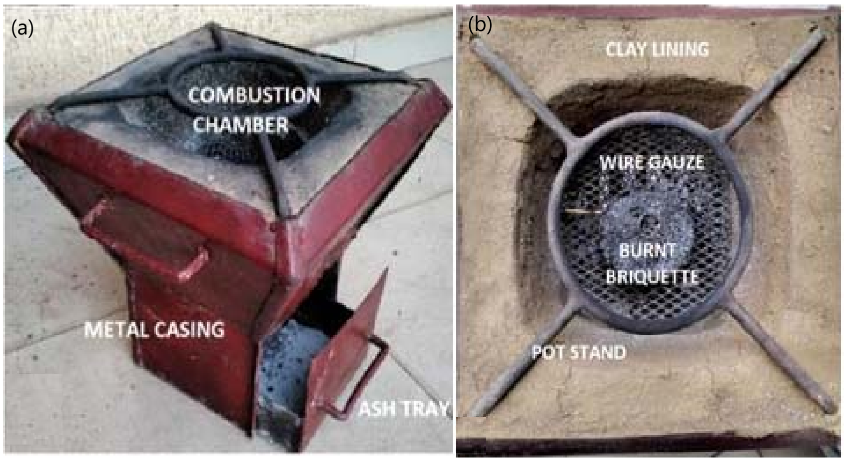

Fig. 1(a-b): Developed stove showing the configuration and combustion chamber

a combustion chamber. The combustion chamber has a clay lining. The clay lining insulated the outer mild steel plate to reduce heat loss to the environment. The main combustion chamber (Fig.1b) was separated from the secondary air inlet spout and ash compartment using a strong wire-mesh grate supported by five pieces of 6.25 mm rods embedded into the clay lining. The clay wall lining is 25 mm thick and provides insulation for the stove. The top dimensions of the combustion chamber are 486.7×135 mm and the base dimension (100×100 mm), is designed to contain 4 pieces of briquettes, 50 mm in diameter and 55 mm in height, respectively. The volumetric capacity of the combustion chamber is 518.6 cm^3. The combustion chamber was designed to contain a maximum of 4 standardized briquettes.

The grate separates the combustion chamber and the ash compartment and consists of a removable grate made of 1 mm thick wire gauze and an area of 200 cm^2. The grate is located at the base of the combustion chamber constructed of 5 mm metal rods and metal gauze to prevent fuel escape into the ashtray. The metal grate provides support for briquettes and allows the free flow of primary air and the passage of ashes produced during combustion. The briquettes are loaded on the grates, while the ashes drop into the ash container below.

The ashtray is a removable rectangular metal box with an open end to receive the ash dropping through the metal grate. An attached handle makes it easy for quick removal and disposal of the tray contents. A rectangular pot stand with a central circular ring positioned above the combustion chamber provided a rest platform for the pot and the pot stand was fabricated with a ¼-inch MS rod and has a dimension of 486.7×135 mm. A 25 mm diameter vent opened directly into the base of the combustion chamber to provide a secondary air supply by updraft during combustion. The ash compartment houses the collector with a handle to aid the easy removal of ashes from the stove. The collector was constructed of mild steel, 1 mm thick, while the handle diameter is 3.2 mm and length is 66 mm. Figure 2 shows the orthographic drawing of the stove.

Stove design equations and calculations

Combustion chamber size: The size of the combustion chamber depends on the size and the average number of briquettes burned at a time within the combustion chamber. The number of briquettes required to fill the chamber is a function of the chamber volume, area of briquette and height of briquette mathematically derived and expressed according to Bello *et al.* [5]:

$$n = \frac{V}{A.h_b} \tag{1}$$

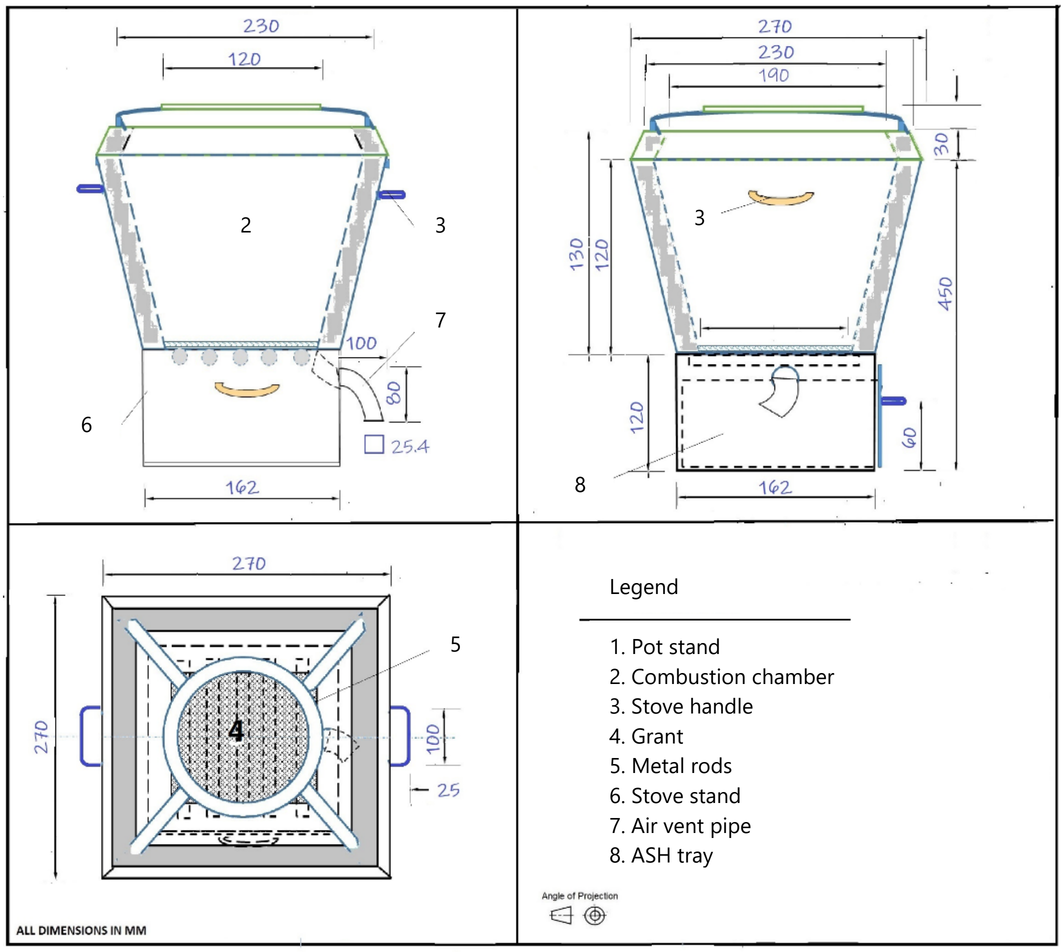

Fig. 2: Orthographic drawing of developed biomass stove

where, n is the number of briquettes required to fill the combustion chamber, A is area and V is the volume of the combustion chamber geometrically expressed by the expression according to Bello *et al.*[5]:

$$V = n.\frac{1}{3}(A_1 + A_2 + \sqrt{A_1 \times A_2})h \tag{2}$$

A_1, A_2 represent the areas of the lower and upper frustums and h is the height of the combustion chamber[5] recommended a diameter-to-height ratio of briquette of 0.75 mm i.e.:

$$d = 0.75\ h$$

Therefore:

$$n = \frac{0.75\ V}{A.d} \tag{3}$$

The combustion chamber size requires the determination of area and number of briquettes to be contained as follows.

Total area of combustion chamber:

Area of lower surface of the combustion chamber: $12.7 \times 12.7 = 161.29\ cm^2$

Area of upper surface of the combustion chamber: $15.07 \times 15.07 = 227.11\ cm^2$

Estimated height of the combustion chamber: 120.45 mm

The volume of the combustion chamber is determined:

$$V = \frac{1}{3}(161.29+227.11+\sqrt{161.29\times 227.11})\,12.45 = 2406.13\text{ cm}^3$$

Size of briquette: Area of a briquette sample:

$$A = \frac{\pi (D^2 - d^2)}{4} \tag{4}$$

where, D = 82 mm and d = 14 mm:

$$A = \frac{\pi (8.2^2)}{4} = 52.81\text{ cm}^2$$

Total number of briquettes required to fill the chamber:

$$n = \frac{0.75\times 2406.13}{52.81\times 8.2} = \frac{1804.60}{461.437} = 4.17 » 4\text{ briquettes}$$

Lining (insulation) and surface area: The material considered for insulation is clay, which is readily available and has lower heat conduction. Equation 5 evaluates the surface areas of one side of the clay lining[6]:

$$A = \frac{1}{2\,(a+b)\,h} \tag{5}$$

where, A is surface area of clay lining (m^2), a and b are lengths of lower and upper surfaces:

For four surfaces A = 4×½(a+b) h

= 4×½(12.70+15.07) 12.45 = 691.47 cm^2

Heat transfer per unit area of clay lining: Equation 6 evaluated the heat transfer per unit area of clay lining[6]:

$$\frac{q}{A} = \left(\frac{k}{s}\right) dT \tag{6}$$

where, q is heat transfer (W/hr), q/A is heat transfer per unit area (W/m^2), k is thermal conductivity of clay lining material (0.15-1.8 W/mK), dT = (T_1-T_2) = temperature difference (°C) and s is wall thickness 25 mm:

$$q = \frac{1.8}{0.025}(31-100)\times 0.69147 = 3.435\,\frac{\text{kW}}{\text{h}}$$

Airflow required for combustion: This is the airflow rate of flow required in gasification process, dependent on the stoichiometric air requirement of the fuel. The airflow rate can be computed using the expression[5]:

$$AFR = \frac{\varepsilon \times FCR \times SA}{\rho_a} \tag{7}$$

where, AFR is airflow rate, m^3/hr, is equivalence ratio, 0.3 to 0.4, FCR is fuel consumption rate, kg/hr (experimental value), SA is Stoichiometric air of fuel (for rice, SA is 4.5 kg air per kg rice husk) and r_a is air density, 1.25 kg/m^3 [5]:

$$AFR = \frac{0.4 \times FCR \times 4.5}{1.25}$$

Superficial air velocity: The speed or velocity of the airflow within the fuel, regarded as superficial air velocity was computed using the Eq. 8:

$$V_s = \frac{AFR}{\text{Area of inner combustion chamber}} \quad (8)$$

where, V_s is superficial gas velocity, (m/sec), AFR is airflow rate and (m^3/hr).

Stove grates and ashtray: There are two grates; removable and fixed grates. The removable grate is a rectangular wire mesh folded into the lower portion of the combustion chamber. The dimensions of the removable grate are length = 143, breadth = 3.5 and t = 1 mm.

The fixed grate was made from 7 pieces of 12.5 mm diameter rod of length = 120 mm each. The clearance between successive grates was 15 mm and the fixed distance between the extreme grates and stove wall was 10 mm.

The ashtray is a removable square box made of MS plate cut into the following dimensions. The t is 2 mm, length is 140 mm, breath is 140 mm and height is 50 mm. Handle length is 100 mm and the thickness is 6.25 mm.

Stove dimensions: Overall stove dimension: L = 265, B = 265 and H = 285 mm
Lower surface of the combustion chamber is L = 127 and B = 127 mm
The upper surface of the combustion chamber is L = 150.7×B = 150.7 mm
The height of the combustion chamber is 124.5 mm

Stove performance variables

Briquette ignition and burn characteristics: This was conducted by burning briquettes in free-air (i.e., open-air) and stove. For the open-air test, a set of whole briquettes placed on individual wire mesh platforms were ignited with matchsticks simultaneously following[19]. About 2 mL of supplemental kerosene was added to each briquette to support ignition until the whole briquette was covered in flame. The flame heights in each experiment were measured using a graduated paperboard placed in the background.

Ignition time: The ASTM E1321-13[20] standard test procedure was used to measure the briquette ignition time and flame spread parameters. To ensure uniformity in briquette ignite, each one was set atop a platform situated above the burner. A stopwatch was used to monitor the ignition time.

Water boiling test (WBT): Stove performance was evaluated using standard WBT procedures provided by Obi[21]. This test is suitable for stove optimization assessment and a rough approximation of relative fuel savings where laboratory or field tests are not practicable. To conduct water-boiling tests, 1.2 kg of water was introduced into a pot and three pieces of briquettes (~18 g) were combusted to raise water temperature to 100°C under a controlled environment[22]. Temperature data was taken at atmospheric pressure and 5 min intervals until the water boils using a 0-360°C range mercury in glass thermometer manufactured in India. When the water reached boiling, the remaining water in pot weighed and recorded alongside the char and final water temperature. For experimental analysis, a controlled outdoor experiment was set up.

Controlled cooking tests (CCT): This test stimulates the cooking of a typical meal in an ideal kitchen situation to determine specific stove parameters. Locally processed rice and white yam were used in the control-cooking test (CCT) to evaluate the stove performance using each briquette. The time spent in cooking, specific fuel consumption and fuel consumption rates of burning untreated, torrefied and fermented briquettes were used in performance evaluation. The test was performed by boiling the foods with a weighed mass of fuel ignited in the stove chamber. A Samsung stopwatch recorded the cooking time and the cooked yam weighed with an SF-400 digital scale. Furthermore, the amount of fuel left after cooking was evaluated using a weighing scale.

Stove performance variables employed in stove tests according to Nhuchhen and Afzal[23] procedures include the following:

Measured variables

- **Time taking to boil water in the pot (Δc_c):** The total time taken to raise water to boiling point
- **Time spent in cooking food (hr/kg):**

$$\text{Ts} = \frac{\text{Total time spent in cooking } (T_{ts})}{\text{Total weight of cooked food } (T_{wc})}\left(\frac{\text{hr}}{\text{kg}}\right) \tag{9}$$

- **Time to consume fuel:** Total time required, including ignition time and time to completely burn fuel in the stove
- **Fuel consumed (f_{cm}):** The amount of wood used to raise water to boiling point, as measured by variations in the initial weight and the remaining briquette weight after the test

Derived variables

- **Briquette burn rate (r_{cb}):** The burn rate is the optimized fuel consumption for a particular stove and cooking situation. The mass-loss method according to Onuegbu *et al.*[24], was used to compute the burn rate at a certain period using the expression:

$$\text{Burn rate} = \frac{\text{Total weight of the burnt briquette}}{\text{Total time taken}} = \left(\frac{f_{cd}}{t_{cd}}\right) \tag{10}$$

- **Stove thermal efficiency (η_t):** The percentage of the work done in heating and evaporating water and the energy consumed in briquette burning, evaluated by the ratio of energy required to evaporate water to the energy required to burn briquettes, calculated using Nhuchhen and Afzal[23] technique:

$$\eta_{th}\,(100\%) = \frac{(P_{ci} - p_f) \times (T_{ci} - T_{cf}) + 2260W_{cv}}{\text{LHV} \times f_{cd}} \tag{11}$$

- **Specific fuel consumption:** The proportion of briquette equivalent used to achieve a specific task (cooking, boiling, etc.) to the task weight expressed as:

$$\text{SFC} = \frac{\text{Mass of consumed fuel}}{\text{Total mass of cooked food}} \tag{12}$$

- **Fuel consumption rate (FCR):** This refers to the rate of fuel consumption per unit of time inside the chamber, determined using the expression:

$$FCR = \frac{\rho_{rh} \times V_r}{t} \quad (13)$$

where, is time required to consume fuel, (hr), V_r is chamber volume, (m^3), r_{rh} is fuel density, (kg/m^3) and FCR is fuel consumption rate (kg/hr).

Statistical analysis: Statistical analysis tools used in this study include established relationships between dependent and independent variables, Analysis of Variance (ANOVA) and correlation[25] at $\alpha_{0.05}$.

RESULTS AND DISCUSSION

Stove development: Table 1 shows the designed specifications. The combustion chamber has a total volume of 2.41×10^2 cm^3 with a capacity to contain 3-4 briquettes of approximately 80.00 mm diameter and 60.00 mm height. The stove's mean fuel consumption varied between 0.56 and 0.68.

Stove performance

Flame propagation and smokiness: The flame growth correlates to the three briquette phase burning described by Baharin *et al.*[19] from the ignition stage to the steady-state flame combustion phase and finally to the decomposition phase. Stove smokiness was influenced by two factors; type of fuel (briquette) burned in the stove and volume of airflow into the combustion chamber[26]. The torrefied briquettes burn with lesser emission of smoke than those of untreated and fermented briquettes due to the significant reduction in volatile matter contents of feedstock during torrefaction. There was an improved supply of air into the combustion chamber through the air vent and the opening in the ashtray. This further increased the thermal efficiency of the stove.

Water boiling and cooking tests: Figure 3(a-e) shows the experimental setups of the water boiling (Fig. 3a) and cooking tests conducted using different briquettes to evaluate the performance of the biomass stove[27]. The water boiling test, WBT) was used to compare the time required to heat water temperature to 100°C.

Fig. 3(a-e): WBT/CCT showing setup and products, (a) WBT/CCT setup, (b) Raw rice, (c) Cooked rice, (d) Uncooked yam and (e) Cooked yam

Table 1: Designed values of designed biomass burning stove

Parameter	Values
Overall dimension of the stove	L = 265, B = 265 and H = 285 mm
Dimension of the lower face of the combustion chamber	L = 127 and B = 127 mm
Dimension of the upper face of the combustion chamber	L = 150.7×B = 150.7 mm
Height of the combustion chamber	124.5 mm
Volume of the combustion chamber	2406.13 cm^3
Combustion chamber capacity	4 briquettes/full capacity
Surface area of the clay lining	691.47 cm^2
Heat transfer per unit area of clay lining	3.435 kW/hr

Table 2: Cost and material analysis of construction of biomass stove

Part	Description and dimensions	Quantity	Amount (NGN)
Fixed grate	5 mm dia×200 mm MS rod	6	500.00
Removable grate	Wire gauze 500×500 mm	1	300.00
Pot stand	5 mm dia MS rod	¼ length	500.00
Combustion chamber	2 mm MS plate 1219.2×609.6 mm	1	1 500.00
Ash tray	2 mm MS plate 609.6×304.8 mm	1	
Lining clay	Montmo~2 microns	5 kg	1, 500.00
Workmanship			3 000.00
	Total		7, 300.00

The control cooking test results revealed a 3.435 kW/hr thermal output per unit surface area within the combustion chamber. The stove thermal efficiencies varied between 31.47 and 39.89% for untreated briquettes, 17.13, 38.52% for torrefied briquettes and 23.84 and 39.89% for fermented briquettes respectively. The mean specific fuel consumption (SFC) to cook 206 g of rice (Fig. 3b-c) and 175 g of white yam (Fig. 3d-e) increased from 0.718 to 0.745 for untreated newsprint briquettes, 0.714 to 0.748 for torrefied briquettes, in cooking rice and yam, respectively[26].

Comparative performance advantages over existing stoves: The developed stove performance indices showed good performance with thermal efficiency values obtained for different briquettes within the 35% thermal efficiency reported as suitable for energy-efficient biomass cookstove[12]. The developed stove is eco-friendly and portable with great potential for improving indoor air quality[13]. Evaluation of the leftover fuel in the combustion chamber after cooking showed that complete fuel combustion was achieved with minimal heat losses due to the clay lining. This observation showed significant improvement over the report of Anggraeni *et al.*[14] on ideal conditions and parameters for stove development.

Economics of production: The major factor that influences the economics of production is the cost of materials for construction and technology. The major materials of construction include low-cost mild steel plates sourced from the open junk market and the clay for the lining sourced from a potter mold site. Table 2 contains the materials of construction and cost. Technology involvement includes simple designs, portability and ergonomic considerations. The stove is relatively cheap N7, 300 NGN (~US$7) compared to most improved stoves (US$35–$70), depending on model)[28]. The stove has a comparative advantage in cost of production, user preference and efficient performance over other conventional stoves.

CONCLUSION

The study concluded that the developed stove performance indices showed good performance with reduced smokiness compared with existing stoves. The thermal efficiency values are within the range of values reported as suitable for energy-efficient biomass stoves. The stove is portable and eco-friendly, with great potential for improving indoor air quality in domestic applications. Complete burning of fuel in the combustion chamber with minimal heat losses due to the clay lining is an indication of significant improvement over existing stoves.

SIGNIFICANCE STATEMENT

Owing to the large number of available users of stoves globally, the development of stoves has become a vital integral part of bioenergy and biofuel research. The growing attention on climate change, user-friendly stoves and improvement in fuel quality, made improvements in stove technology continue to take central focus in global energy research. This study provides a significant contribution to this growing global energy research outlook, especially with a shift from the wood and charcoal stoves development to the rapidly growing biomass stove technology development.

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