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Experimental Analysis of Firewood Combustion Efficiency and Fuel Consumption Patterns for Sustainable Cooking in Bayelsa State, Nigeria

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Abstract: In rural homes across Bayelsa State, Nigeria, firewood remains the primary cooking fuel despite serious concerns regarding environmental sustainability, fuel efficiency, and deforestation. This research assesses the combustion efficiency, heat transfer performance, and fuel consumption patterns of eleven commonly used firewood species to identify the most environmentally friendly cooking options. Key performance measures—including boiling time, heat transfer rate, and quantity of firewood consumedwere evaluated using controlled water boiling tests (WBT). The results revealed that Mangrove and Amowei were the most efficient firewood varieties, demonstrated by shorter boiling times (633–685 seconds), higher heat transfer rates (2.224–1.908 kW), and lower fuel consumption (0.40–0.45 kg per session). In contrast, Mahogany and Abura performed poorly, requiring over two kilograms of fuel per session and significantly prolonging cooking times (almost 2500 seconds). These findings emphasise the importance of selecting firewood with low energy consumption to enhance fuel economy, reduce costs, and mitigate environmental damage. Promoting sustainable firewood harvesting practices and utilising advanced cookstove technology can improve household energy efficiency. Policymakers and rural communities can leverage this research to make informed energy choices that balance environmental preservation with economic viability.
Keywords: Firewood combustion efficiency, heat transfer, fuel consumption, sustainable cooking, rural energy use, biomass fuel

I. INTRODUCTION

Firewood continues to be an important source of energy for households in Nigeria, especially in rural and semi-urban regions where access to modern fuels like liquefied petroleum gas (LPG) and electricity is limited[1]. Despite global initiatives encouraging the adoption of cleaner energy options, more than 70% of households in Nigeria still depend on biomass fuels such as firewood and charcoal for their daily cooking needs[2]. This substantial dependence on firewood raises important issues related to energy efficiency, deforestation, and indoor air pollution [3]. The effectiveness of firewood combustion is influenced by several factors, including the type of wood, moisture levels, combustion temperature, and stove design[4]. Inefficient combustion results in greater fuel consumption, longer cooking times, and higher emissions of carbon monoxide (CO) and particulate matter (PM2.5), which adversely affect both human health and the environment[5]. These issues underscore the necessity for a comprehensive analysis of firewood usage's thermodynamics and energy efficiency, particularly in regions like Bayelsa State, where firewood serves as the primary cooking fuel. Firewood is still the most frequently used cooking fuel in Nigeria, with over 80% of rural households depending on it for food preparation[6]. Research has shown that the preference for firewood is primarily based on cost, availability, and cultural habits rather than efficiency factors[7]. Nonetheless, excessive firewood consumption contributes to rapid deforestation, soil deterioration, and respiratory problems due to long-term exposure to smoke[8]. Inefficient cooking techniques make the environmental impact of firewood use even worse. The traditional three-stone fire method, still commonly used in many Nigerian homes, loses as much as 90% of the heat it generates to the environment, resulting in unnecessary fuel waste and extended cooking times[9].

The thermodynamics of firewood combustion involves three key processes: drying, pyrolysis, and oxidation [5]. Efficient combustion occurs when the wood reaches sufficiently high temperatures to enable complete oxidation, thereby reducing emissions and maximising energy output. However, moisture content, firewood density, and airflow regulation significantly affect combustion quality[10]. Hardwoods like mangroves and mower typically provide greater combustion efficiency because of their dense composition and high calorific content, while softwoods ignite faster but produce lower heat intensity[11]. The moisture in wood leads to heat loss through the evaporation of water, which consequently diminishes the stove's overall efficiency[12].

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Conventional stoves often lack sufficient insulation and regulated airflow, resulting in poor heat transfer, whereas enhanced cookstoves improve thermal efficiency by better retaining heat[13]. Although recent studies have explored the efficiency of different types of biomass fuels,[9] found that various types of fuelwoods in Nigeria burn at different efficiency levels. Some species can produce over 50% more energy than others. Furthermore, [2] reported that an increasing number of people in Nigeria are using firewood due to the rising price of LPG.

Despite efforts to transition to cleaner energy, numerous challenges obstruct the adoption of alternative fuels in Nigeria. Most rural households consider LPG and electricity expensive and inaccessible[14]. Policies that promote cleaner cooking solutions have not been effectively implemented, leading to a continued reliance on firewood[15]. Existing studies have focused on the general use of biomass for household energy. However, there remains a lack of empirical data on firewood combustion efficiency, heat transfer performance, and fuel consumption rates specific to different wood species utilized in Nigeria [14]. In Bayelsa State, research on which types of firewood provide the best heat transfer and the least fuel wastage has been limited. Furthermore, while improved biomass stoves are promoted as a solution for inefficient firewood use, few comparative studies exist between traditional open-fire cooking and enhanced stoves[15]. Without proper thermodynamic assessments, households may use low-efficiency firewood, worsening environmental and economic issues. This research aims to fill the gaps by analyzing the efficiency of firewood combustion in terms of heat transfer performance and fuel usage rates. It will assess the heat transfer characteristics of different firewood species commonly used in Bayelsa State and determine the most fuel-efficient variety to decrease firewood consumption and improve cooking efficiency. The findings can support government interventions to promote improved cookstoves, firewood regulation policies, and afforestation programmes to combat deforestation and air pollution.

Existing studies focus on general biomass energy trends; however, few have experimentally investigated the efficiency of specific firewood species utilised in rural Nigeria. This study aims to fill that gap by performing direct experimental comparisons of firewood combustion efficiency, heat transfer, and fuel consumption.

II. MATERIALS AND METHODS

A. *Experimental Setup and Firewood Selection*

The experiment follows a controlled laboratory setup in which a standard aluminum cooking pot measures heat transfer efficiency. Infrared thermometers capture temperature changes at various stages of combustion. Firewood samples are weighed before and after burning to determine fuel consumption. Water boiling tests (WBT) evaluate the efficiency of different kinds of firewood. An infrared thermometer checks the pot's starting and ending temperatures, ensuring accurate heat transfer measurements. Eleven firewood species were chosen based on their local use in Bayelsa State, including Mangrove, Amowei, Ewono, Owosso, Mahogany, Indian Mahogany, Abura, Iroko, Bush Mango, Kuru, and Akololor. Before testing, the wood types were dried to a uniform moisture level to reduce differences in combustion behavior. Each firewood specimen was weighed before and after burning to enable a comparative analysis of mass loss, burn rate, and energy efficiency. The cooking method employed a traditional three-stone fire arrangement, the most prevalent method in rural Nigeria.

Table 1: Cooking Pot Specifications

Parameter	Value	Unit	Description
Material	Aluminum	—	The pot is made of aluminum for better heat conductivity.
Initial Pot Temperature	230K, 300K	Kelvin (K)	Ambient temperature of the pot before heating.
Thermal Conductivity (k)	0.202	kW/m·K	Thermal conductivity of aluminum material.
Height (h)	65	mm (0.065 m)	The vertical height of the cooking pot.
Diameter (d)	180	mm (0.18 m)	Diameter of the pot.
Thickness (t)	1	mm (0.001 m)	The thickness of the aluminum pot.
Surface Area (A)	0.025	m^2	The total exposed surface area of the pot.

B. Water Boiling Test (WBT) and Heat Transfer Calculations

Heat transfer efficiency is evaluated based on a substance's specific heat capacity, which is the quantity of heat required to raise the temperature of a unit mass of a substance.

The rate of heat flow is proportional to the area of a cross-section through which the heat flows, to be measured perpendicular to the direction of heat flow and the temperature gradient at the section.

$$Q = \frac{-KA(T_1 - T_2)}{x} \quad (1)$$

Where, Q = Rate of heat flow (kw), A = Cross–Sectional areas (m^2)

$$Q = mc\Delta T \quad (2)$$

Where, Q = Heat energy required (J) m = Mass of water (kg) C = Specific heat capacity of water (4186 J/kg·K) and ΔT = Temperature rise of water (K)

Using the infrared thermometer, the pot's temperature at ambient temperature conditions was 27^0C = 300K. From the table above, the normal temperature of the pot (300k) corresponded to the thermal conductivity at 202w/m K; therefore, the thermal conductivity of the aluminium pot was 0.202kw/m k

Area of the pot = $A = \frac{\pi d^2}{4} = \frac{3.142 \times 0.18)^2}{4} = 0.25m^2$

M = 2 kg (mass of water), C= 4186 J/kg·K (specific heat of water)

$$P = \frac{C_p A(T_{hot} - T_{Cold})}{d} \quad (3)$$

$$Q_{input} = Q_{useful} + Q_{Loss} \quad (4)$$

$$\eta = \frac{Q_{useful}}{Q_{input}} \times 100\% \quad (5)$$

Where, Q_{input} = Total energy from fuelwood combustion (J) Q_{useful} = Heat used for cooking (J) , η = Efficiency (%) and Q_{Loss} = Heat lost to surroundings (J)

C. Data Collection, Statistical Analysis, and Accuracy Control

The combustion of firewood was assessed using three primary criteria: the time taken to boil water (in seconds), the weight of burnt firewood (in kg), and the rate of heat flow (in KJ/s). Firewood efficiency was evaluated; relationships between the type of firewood and heat transfer efficiency were subsequently identified. Before use, each instrument – including the digital weighing scale and infrared thermometer – was calibrated to ensure precision in the experiment. Each type of firewood was tested three times, and the average results were used to minimize random errors. Could reduce external influences on combustion rates by controlling environmental variables such as humidity and wind. Data collection led to the creation of bar charts and graphical representations that assessed the fuel economy and energy efficiency of each type of firewood. This study aimed to identify the most efficient type of firewood capable of reducing fuel consumption and optimizing heat transmission, thereby supporting environmentally friendly cooking practices in Bayelsa State, Nigeria. The findings will guide households and policymakers towards the best firewood sources to improve rural livelihoods, mitigate deforestation, and enhance energy efficiency.

III. RESULTS AND DISCUSSION

A. Firewood Combustion Efficiency

Figure 1 shows the average heat produced by eleven types of firewood. Notably, mangrove firewood is highlighted as the most effective, reaching a peak heat output of 2.224 kW and boiling water in 633 seconds. On the other hand, mahogany is the least efficient, with a heat rate of only 0.100 kW and an extended boiling time of 2546 seconds. Mangrove and Amowei firewood perform exceptionally well, providing high heat output and quick cooking times.

Mahogany, Iroko, and Abura are the least efficient types, as they take longer to boil water and require more fuel. Mangrove also reached the highest combustion temperature of 768°C, confirming its status as the best firewood for heat efficiency.

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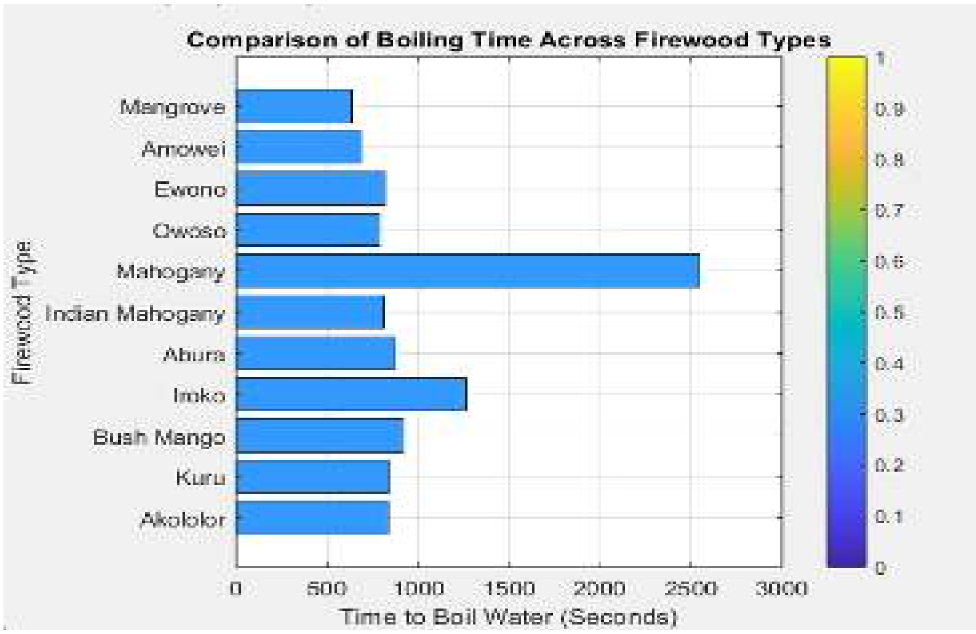

Figure 1: Comparison of Boiling Time Across Firewood Types

The results are consistent with previous research by [1], which found that hardwood species like Mangrove and Amowei have lower moisture levels and greater energy density, thus improving combustion efficiency. Similarly,[4] noted that firewood species with elevated lignin content generate more stable flames and enhance heat retention.

B. *Thermal Efficiency and Analysis of Heat Transfer*

With a weight of 0.40 kg and 0.45 kg, respectively, Mangroves and Amowei exhibited the lowest fuel consumption rates, making them the most efficient firewood choices. In contrast, Mahogany and Abura consumed over 2 kg, indicating substantial energy waste and inefficiency. Mangrove achieved the quickest boiling time of 633 seconds and registered the highest heat transfer rate, 2.224 kW, demonstrating its effectiveness.

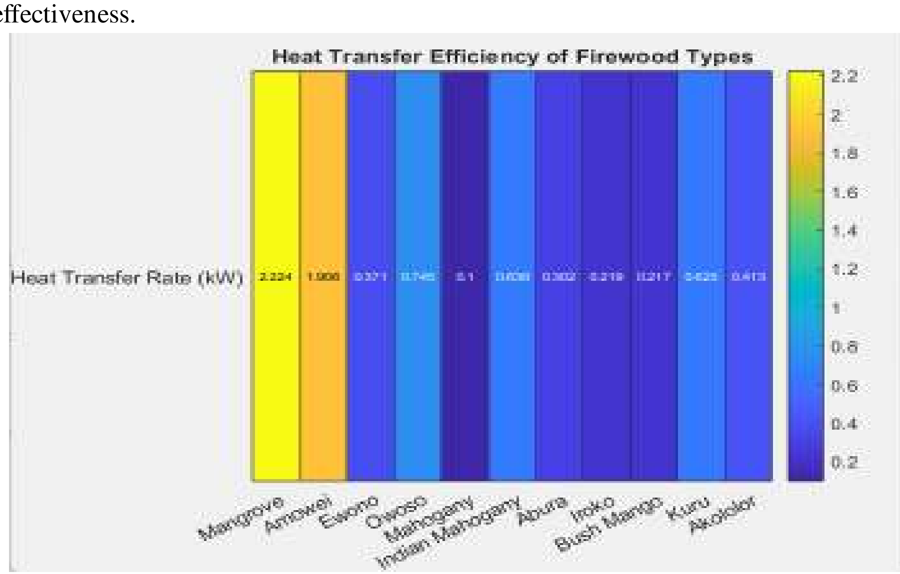

Figure 2: Heat Transfer Efficiency of Firewood Types

C. *Sustainable Consumption of Firewood*

Assessing the sustainability of a cooking fuel source requires first examining the rate of firewood consumption. Table 2 displays the quantity of wood burned during combustion for each type of firewood.

Table2: Firewood Fuel Consumption and Energy Loss

Firewood Type	Mass of Wood Before Burning (kg)	Mass of Wood After Burning (kg)	Mass Expended (kg)	Max Bottom Pot Temp (°C)	Time Taken (Sec)	Rate of Heat Flow (KJ)
Amowei	4.00	3.55	0.45	424	685	1.908
Mangrove	5.20	4.80	0.40	768	633	2.224
Abura	3.00	0.78	2.22	358	877	0.302
Iroko	3.80	1.68	2.12	381	1263	0.219
Bush Mango	4.20	2.25	1.95	432	920	0.217
Ewono (Ironwood)	4.20	1.56	1.94	221	818	0.371
Kuru	5.00	3.88	1.12	385	840	0.625
Indian Mahogany	3.00	1.87	1.13	388	814	0.639
Mahogany	5.00	2.70	2.30	353	2546	0.100
Owoso	2.50	1.50	1.00	224	789	0.745
Akololor	2.50	0.80	1.70	372	838	0.413

Table 2 reveals that Mahogany and Abura had the highest consumption levels, using 2.3 kg and 2.22 kg, respectively, suggesting considerable fuel waste. Mangrove and Amowei exhibited the lowest firewood consumption rates, at 0.40 kg and 0.45 kg, respectively.

Figure 3 highlights Mangrove and Amowei as the most fuel-efficient firewood options, with each boiling session requiring just 0.40 kg and 0.45 kg. In contrast, Mahogany and Abura reached 2 kg per session, reflecting the most excellent fuel consumption and revealing significant fuel waste and low efficiency.Firewood varieties that exhibit lower consumption rates—such as Mangrove and Amowei—generate more heat output for each unit of mass. Both Mahogany and Iroko suffered significant mass loss, resulting in more frequent refills and increased overall costs for firewood. Choosing efficient firewood can contribute to sustainable cooking practices and substantially reduce energy expenses at home.The findings align with those of [2], which underlined for rural homes that low mass loss and high energy density firewood species are more sustainable and reasonably priced. Moreover,[11] underlined the need to employ sustainable rural energy utilizing adequate firewood to help reduce deforestation.

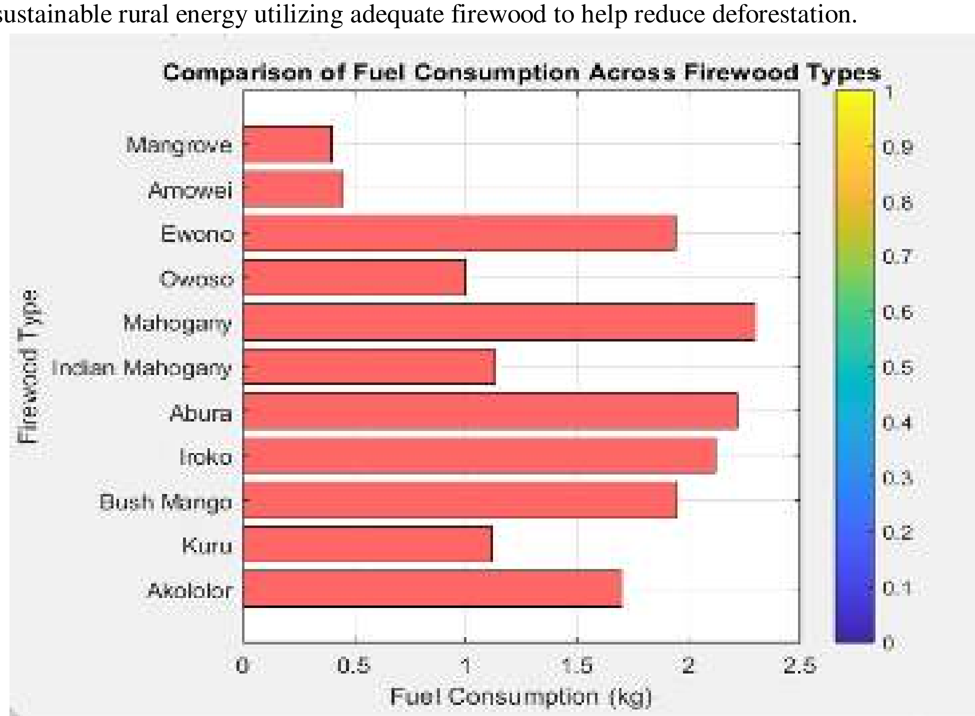

Figure 3: Fuel Consumption Comparison Across Firewood Types

D. Comparative Analysis of Firewood Performance

A comprehensive assessment of the various types of firewood was conducted. Based on an in-depth evaluation of boiling times, heat transfer efficiency, and fuel economy, the wood was ranked as shown in Table 3.

Table 3: Efficiency Ranking of Firewood Types

Rank	Firewood Type	Overall Performance
1	Mangrove	Most Efficient & Sustainable
2	Amowei	High Efficiency & Low Fuel Use
3	Owoso	Moderate Efficiency
4	Indian Mahogany	Moderate Performance
5	Kuru	Average Efficiency
6	Akololor	Average Performance
7	Ewono	Below Average Efficiency
8	Bush Mango	Fuel Consumption
9	Iroko	Poor Efficiency & High Fuel Use
10	Abura	Poor Performance
11	Mahogany	Least Efficient & Most Unsustainable

The remarkable efficiency and low fuel consumption of mangrove and amowei make them ideal choices for cooking. In contrast, mahogany and abura are less effective, requiring more fuel and longer cooking times, which makes them unsustainable options. Selecting the right firewood can help reduce energy costs, improve cooking efficiency, and alleviate deforestation.

E. Policy and Sustainability Implications

The results of this study provide substantial support for policy recommendations aimed at enhancing firewood usage in Nigeria and promoting environmentally friendly cooking methods. By employing more efficient types of firewood, such as Mangrove and Amowei, rural households could reduce their fuel consumption by up to 50%, resulting in cost savings and improved cooking efficiency.Improved cookstoves can lead to increased thermal efficiency. Using energy-efficient biomass stoves can improve combustion efficiency and lower fuel waste. The study by [16] advocates for the adoption of modern biomass cookstoves as a means to improve fuel efficiency and reduce deforestation. High-quality firewood reduces the need for firewood, alleviating deforestation and its environmental impacts.[13]emphasize that effectively utilizing firewood can reduce carbon emissions and support conservation initiatives. Government programs should encourage the use of alternative energy sources (LPG, ethanol, biogas), regulate the collection of firewood, and promote reforestation to reduce reliance on firewood in Nigeria.

IV. CONCLUSION

This study investigates the combustion efficiency, heat transfer rates, and fuel usage trends of eleven commonly used firewood types in Bayelsa State, Nigeria. The findings indicate that Mangrove and Amowei are the most efficient species, demonstrating excellent heat transfer rates, reduced boiling times, and lower fuel consumption. In contrast, Mahogany and Abura exhibited poor efficiency, resulting in excessive firewood usage and longer cooking times. The choice of firewood has a significant impact on energy efficiency and cooking duration. Households should prioritise dense hardwoods (Mangrove, Amowei) for better fuel economy. Government policies should promote energy-efficient cooking technologies and sustainable firewood harvesting practices. Future research should explore the computational modelling of firewood combustion, alternative biomass options, and clean cooking innovations to enhance energy sustainability in rural Nigeria.

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