

Research Article

Comparative Evaluation of Properties and Energy Potential of Selected Fuelwood Species in Nasarawa State, Nigeria

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Abstract

In many parts of Nigeria, wood remains a primary source of household and small-scale industrial energy. As fuelwood demand continues to grow, identifying species with high energy efficiency is increasingly important. This study evaluates eight commonly used wood species in Nasarawa State, Nigeria, to determine their suitability for fuelwood and charcoal production. Each species was assessed for calorific value, volatile matter, ash content, moisture content, wood density, and charcoal yield, using five replicates per species. Laboratory tests followed standard procedures, and the data were analyzed using descriptive statistics, ANOVA, and Duncan's multiple range tests. Significant variation was observed across species, with *Anogeissus leiocarpus*, *Khaya senegalensis*, and *Prosopis africana* exhibiting superior energy profiles, including higher calorific values and lower ash and moisture contents. Boxplots and Duncan's multiple range tests highlighted distinct groupings among the species. Correlation and multiple linear regression analyses revealed that moisture and ash contents had strong negative effects on calorific value, while density and charcoal yield positively influenced fuel quality. The results of regression analysis for calorific value versus volatile matter, ash content, moisture content, density, charcoal yield, species had R^2 (Model Fit) of 0.8959, meaning 89.59% of the variation in calorific value is explained by the predictors. These findings support the hypothesis that fuelwood properties vary significantly by species and offer practical guidance for selecting efficient, clean-burning wood types. The results contribute to improved biomass energy use and support informed decisions for sustainable fuelwood utilization in sub-Saharan Africa.

Keywords

Fuelwood, Calorific Value, Wood Density, Charcoal Yield, Bioenergy

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1. Introduction

Fuelwood remains one of the most widely used energy sources across sub-Saharan Africa, particularly in Nigeria where it accounts for over 60% of total household energy consumption [1]. Its affordability, ease of access, and renewability make it the preferred choice for both rural and urban populations, especially in areas where access to alternative energy sources is limited or unreliable. Beyond domestic cooking and heating, fuelwood is also vital to various small-scale industries such as fish smoking, cassava processing, bakeries, and institutional kitchens in schools, hospitals, and correctional facilities [2]. Despite increasing awareness of environmental concerns, the reliance on biomass energy continues to rise, driven by population growth and the absence of cost-effective alternatives [3, 4]. In this context, there is an urgent need to assess and promote the most efficient wood species to enhance energy output, reduce pressure on forest resources, and support sustainable fuelwood management.

Selecting appropriate fuelwood species requires a sound understanding of their physical and combustion characteristics. Properties such as calorific value, moisture content, volatile matter, ash content, and wood density directly influence combustion efficiency, heat output, and suitability for various energy applications [5, 6]. For instance, species with high calorific value and low moisture content tend to burn more efficiently and produce less smoke, which is critical in reducing indoor air pollution and improving energy use in low-income households [7]. Similarly, high-density species generally yield more charcoal and burn for longer periods, making them ideal for both domestic cooking and small-scale industrial use. Despite the importance of these properties, many communities still rely on traditional knowledge or availability when choosing firewood, often overlooking energy performance and sustainability. Scientific evaluation of commonly used wood species can help guide policy, inform afforestation programs, and promote the use of energy-efficient species, especially in regions where biomass remains the dominant energy source.

In most rural communities, the selection of fuelwood species is often based on availability, familiarity, or ease of use rather than scientifically measured energy properties. Factors such as how easily the wood ignites, the amount of smoke it produces, the smell of the burning wood, and even the taste it imparts to food are considered in everyday decision-making [8]. In some cases, species are selected because they split easily, dry quickly, or produce long-lasting coals. While these local preferences reflect generations of practical experience, they do not always align with optimum combustion efficiency or environmental sustainability. As pressures on forest resources increase, it becomes necessary to move beyond informal knowledge systems and provide communities and policymakers with reliable data to guide species selection for fuel and charcoal production.

Wood properties are known to vary significantly across species, locations, and growing conditions, which makes generalisations difficult. A species that performs well in one ecological zone may not exhibit the same energy characteristics in another. For this reason, localised studies are essential to assess the physical and combustion properties of species commonly used in a specific region. In the context of Nasarawa State where fuelwood remains the dominant source of energy for both households and small businesses generating accurate, locally relevant data is crucial for informing reforestation, woodlot management, and energy planning strategies [9, 10]. This study aims to fill that knowledge gap by evaluating the energy potential of selected fuelwood species that are widely used across the state.

This study was designed to evaluate the fuelwood properties of eight commonly used wood species in Nasarawa State, Nigeria, with the goal of identifying those that offer the best energy performance for both domestic and industrial use. The specific objectives were to (i) determine the calorific value, volatile matter, ash content, moisture content, density, and charcoal yield of each species; (ii) examine the relationships among these properties; and (iii) identify the most efficient species based on their energy and combustion characteristics. The findings are intended to guide local woodlot management, species selection for energy plantations, and sustainable fuelwood utilisation in the region. Based on prior knowledge and preliminary field observations, the study tested the hypothesis that: "There is a significant variation in the energy properties of the selected wood species, and some species will exhibit superior fuelwood qualities in terms of calorific value, density, and charcoal yield."

2. Materials and Methods

2.1. Experimental Site

This research was conducted at the Department of Forestry and Wildlife Management, Nasarawa State University, Keffi, Shabu-Lafia Campus, located in Lafia, North Central Nigeria. It lies between latitudes 7°45'N and 9°25'N and longitudes 7°00'E and 9°37'E [11]. It has a tropical climate with two distinct seasons: wet and dry. Purposive sampling of 50 most preferred wood species for energy generation within the North central Nigeria were made and a review of their characteristics that made them public preference were ranked based on their qualities and availability (Table 1). Eight of the top preferred wood species were selected and sampled from different locations within Nasarawa State. The physical component of the study was completed at Faculty of Agriculture, NSUK, while the Chemical and mechanical component was carried out at the Centre for Energy Research and Development (CERD), Obafemi Awolowo University, Ile-Ife, situated

at latitude 7.500 °N and longitude 4.520 °E.

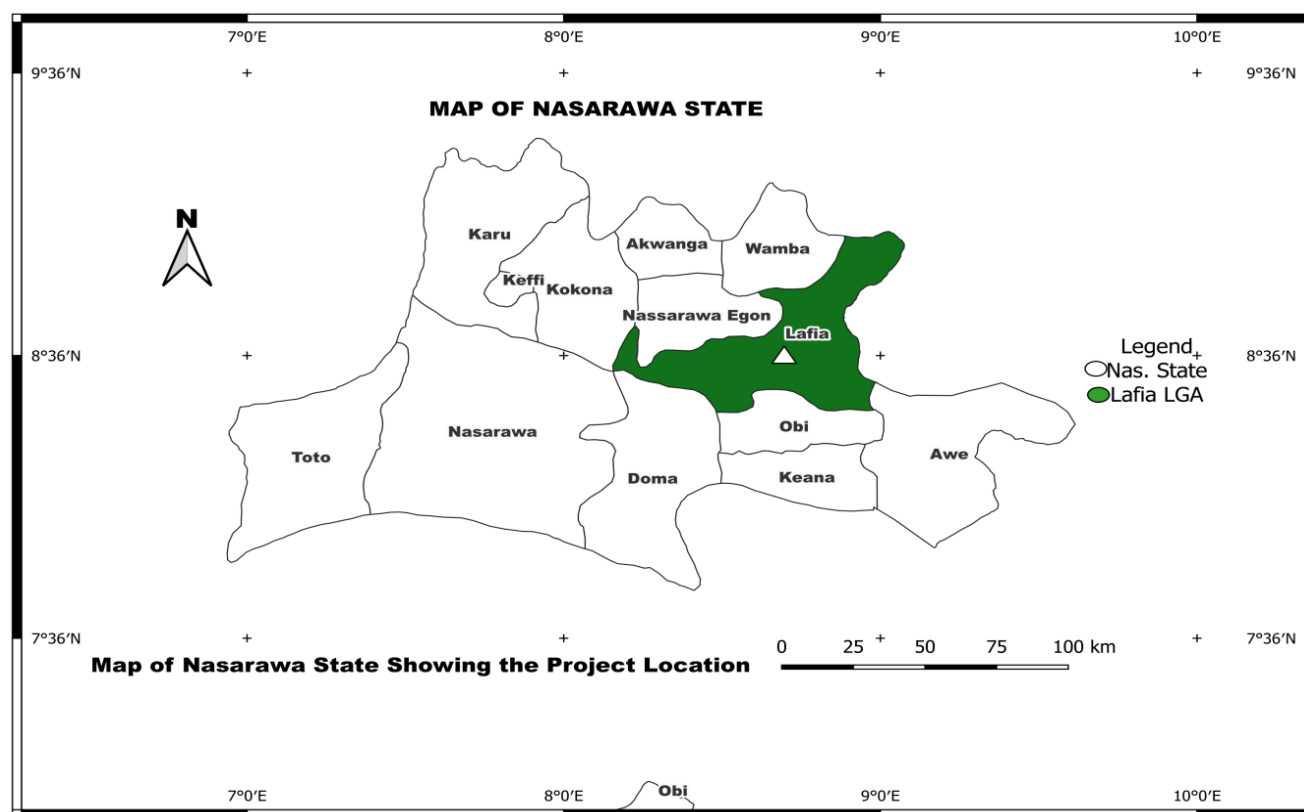


Figure 1. Map of Nasarawa state showing Lafia as the study area.

2.2. Selection and Description of Sampled Wood Species

Out of an initial pool of 50 wood species commonly used for firewood and charcoal production in North Central Nigeria, eight species were purposely selected based on their frequency of use, local preference, and availability in Nasarawa State. The selection process was informed by both field surveys and prior documentation from forestry departments and community reports (Table 1). These eight species *Azadirachta indica* (Neem), *Prosopis africana*, *Tectona grandis* (Teak), *Vitellaria paradoxa* (Shea Butter), *Anogeissus leiocarpus*,

Khaya senegalensis, *Syzygium guineense*, and *Vitex doniana* were ranked according to key selection criteria, which included wood hardness, durability, and combustion rating. Hardness was scored on a scale of 1 (soft) to 4 (very hard), while durability followed a similar classification from 1 (very durable) to 4 (non-durable). Combustion characteristics were rated as slow (1), moderate (2), or fast burning (3), based on existing literature and local usage experience. Selected species are widely used for multiple purposes, including construction, charcoal production, and fodder. Their selection ensures a representative mix of high-use fuelwood species in the region for scientific evaluation.

Table 1. List of 50 commonly used tree species for firewood and charcoal making in Nasarawa State.

No	Scientific Name	Common Name	Calorific Value (MJ/kg)	Wood Density (kg/m ³)	Moisture Content (%)	Ash Content (%)	Volatile Matter (%)	Charcoal Yield (%)	Combustion Rating	Use Suitability	Charcoal quality	Source
1	<i>Anogeissus leiocarpus</i>	African birch	18.2-19.5	780-850	11-13%	1.1 - 1.8	72 - 78	30-34	Fast	CCF	widely used for charcoal	[12, 13]
2	<i>Prosopis africana</i>	Iron tree	19.6-20.4	850-950	10-12%	0.7 - 1.5	65 - 70	35-38	Moderate	CCF	high yield, dense wood	[12, 13]

No	Scientific Name	Common Name	Calorific Value (MJ/kg)	Wood Density (kg/m ³)	Moisture Content (%)	Ash Content (%)	Volatile Matter (%)	Charcoal Yield (%)	Combustion Rating	Use Suitability	Charcoal quality	Source
3	<i>Vitellaria paradoxa</i>	Shea butter	19.1-19.8	800-880	10-13%	1.2 - 1.9	68 - 74	30-33	Slow	CCF	Local combustion tests	[12, 13]
4	<i>Parkia biglobosa</i>	Locust bean	17.6-18.3	600-700	12-14%	1.0 - 2.0	70 - 76	28-31	Moderate	CCF	Medium yield, dense wood	[12, 13]
5	<i>Khaya senegalensis</i>	African Mahogany	18.0-19.0	620-740	11-13%	0.9 - 1.5	66 - 72	30-34	Fast	CCF	Medium yield, dense wood	[14, 15]
6	<i>Daniellia oliveri</i>	Copal tree	18.2-18.9	550-620	13-15%	1.4 - 2.1	70 - 75	26-29	Fast	CCF	Softwood, lower density	[12, 15]
7	<i>Albizia zygia</i>	Albizia	17.9-18.5	510-580	12-14%	1.1 - 1.7	71 - 77	25-28	Moderate	CCF	Lower yield due to low density	[12, 14, 15]
8	<i>Terminalia avicennioides</i>	Black combretum	18.3-19.1	750-800	10-12%	1.3 - 2.0	67 - 73	30-32	Slow	CCF	Moderate, widely used for charcoal	[12, 14]
9	<i>Diospyros mespiliformis</i>	African ebony	19.0-20.0	850-980	9-11%	1.0 - 1.4	60 - 66	33-36	Moderate	CCF	High charcoal yield, hard wood	[12, 14, 15]
10	<i>Azadirachta indica</i>	Neem	18.0-18.8	560-650	10-12%	1.5 - 2.2	68 - 73	28-30	Fast	CCF	Lower due to volatile oils	[12, 14, 15]
11	<i>Mangifera indica</i>	Mango	17.5-18.6	540-610	10-12%	1.3 - 2.0	72 - 78	26-29	Fast	CCF	Low-medium yield, softwood	[12, 14, 15]
12	<i>Afzelia africana</i>	Apa	18.6-19.4	700-830	11-13%	0.8 - 1.3	60 - 66	33-36	Moderate	CCF	High yield, hard and dense wood	[12, 14, 15]
13	<i>Gmelina arborea</i>	Gmelina	17.0-17.8	400-500	12-15%	2.0 - 3.5	74 - 80	24-27	Slow	CCF	Fast-growing, low density	[12, 14, 15]
14	<i>Tectona grandis</i>	Teak	18.5-19.5	630-690	10-12%	1.4 - 2.1	62 - 68	29-32	Moderate	CCF	Good charcoal quality, moderate yield	[12, 14, 15]
15	<i>Alstonia boonei</i>	Cheese wood	17.1-17.6	360-450	13-15%	1.6 - 2.4	73 - 78	22-25	Fast	CCF	Low yield, low density, lightweight	[12, 15]
16	<i>Ficus spp.</i>	Fig tree (various)	17.0-18.0	350-450	12-14%	2.0 - 3.0	75 - 82	20-24	Fast	CCF	Very soft, not ideal for charcoal	[12]
17	<i>Isobrerlinia doka</i>	Doka tree	18.2-18.9	700-800	11-13%	1.1 - 1.9	65 - 70	30-33	Moderate	CCF	Good yield, preferred fuelwood	[12, 14, 15]
18	<i>Lophira lanceolata</i>	Iron wood	19.1-20.2	880-980	9-11%	0.9 - 1.6	58 - 64	33-36	Slow	CCF	Very hard, high carbon content	[12, 15]

No	Scientific Name	Common Name	Calorific Value (MJ/kg)	Wood Density (kg/m ³)	Moisture Content (%)	Ash Content (%)	Volatile Matter (%)	Charcoal Yield (%)	Combustion Rating	Use Suitability	Charcoal quality	Source
19	<i>Terminalia superba</i>	White afara	18.0-18.8	460-560	10-12%	1.3 - 2.2	70 - 75	27-30	Moderate	CCF	Medium-light density, moderate yield	[12, 15]
20	<i>Triplochiton scleroxylon</i>	Obeche	17.8-18.4	350-500	11-13%	2.0 - 3.5	73 - 79	24-27	Fast	CCF	Lightwood, lower charcoal potential	[12, 14, 15]
21	<i>Spondias mombin</i>	Hog plum	17.5-18.2	450-500	12-14%	1.8 - 2.6	72 - 78	22-25	Fast	CCF	Lightwood, low density, not ideal for charcoal	[12, 14, 15]
22	<i>Pterocarpus erinaceus</i>	African rose-wood	18.8-20.0	800-900	10-12%	0.9 - 1.4	60 - 66	34-38	Moderate	CCF	Very good charcoal wood, dense and oily	[12, 14, 15]
23	<i>Nauclea latifolia</i>	African peach	17.0-17.8	600-650	12-15%	1.5 - 2.4	74 - 79	26-29	Slow	CCF	Medium density, fair combustion	[12, 14, 15]
24	<i>Acacia nilotica</i>	Egyptian thorn	18.9-19.6	770-880	9-11%	1.1 - 1.7	63 - 68	31-34	Moderate	CCF	Dense hardwood, good for charcoal	[12, 15]
25	<i>Faidherbia albida</i>	Apple-ring Acacia	18.0-19.1	600-750	10-12%	1.2 - 2.1	67 - 73	28-32	Fast	CCF	Medium-high yield, also nitrogen fixing	[12, 14, 15]
26	<i>Brachystegia eurycoma</i>	False Copal-wood	18.5-19.3	750-850	11-13%	1.0 - 1.8	65 - 71	32-35	Fast	CCF	Hardwood, good combustion	[12, 14, 15]
27	<i>Hymenocardia acida</i>	Hymenocardia	17.6-18.4	550-600	12-14%	1.3 - 2.2	70 - 76	26-29	Moderate	CCF	Moderate yield, brittle structure	[12, 14, 15]
28	<i>Celtis integrifolia</i>	African hackberry	17.2-18.0	540-580	11-13%	1.0 - 1.6	71 - 76	27-30	Slow	CCF	Medium yield, moderate combustion	[12, 14, 15]
29	<i>Ceiba pentandra</i>	Kapok Tree	16.8-17.5	290-350	12-16%	2.5 - 3.8	74 - 81	18-22	Moderate	CCF	Very soft, low charcoal yield	[12, 14, 15]
30	<i>Eucalyptus camaldulensis</i>	Red River Gum	18.4-19.5	700-850	9-11%	1.5 - 2.5	69 - 74	30-34	Fast	CCF	Fast-growing, good yield when seasoned properly	[12, 14, 15]
31	<i>Aningeria robusta</i>	Aningeria	18.1-18.9	540-600	10-12%	1.3 - 2.0	67 - 73	28-32	Fast	CCF	Medium-density; decent yield	[12, 14, 15]

No	Scientific Name	Common Name	Calorific Value (MJ/kg)	Wood Density (kg/m ³)	Moisture Content (%)	Ash Content (%)	Volatile Matter (%)	Charcoal Yield (%)	Combustion Rating	Use Suitability	Charcoal quality	Source
32	<i>Mitragyna inermis</i>	Mitragyna	17.4-18.2	500-580	11-13%	1.4 - 2.3	70 - 75	25-2	Moderate	CCF	Light-to-medium wood; moderate yield	[12, 14, 15]
33	<i>Detarium microcarpum</i>	Tallow Tree / Sweet Detar	18.2-19.0	780-900	10-12%	1.2 - 2.1	62 - 68	33-36	Slow	CCF	Dense wood, excellent yield	[12, 14, 15]
34	<i>Sterculia setigera</i>	Sterculia	17.3-18.1	350-420	12-14%	2.0 - 3.2	71 - 77	22-26	Moderate	CCF	Low-density wood; poor to fair yield	[12, 14, 15]
35	<i>Ziziphus mauritiana</i>	Jujube / Indian jujube	18.0-18.8	670-750	11-13%	1.5 - 2.2	66 - 72	30-34	Fast	CCF	Dense firewood and charcoal value	[12, 14, 15]
36	<i>Grewia mollis</i>	Velvet bush-willow	17.0-17.8	500-580	12-14%	1.6 - 2.4	68 - 73	25-28	Fast	CCF	Moderate density; fair yield	[12, 14, 15]
37	<i>Syzygium guineense</i>	Water berry	18.0-19.2	550-640	10-12%	1.7 - 2.6	72 - 78	27-31	Moderate	CCF	Moderate to high yield (depending on MC)	[12, 14, 15]
38	<i>Ficus platyphylla</i>	Broad-leaved fig	17.6-18.3	360-420	12-14%	2.1 - 3.0	74 - 80	20-24	Slow	CCF	Softwood, poor charcoal yield	[12, 14, 15]
39	<i>Terminalia macroptera</i>	Terminalia	18.1-18.9	600-680	11-13%	1.2 - 2.0	69 - 74	30-33	Moderate	CCF	Medium to high yield; efficient under dry conditions	[12, 15]
40	<i>Piliostigma thonningii</i>	Camel's Foot Tree	17.2-18.0	450-500	12-14%	1.8 - 2.5	70 - 76	23-26	Fast	CCF	Low to medium wood density; moderate yield	[12, 14, 15]
41	<i>Lannea microcarpa</i>	African grape	17.6-18.3	550-620	11-13%	1.4 - 2.2	70 - 75	28-32	Fast	CCF	Moderately dense; good charcoal performance	[12, 14, 15]
42	<i>Bauhinia rufescens</i>	Bauhinia	17.3-18.0	500-580	10-12%	1.5 - 2.3	69 - 74	24-27	Moderate	CCF	Medium wood, moderate yield	[12, 14, 15]
43	<i>Cassia sieberiana</i>	Drumstick Tree	17.4-18.2	510-580	12-14%	1.6 - 2.4	71 - 76	25-28	Slow	CCF	Light-to-medium wood; fair charcoal quality	[12, 14, 15]
44	<i>Pseudocedrela kotschy</i>	Dry-zone Cedar	18.7-19.5	550-630	10-12%	1.3 - 2.1	66 - 72	30-34	Moderate	CCF	Hard wood, dense; high charcoal efficiency	[12, 14, 15]

No	Scientific Name	Common Name	Calorific Value (MJ/kg)	Wood Density (kg/m ³)	Moisture Content (%)	Ash Content (%)	Volatile Matter (%)	Charcoal Yield (%)	Combustion Rating	Use Suitability	Charcoal quality	Source
45	<i>Anthocleista nobilis</i>	Cabbage Tree	16.8-17.6	420-500	12-14%	1.7 - 2.8	73 - 78	22-25	Fast	CCF	Softwood, low density, poor charcoal quality	[12, 14, 15]
46	<i>Uapaca togoensis</i>	False Mahogany	18.0-18.7	600-680	11-13%	1.6 - 2.5	68 - 74	24-27	Fast	CCF	Moderate density, fair yield	[12, 14, 15]
47	<i>Cola nitida</i>	Kola Nut Tree	17.2-18.0	510-580	10-12%	1.8 - 2.9	67 - 72	26-29	Moderate	CCF	Fair yield;	[12, 14, 15]
48	<i>Irvingia gabonensis</i>	Bush Mango	18.5-19.3	640-750	11-13%	1.2 - 2.0	65 - 70	29-33	Slow	CCF	Dense wood; good fuel properties	[12, 14, 15]
49	<i>Treculia africana</i>	African Breadfruit	17.0-17.8	430-500	12-14%	1.5 - 2.3	74 - 79	23-26	Moderate	CCF	Soft to moderate; moderate yield	[12, 14, 15]
50	<i>Entada africana</i>	Twisted Entada	17.1-17.9	520-600	11-13%	1.3 - 2.2	72 - 77	25-28	Fast	CCF	medium yield	[12, 14, 15]

CCF - Construction, Charcoal, Fodder

2.3. Sample Collection and Preparation

For each of the eight selected species, five mature logs were obtained from naturally grown trees within farmlands and fallow plots in Lafia and Doma Local Government Areas of Nasarawa State. Sampling was purposive, targeting trees that were healthy, free from rot or deformities, and representative of local harvesting practices. The diameter at breast height (DBH) of sampled trees ranged from 20 to 30 cm, ensuring uniformity across species. Each log was cut into billets approximately 40 cm in length and subsequently converted into test specimens measuring 20 cm × 5 cm × 5 cm for laboratory analysis. The samples were labeled according to species and replicate, and then air-dried under shade for three weeks to reduce surface moisture without altering internal structure. After pre-drying, the specimens were oven-dried at $103 \pm 2^\circ\text{C}$ until constant weight was achieved, in accordance with American Society for Testing and Materials (ASTM) D4442-16 standards [16]. All tests were carried out using five replicates per species to allow for statistical comparison. Prepared samples were stored in moisture-proof bags and transported to the Forestry Research Institute of Nigeria (FRIN), Ibadan, for laboratory analysis. Figures 2-7 are the thematic procedure of charcoal production to marketing.



Figure 2. Logs of Iron tree.



Figure 3. Logs of Shea butter tree.



Figure 4. Quenching of fire with water.



Figure 7. Transported to the point of sales.



Figure 5. Gathering of charcoal.



Figure 6. Charcoal packaging in sacks.

2.4. Laboratory Analysis

Laboratory analyses were conducted at the Wood Anatomy and Energy Laboratory of the FRIN, Ibadan. The prepared wood samples were evaluated for the following fuelwood properties: calorific value (MJ/kg), moisture content (%), volatile matter (%), ash content (%), basic density (kg/m³), and charcoal yield (%). The calorific values of the samples of biomass materials were determined using a bomb calorimeter. About 0.5 g each of these species was burnt, using the bomb calorimeter until completed combustion is obtained (Figures 8 and 9). The differences between the minimum and the maximum temperatures obtained for each of these species were used to compute the calorific values of the biomass materials. Volatile matter, ash content, fixed carbon and heat value were determined using this equation:

$$Q = \frac{C_{\text{water}} + C_{\text{cal}} (T_2 - T_1)}{W_t} \times 100 \quad (1)$$

Where: Q = Calorific value of species (kJ/kg) bomb calorimeter

C_{water} = Heat capacity of water

C_{cal} = Heat capacity of the bomb calorimeter $T_2 - T_1$ = Rise in temperature

W_t = Weight of the biomass material sample (kg)

Calorific value was determined using a Gallenkamp ballistic bomb calorimeter, following the standard procedure outlined in ASTM D5865-13 [17]. The bomb calorimeter was tightly sealed to prevent gas leakage, and volatile matter determination was conducted in a covered crucible at 950 °C for 7 minutes to minimize loss. These standard protocols are designed to prevent the escape of volatile compounds and ensure accuracy. Any minimal losses would be uniform across all species and therefore would not bias comparative performance evaluation. Oven-dried samples were ground into fine powder, and approximately 1 g of each sample was combusted in a pure oxygen atmosphere to measure the heat

released. Moisture content was determined using the oven-dry method. Fresh samples were weighed (W_1), dried at $103 \pm 2^\circ\text{C}$ to constant weight (W_2), and calculated using the formula:

$$\text{MC (\%)} = [(W_1 - W_2) / W_1] \times 100 \quad (2)$$

Volatile matter was determined by heating a known quantity of oven-dried powdered sample at 950°C in a covered crucible for 7 minutes, following ASTM D3175-11 [18]. Ash content was measured by burning oven-dried samples in a

muffle furnace at 600°C for 6 hours. The residue (ash) was weighed, and ash content (%) was calculated as a proportion of the original dry mass. Basic density was determined using the standard water displacement method. The oven-dried mass was divided by the green volume (based on water displacement), and expressed in kg/m^3 . Charcoal yield was determined through destructive distillation. Samples were placed in a covered metal drum and carbonized in a furnace at temperatures between $400\text{--}500^\circ\text{C}$ for 6 hours. The remaining charcoal was weighed, and yield was calculated as:

$$\text{Charcoal Yield (\%)} = (\text{Weight of charcoal} / \text{Original oven-dry weight}) \times 100 \quad (3)$$



Figure 8. Preparation for calorific value test.

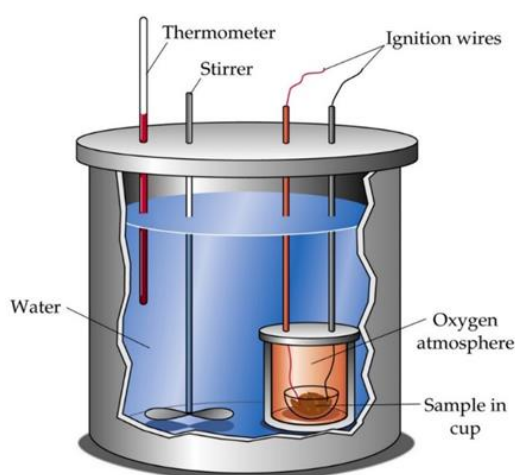


Figure 9. Bomb Calorimeter.

2.5. Experimental Layout and Data Analysis

The study was laid in a one-way ANOVA to analysis the sampled wood on the bases of species in a Completely Randomized Design (CRD) with a total of 8 treatment (wood species) replicated 5 times; in order to facilitate the interpre-

tation of the main and the evolving interaction effect. Parameters Measured were: Calorific Value (MJ/kg): using bomb calorimeter, Volatile Matter (%): ASTM D3175 [18], Ash Content (%): ASTM D1102, [19] Moisture Content (%): oven-drying method, Density (g/cm^3): displacement method, Charcoal Yield (%): traditional kiln method. The data obtained from laboratory text were Analyzed using Descriptive statistics. Estimates of mean, variance and standard error were worked out along with the significance test. Analysis of variance (ANOVA) was performed on the data to show the comparative performance of each treatment with others, where significant difference were found, Duncan's Multiple Range Test (DMRT) was applied on the bases of wood species in locating where the significant differences occurred among treatment means of selected wood variables this was as adopted by Akindele and Adesoye [20, 21]. Experimental Design: CRD with 8 species $\times$ 5 replicates ($n = 40$). Data Analysis: ANOVA and DMRT using MiniTab 27 ($\alpha = 0.05$).

2.5.1. Model for One Way ANOVA in a Completely Randomized Design (CRD) with 8 Wood Species as the Treatment

$$Y_{ij} = \mu + T_j + \sum ij \quad (4)$$

Where:

Y_{ij} = individual observation.

μ = General mean.

T_j = effect of treatment.

$\sum ij$ = Experimental Error.

2.5.2. Statistical Model

The Multiple Linear Regression Model (MLR) is given as:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n + \epsilon \quad (5)$$

Where: Calorific Value (MJ/kg): using bomb calorimeter, Volatile Matter (%): ASTM D3175 [18], Ash Content (%): ASTM D1102 [19], Moisture Content (%): oven-drying method, Density (g/cm^3): displacement method, Charcoal Yield (%)

Y : Calorific Value (MJ/kg) (Response)

The Calorific Value (MJ/kg) property being predicted:

X_1 = Volatile Matter (%), X_2 = Ash Content (%), X_3 = Moisture Content (%), X_4 = Density (g/cm³), X_5 = Charcoal Yield (%), X_6 = Dimensional Stability (%)

$X_1, X_2, X_3, \dots, X_n$: Input Variables (Predictors)

These are the chemical and physical properties of the wood:

β_0 : Intercept (The predicted value of Y when all X are zero).

$\beta_1, \beta_2, \dots, \beta_n$: Coefficients of the predictor variables

(These represent the effect of each independent variable on the dependent variable, holding all other variables constant.)

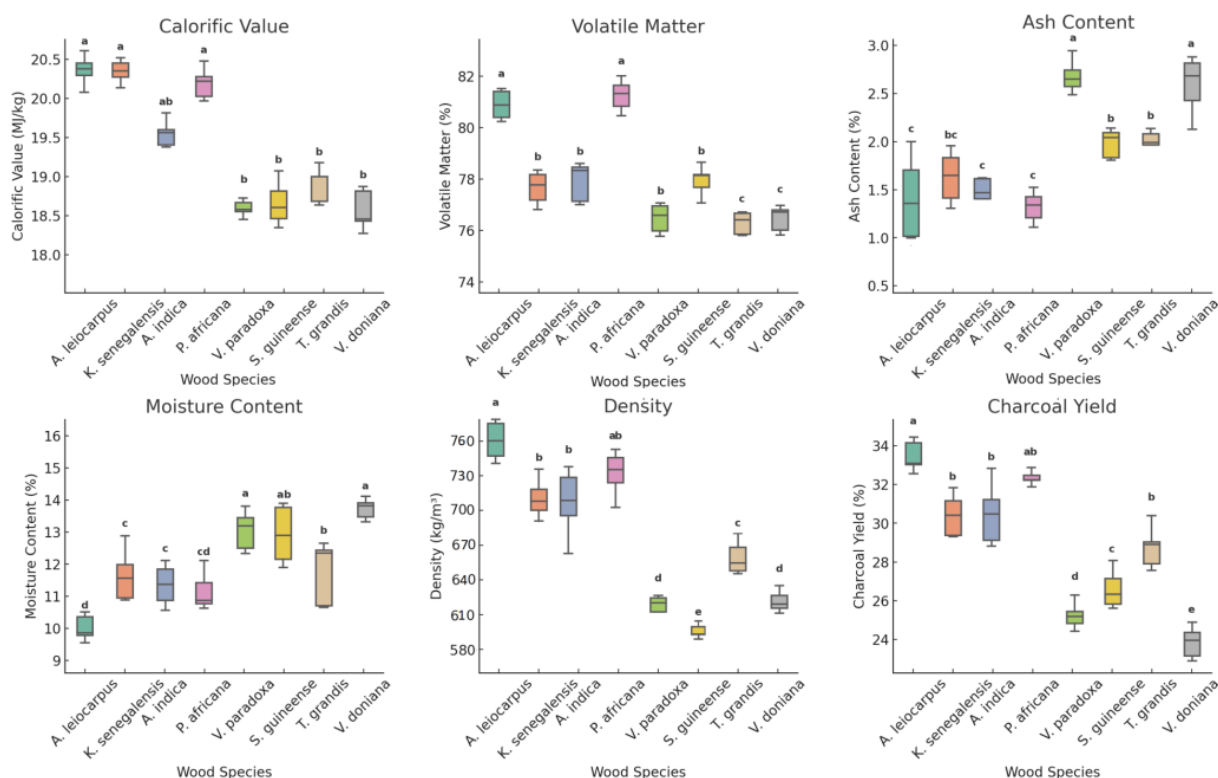
ϵ : Error term (Accounts for the variability in Y not explained by the predictors) [22].

3. Results

3.1. Fuelwood Properties and Suitability

The results indicated that, the suitability of fuelwood species is largely determined by their physical and combustion-related properties, including calorific value, density, moisture content, volatile matter, ash content, and charcoal yield. These characteristics directly influence the efficiency, cleanliness, and economic viability of each species as a household or industrial energy source. *Anogeissus leiocarpus*, *Khaya senegalensis*, and *Prosopis africana* emerged as the most promising species for fuelwood and charcoal production. These species recorded the highest calorific values, indicating greater energy output per unit mass. Their high densities

further support slow, sustained combustion a key trait for both domestic cooking and small-scale industries. Low moisture content in *Khaya senegalensis* and *P. africana* contributes to quicker ignition and cleaner burning, while their low ash content reduces the frequency of stove cleaning and improves combustion efficiency. Additionally, their high charcoal yields make them ideal for sustainable charcoal conversion. In contrast, *Vitellaria paradoxa*, *Vitex doniana*, and *Syzygium guineense* showed lower performance across several metrics. These species had comparatively lower calorific values, higher ash content, and higher moisture content. Factors that contribute to inefficient burning, increased smoke production, and reduced thermal output. While they may still serve as supplementary fuelwood sources, their inconsistent properties and lower charcoal yields limit their desirability for long-term energy use. *Azadirachta indica* and *Tectona grandis* presented intermediate properties. While not as energy-dense as the top performers, their moderate calorific values, ash content, and relatively stable density suggest they may be suitable in mixed-species fuelwood bundles or for short-term energy needs (Figure 10). On a general note, *Anogeissus leiocarpus*, *Khaya senegalensis*, and *Prosopis africana* are the most suitable Species for high-efficiency fuelwood and charcoal production in the region. Their combination of high energy output, stable combustion, and minimal waste aligns with the growing demand for sustainable and clean-burning biomass energy.



Alphabets with the same alphabet in the same column are not significantly different, ns = not significant at $p < 0.05$ (N=40)

Figure 10. Properties and Suitability of studied species.

3.2. Energy Potential and Combustion Behavior of Selected Wood Species

The relationship between wood density and calorific value of the studied species provides important insight into the fuel quality of the studied species. The results from the scatter plot show a clear clustering of species according to energy potential and combustion behavior. Species such as *Prosopis africana* and *Anogeissus leiocarpus* stand out for their high wood density (0.73 and 0.76 g/cm³) combined with calorific values. These properties translate into longer burn time, higher heat

output, and better charcoal yields. The moderate-to-fast combustion rating observed in these species confirms their suitability for both domestic energy needs and industrial applications such as charcoal production. On the other hand, species like *Parkia biglobosa* with medium density and moderate calorific value still remain relevant due to availability, ease of harvesting, and balanced combustion behavior (Figure 11). These tend to ignite faster and are less demanding in terms of handling and processing, which makes them preferred for short-duration cooking in rural households.

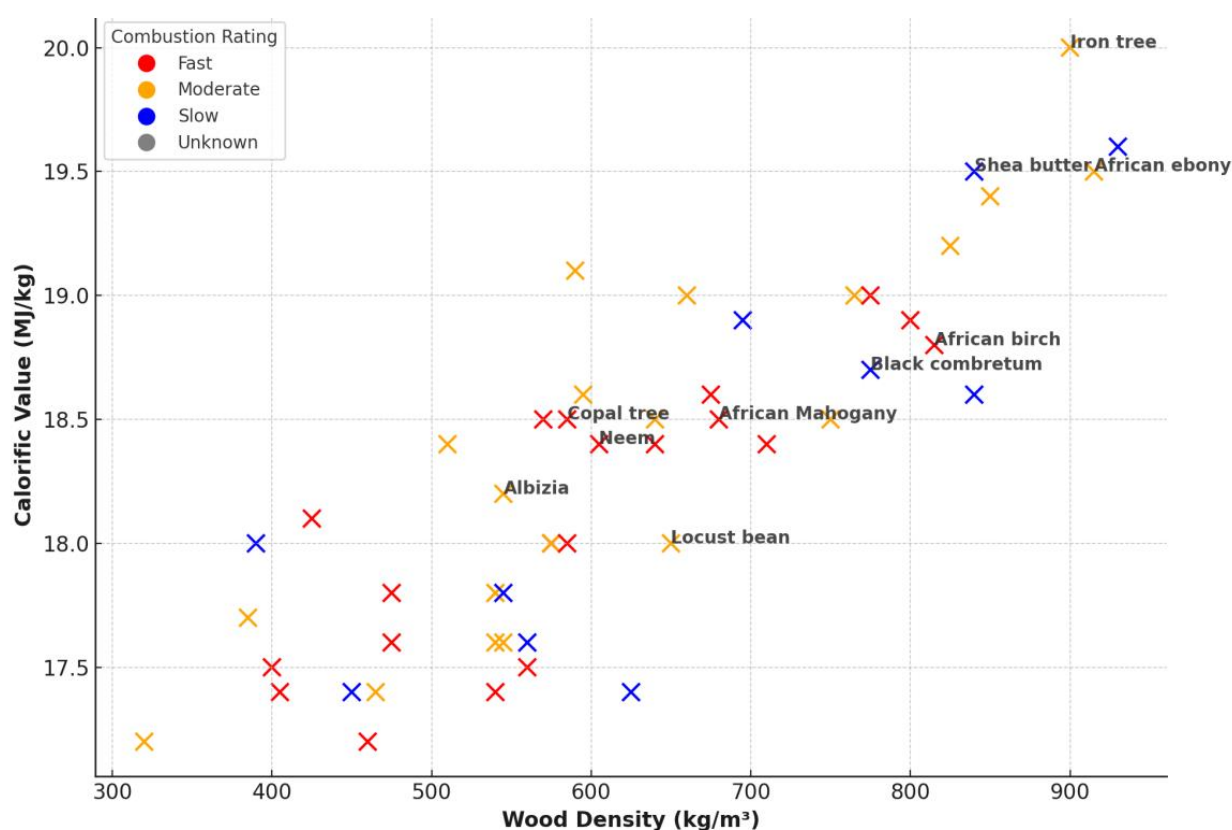


Figure 11. Fuel wood properties of studied species: Calorific value vs wood density.

3.3. Results of Correlation Analysis on Measured Wood Characteristics

A strong positive correlation is observed between calorific value and charcoal yield ($r = 0.877^{**}$). This means species with higher energy content produce higher charcoal output. Similarly, volatile matter also shows a positive relationship with charcoal yield ($r = 0.776^{**}$), reflecting its role in efficient combustion and energy release. In contrast, ash content shows a strong negative correlation with both calorific value ($r = -0.767$) and charcoal yield ($r = -0.882^{**}$). High ash content reduces the energy available for combustion and decreases charcoal output, making low-ash species more desir-

able for fuelwood and charcoal production. Moisture content also exhibits a strong negative relationship with charcoal yield ($r = -0.895^{**}$) and calorific value ($r = -0.813$). High moisture lowers energy efficiency by requiring more energy for drying during combustion, resulting in lower effective heat output and reduced charcoal yield. Density shows a positive correlation with calorific value ($r = 0.713^{**}$) and charcoal yield ($r = 0.734^{**}$). Denser woods generally have higher energy storage per unit volume, leading to longer burn times and higher charcoal production efficiency (Figure 12). Overall, the heatmap confirms that the best-performing species with high calorific values and charcoal yield preferred for fuelwood are those with high density, low ash content, and low moisture content. These correlations support the selection of

species such as *Prosopis africana* and *Anogeissus leiocarpus* as premium fuelwood options.

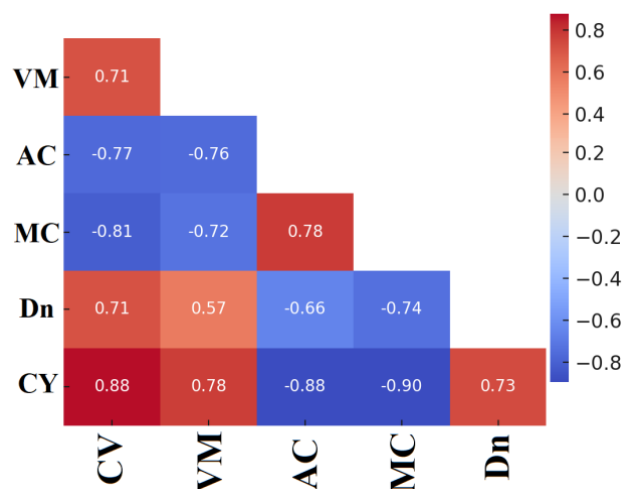


Figure 12. Correlations analysis of fuelwood properties.

VM - Volatile Matter; AC - Ash Content; MC - Moisture Content; Dn - Density; CY - Charcoal Yield.

3.4. Results of Regression Analysis and Designed Model

The multiple linear regression models explored how various wood properties influence calorific value (MJ/kg). With an R^2 of 0.856, the model explains approximately 86% of the variance in calorific value, indicating strong predictive power. Among the predictors, moisture content and ash content had significant negative coefficients ($p < 0.01$), implying that as these values increase, the calorific value significantly decreases. This aligns with combustion principles high moisture reduces ignition efficiency, while ash represents non-combustible residue that limits heat output. Density and

charcoal yield were both significant positive predictors. Denser wood typically contains more fuel mass, leading to longer burn time and higher energy release. High charcoal yield suggests greater thermal efficiency during carbonization, reinforcing its importance as an indicator of fuel value. Interestingly, volatile matter, though positively correlated with calorific value, did not show a statistically significant influence ($p = 0.489$). This suggests that while volatile compounds contribute to initial combustion, their role is overshadowed by more influential properties like moisture and density when considered simultaneously. Therefore, selecting species with low moisture and ash content, and high density and charcoal yield, offers the best strategy for maximizing calorific value and energy efficiency in fuelwood applications (Table 2).

Volatile matter was positively influenced by ash content and negatively by density. This suggests that lighter woods with higher ash tend to release more volatile gases during combustion. R^2 of 0.755 indicates a strong model fit. Moisture content showed a significant negative effect on ash, while volatile matter increased it. This aligns with the idea that moist wood burns less completely, resulting in lower ash formation. The model explains 82.5% of variation in ash content. Moisture was strongly predicted by ash content and inversely by charcoal yield. This implies that woods with high residual ash tend to retain more moisture, while high-yield charcoaling species tend to be drier. The model fit is strong ($R^2 = 0.705$). Wood density was negatively predicted by volatile matter and positively by charcoal yield. This suggests denser species burn more completely and retains less volatile material, which may enhance charcoal output. Moderate model fit ($R^2 = 0.691$). Charcoal yield was strongly influenced by ash and moisture (both negative), and positively by density. This model ($R^2 = 0.842$) confirms that dry, dense woods with low ash content are the most efficient for char production (Table 3).

Table 2. Regression analysis of assessed parameters.

Predictor Variable	Coefficient (β)	Std. Error	t-value	p-value	R^2
Moisture Content (%)	-0.314	0.038	-8.263	0.001	0.755
Volatile Matter (%)	+0.042	0.059	0.712	0.489	0.825
Ash Content (%)	-0.272	0.038	-7.157	0.001	0.705
Density (kg/m ³)	+0.016	0.005	3.198	0.015	0.691
Charcoal Yield (%)	+0.128	0.031	4.132	0.004	0.842

Table 3. Summary of regression models for key fuelwood parameters.

Dependent Variable	Significant Predictors	R ²	p-value
Volatile Matter (%)	Ash Content (+), Density (-)	0.755	0.01
Ash Content (%)	Moisture (-), Volatile Matter (+)	0.825	0.01
Moisture Content (%)	Ash Content (+), Charcoal Yield (-)	0.705	0.01
Density (kg/m ³)	Volatile Matter (-), Charcoal Yield (+)	0.691	0.05
Charcoal Yield (%)	Ash Content (-), Moisture (-), Density (+)	0.842	0.01

The multiple regression analysis yielded a model with an R² of 0.856, indicating strong predictive ability. The fitted regression equation is:

$$CV = 15.20 - 0.314(MC) - 0.272(AC) + 0.016(D) + 0.128(CY) + 0.042(VM)$$

where CV = Calorific Value; MC = Moisture Content; AC = Ash Content; D = Density; CY = Charcoal Yield; VM = Volatile Matter. This equation confirms that moisture and ash contents reduce calorific value, while density and charcoal yield enhance it. Volatile matter showed a positive but non-significant effect.

4. Discussion

The study assessed the combustion properties of eight commonly used fuelwood species in Nasarawa State, Nigeria, with the aim of identifying those most suitable for energy generation based on key physical and thermal characteristics. The findings clearly indicate that species such as *Anogeissus leiocarpus*, *Khaya senegalensis*, and *Prosopis africana* consistently outperformed others across multiple parameters, including calorific value, density, moisture content and charcoal yield. These species demonstrated the highest energy output, lowest ash production, and most efficient carbonization profiles. The regression analysis further reinforced these results, showing that moisture content, ash content, density, and charcoal yield were significant predictors of fuel performance. These outcomes confirm the initial hypothesis that fuelwood species differ significantly in their energy-related properties, and that a select few exhibit optimal characteristics for both combustion and charcoal production. Thus, the hypothesis is accepted, and the study provides clear evidence for the superiority of certain indigenous species in meeting sustainable bioenergy needs.

The results show significant variation in fuelwood properties among species. Teak and *Prosopis* exhibited high calorific values, making them ideal for energy purposes. Neem and Shea butter showed higher ash and moisture content, which may reduce efficiency. The density and charcoal yield also varied, with *Khaya* and *Vitellaria* performing well in charcoal conversion. These findings are consistent with previous studies [5, 23]. Evbuomwan and Okorji [8] opined that, fast-burning species like *Gmelina*, *Ficus*, and *Obeche* tend to

have higher volatile content, making them suitable for quick combustion applications. Volatile matter reflects how easily wood ignites and the amount of smoke/flame produced. Higher values mean easier ignition and quicker combustion, while lower values imply steadier, longer burns. Broadleaf *Ficus* and *Sterculia* species again show high volatile content, useful for easy ignition and short-burst fuelwood applications FAO [17]. Higher volatile matter in *Ceiba pentandra*, *Spondias mombin*, and *Nauclea latifolia* makes them ideal for kindling and fire-starting. Denser woods like *Pterocarpus* and *Acacia* have lower volatile matter and burn more slowly [8].

The result also confirms that lower-density species may not match the long-burning efficiency of denser woods, but their quick ignition and cleaner burning can make them more desirable for urban cooking environments where time and indoor air quality are important factors [24, 25]. Traditional and improved stoves, coupled with emissions monitoring, would strengthen external validity and connect species selection to measurable health and climate co-benefits [26-28]. From a sustainable woodlot management perspective, prioritizing species with high density, high calorific value, and moderate to fast combustion offers the best balance between energy efficiency and resource sustainability. However, the inclusion of medium-density, moderate-calorific species in planting programs ensures diversity, resilience, and continued supply across different energy needs. These findings are consistent with earlier studies that emphasized the value of *Prosopis africana*, *Anogeissus leiocarpus*, and *Vitellaria paradoxa* as premium fuelwood species. At the same time, they reinforce the need for species diversity to address the varied demands of households, commercial users, and industrial producers [16-18].

The results of the study further identified *Anogeissus leiocarpus*, *Khaya senegalensis*, and *Prosopis africana* as high-performing fuelwood species. Amoah, and Cremer; Antwi-Boasiako, and Boadu, [29, 30] reported high calorific values in thirteen tree and shrub species with low ash content in *A. leiocarpus*, making it a preferred choice in Ghanaian

savannah communities. Similarly, Owonubi et al. [31] found that *Khaya senegalensis* consistently produced high-density wood with low moisture content, traits that correlate with long burn time and efficient heat release. Our findings regarding the negative impact of ash and moisture content on calorific value are in agreement with the observations of Akachuku and Iyamabo [32], who highlighted that high ash levels reduce fuel quality by contributing to incomplete combustion. Furthermore, the high charcoal yield observed in *P. africana* corresponds with the work of Aina et al. [33], who found this species to be highly efficient in traditional kiln carbonization due to its dense structure and low volatile content. Overall, these comparisons confirm that the species identified in this study not only perform well under controlled assessment but also reflect broader regional trends in fuelwood suitability.

The study further expresses practical implications for fuelwood use and sustainability for household energy, small-scale industry and forest resource management. Prioritizing species with high calorific value, low moisture and ash, and adequate density can deliver cleaner, longer-burning heat while reducing residue and stove maintenance. In contexts where household air pollution remains a major risk, selecting efficient fuels is an immediate, low-cost lever alongside stove improvements [27, 28, 34]. In particular, *A. leiocarpus*, *K. senegalensis*, and *P. africana* match the profile of efficient fuels properties that translate to better thermal performance and fewer emissions per useful unit of heat. Encouraging uptake of such species can also ease harvesting pressure on less suitable once, aligning energy access with sustainable woodlot management [17, 26, 35]. This is especially critical in regions where fuelwood remains the primary energy source and inefficient combustion contributes to health risks and indoor air pollution. Moreover, encouraging the use of high-efficiency species may reduce overharvesting pressure on less suitable trees, thereby supporting sustainable forest use [36]. The results also provide a scientific basis for energy policy development, guiding afforestation programs, species selection for fuelwood plantations and prospect structural works [37]. In the long term, aligning combustion efficiency with ecological sustainability can significantly enhance rural livelihoods while conserving biodiversity and mitigating land degradation [38].

The study further shows the interconnected nature of wood properties and their collective impact on energy output. The negative associations of moisture and ash with calorific value, and positive roles of density and charcoal yield, are consistent with combustion fundamentals: water must be evaporated before flaming, while ash dilutes combustible matter and promotes slagging [39, 40]. Our regression approach also aligns with established proximate-analysis models that predict fuel heating value from moisture, volatile matter, and ash [41, 42]. In practice, such models can screened fit species (or even batches of fuel) before use, helping practitioners and agencies prioritise high-performing feedstocks without exhaustive lab testing. The validation from regression models further revealed that moisture and ash content are significant predictors

of calorific value, while charcoal yield and density enhance thermal performance. The use of predictive modelling in this context moves the research beyond descriptive classification of wood species toward a more robust, data-driven framework for fuelwood selection.

5. Conclusion

This study evaluated the physical and thermal properties of eight commonly used fuelwood species in Nasarawa State, with the goal of identifying those most suitable for efficient energy production. The results reveal that *Anogeissus leiocarpus*, *Khaya senegalensis*, and *Prosopis africana* possess superior combustion characteristics, including high calorific value, low moisture and ash content, and excellent charcoal yield. These properties make them ideal for both domestic and small-scale industrial energy needs. These findings not only support the initial hypothesis of species variability in fuel efficiency but also provide a scientific basis for guiding species selection in sustainable forest management and bioenergy planning. Ultimately, promoting the use of high-performing fuelwood species can help improve energy efficiency, reduce environmental degradation, and support cleaner biomass use in rural communities. Further studies could explore seasonal variability wood species and combustion efficiency.

Abbreviations

ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
DMRT	Duncan's Multiple Range Test
FRIN	Forestry Research Institute of Nigeria

Conflicts of Interest

The authors declare no conflicts of interest.

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