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Performance Evaluation of a Developed Miniature Steam Boiler Using Different Samples of Wood Waste as Fuel for Steam Generation

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Abstract

The adoption of Waste-to-Energy Technology (WTE), which allows solid wastes to be burned in a locally fabricated prototype boiler to generate steam for energy utilization is a response to some of Nigeria's most pressing issues. This study focuses on the performance evaluation of a developed miniature steam boiler using various samples of wood waste as fuel for steam generation. The wood wastes; *Cordia millenii, Terminalia ivorensis*, and *Lophira alata* were characterized to determine the proximate and ultimate analysis to ensure better combustion sustainability. The gross heat of combustion of each residue was measured by calculating the wood waste's calorific value. The test results have shown that the wood wastes had a volatile substance content of more than 72%. A low ash content of 3.91%, 2.67%, and 1.93% were obtained for *Terminalia ivorensis, Cordia millenii*, and *Lophira alata*. Similarly, for *Cordia millenii, Terminalia ivorensis*, and *Lophira alata*, the percentages of fixed carbon obtained were 17.98%, 8.95%, and 27.65%, respectively. Furthermore, the calorific values for *Cordia millenii, Terminalia ivorensis*, and *Lophira alata* are 20.01 MJ/kg, 21.22 MJ/kg, and 19.99 MJ/kg, respectively. Besides, the electrical energy produced by burning 2 kg of wood waste and the efficiency of the steam boiler were found to be 90.33% and 55 kW. Therefore, *Terminalia ivorensis* wood waste sample is the best fuel for the steam boiler as compared to *Cordia millenii*, and *Lophira alata.*

1. Introduction

Among the most important issues facing Nigeria now are the availability of energy and the management of solid waste. The adoption of Waste-to-Energy Technology (WTE), which allows solid wastes to be burned in a locally built prototype boiler to generate steam for energy usage, is an attempt to address both issues. Biomass can be utilized as fuel to test run the boiler for steam generation. Examples of biomass include fiber [1-3], palm kernel shell [4-7], wood waste [8-11], and other combustible waste [12-15]. Nigeria produces a large amount of waste from biomass, a renewable energy source that can replace the fossil fuels that burn and contribute to global warming. Sadly, the country has not been able to completely utilize the waste from biomass to produce energy [16-18]. Several investigations into alternative fuel sources for heat generation that don't require burning fossil fuels were also prompted by developed countries' search for cleaner fuels [16]. Researchers from Nigeria have recently shown a greater interest in biomass energy [19–22].

Nomenclature	
Cv	Calorific value of fuel in kJ/kg
h	Specific enthalpy of steam
hf	Specific enthalpy of feed water
Ma	Mass of water evaporated into steam per kg of fuel at the working pressure
TEP	Thermal energy potential (kW_{th})
V	Rate of wood waste collected per unit time (m^3/s).
W	Original weight of wood of sample (g)
△W	Change in weight of wood sample (g)
% Mc	Percentage moisture content
η	Overall boiler efficiency
ρ	Density (kg/m3),

According to data from the Energy Commission of Nigeria (ECN), 95% of fuel wood is used domestically for cooking and small-scale industrial processes including processing oil seeds and cassava [23]. However, if correctly included in the energy mix, this biomass waste can meet the energy need. The nation's biomass resources include waste paper, sawdust and wood shavings, agricultural crops, oil palm fruit residues, forestry [24-28] and fuel wood residues, animal dung and poultry droppings, energy crops, industrial effluent, and municipal solid waste [29-41]. When biomass is transformed into contemporary energy carriers, it can significantly increase its contribution to the renewable energy industry while also having favorable environmental effects. One of the main pillars of any effective waste management system and a means of securing future energy supply is waste-to-energy. The conversion of waste into climate-friendly electricity benefits both the environment and humanity. A waste-to-energy plant can provide desalinated seawater, district cooling, steam and heating for industry, and electricity, among other products. Furthermore, waste-to-energy plants perform better than other waste treatment methods in the majority of configurations of their environmental effects, including their carbon footprint. As vital parts of thermal power plants, steam boilers are crucial to supplying our energy needs. It is vital to get higher efficiency in steam boilers to maximize energy use and minimize the environmental effect [42, 43]. Boilers and related equipment are always needed to run more effectively because fossil fuels are becoming scarcer and environmental concerns are growing. The need for better boiler design is fueled by this requirement. To determine which aspects of boiler systems require alteration and by what order, a thorough performance study of boiler systems is necessary. The parts that cause the biggest thermodynamic losses are the ones with the greatest room for improvement. The primary fuel source used by enterprises to produce process steam and electricity comes from boilers [44-47]. Therefore, a portable boiler that can accomplish the same task with a suitable output is required. The performance evaluation of a built tiny steam boiler employing various samples of wood waste as fuel for steam generation is the main topic of the current study.

2. Materials and Methods

2.1 Materials and Equipment

The miniature steam boiler generator is a vertical steam boiler with the dimensions of length of 1200mm, width of 1000mm, height of 1100 mm, safety valve outlet diameter of 35 mm, steam outlet diameter of 40 mm, feed water inlet diameter of 20 mm, boiler water drainage diameter of 25 mm, and inner cylindrical drum diameter of 500 mm. It is made from the following materials and equipment:
i. An outer rectangular covering box made with ASTM A516 grade 60carbon steel plate,
ii. An inner cylindrical drum made with an ASTM A537 carbon steel plate,
iii. A rigid frame produced using a mild steel,
iv. A carbon steam pipe designed according to ASME B16.9 A106 standard,
v. A wood sawdust insulation functioning as low thermal conductivity,
vi. A chimney pipe made with a galvanize steel,
vii. Considering the safety of the miniature steam boiler and its operator, a pressure relief valve boiler was installed in the generator,

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viii. For accurate pressure gauging of the generator, a barometer was installed. The pressure gauge is in the range of 1bar –18bar,
ix. A thermometer was installed to measure the temperature that ranges from 0°C-650°C,
x. To evacuate the generated steam from the steam-producing chamber, an HSN 8481 ball valve made with cast iron was used.

2.2 Description of the Flow Process of the Steam Boiler Generator

The steam boiler generator's process chart is displayed in Fig. 1. The thermal energy from the combustion of wood waste samples is used by the steam boiler generator. Heat energy is subsequently transferred to the feed water inside the cylinder drum through the cylinder drum. As the combustion chamber fires more, the temperature of the feed water rises. Once the feed water reaches the boiling point, saturated steam starts to boil. This steam is then collected in a steam drum and heated further by connecting a steam pipe to the flue gas pipe. To further reheat and dry the steam to a superheated state, the reheated steam from the flue gas pipe is delivered into the combustion chamber. A pipe leading from the combustion chamber to the steam distribution manifold, which can hold steam for process operations as well as steam for power generation, connects this dry, superheated steam. Fig. 2 depicts the developed steam boiler generator in pictorial form.

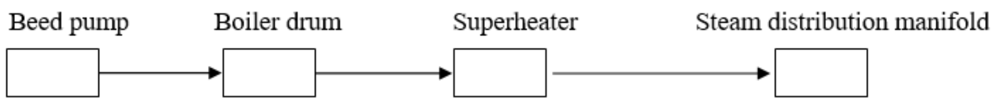


Fig.1 *Description of process chart of the steam boiler generator*

Fig. 2 *Pictorial view of the developed steam boiler generator*

2.3 Sorting and Collection of Wood Waste Samples

This study uses three distinct biomass samples made from wood waste: Omah (*Cordia millenii*), Afara (*Terminalia ivorensis*), and Ekki (*Lophira alata*). From the sawmill, the samples are gathered and sorted. For a week, the primary purpose of the initial visit to the sawmill (refer to Fig. 3) was to inspect the wood processing methods. The available wood sample sorting process comes next. Sorting entails removing undesired items that were affixed to the previously described study samples. The collected biomass wood waste was then labeled with the following information:
i. Omah (*Cordia millenii*),

ii. Afara (*Terminalia ivorensis*), and
iii. Ekki (*Lophira alata*)

a. Saw mill machine b. Saw woods

Fig. 3 *Pictorial of the wood saw mill*

2.4 Preparation of Wood Waste Samples

The collected wood samples were air-dried and this is to lower the moisture content and so stop fungal deterioration. The temperature at which the three samples were dried was 105 °C in the lab oven. Once a steady mass was reached, the drying process was terminated. The samples of waste wood were ground and sieved to 1.5 mm particle sizes using a pulverizing machine. The various samples were subjected to experiments to assess their calorific values and proximal, and final analyses. The American Society for Testing and Materials Standards, ASTM E870-82 [48] and ASTM D4442-07 [49], were followed in doing this.

2.5 Proximate and Ultimate Analyses

In compliance with ASTM E870-82, the proximal and ultimate analyses were performed [19]. Proximate analysis was utilized to analyze the physicochemical characteristics of the wood samples used in this study, including the percentage of fixed carbon, the percentage of ash content, and the volatile matter. Additionally, an ultimate analysis was performed to ascertain the proportions of hydrogen (H), carbon (C), nitrogen (N), oxygen (O), and sulfur (S) in each sample.

2.6 Determination of Calorific Value of the Wood Waste for Combustion

One gram of each prepared sample was weighed and added to the crucible [50]. After recording the samples' initial temperature, a known weight of fuse wire was placed between the electrodes. In addition, the wire was in direct touch with the fuel, primarily to absorb nitrogen and sulfur combustion products. In addition, the bomb received two milliliters of water and oxygen through the valve until a pressure of twenty-five pounds per square inch was attained. The device was then submerged in the calorimeter's water. Stirrings, connecting all required electrical components, and monitoring a constant temperature came next. The temperature was recorded after the fuel was ignited. After the bomb was taken out, the exhaust valve allowed the pressure to drop gradually. The contents of the device were carefully weighed before being subjected to additional scrutiny. The calorimeter and the surrounding water absorbed the heat that the fuel released during combustion. The bomb calorimeter experiment was used to quantify each residue's gross heat of combustion using Equation (1) [50]. Consequently, the wood waste's calorific value for burning was determined.

$$Cv\ (kJ/kg) = \frac{\mathrm{C\Delta T}-(e_1+e_2+e_3)}{\mathrm{m}} \quad (1)$$

where,
Cv = Calorific value of fuel in kJ/kg
$\triangle$T = Change in temperature, m
m = Mass of samples (g)
C = Heat capacity of bomb calorimeter
e_1, e_2, e_3 = Corrections for the formation of nitric acid, sulphuric acid, and fuse wire.

2.7 Determination of Percentage Moisture Content

The moisture content of each wood waste sample was calculated using Equation (2) based on the weight change after oven drying.

$$MC = \frac{\Delta W}{W} \times 100\% \quad (2)$$

where,
MC = Moisture content,
△W = Change in weight of sample
W = Original weight of sample

2.8 Determination of Steam Boiler Efficiency

Equation (3) provides the steam boiler efficiency, which is the ratio of heat used in steam generation to the heat provided by fuel.

$$\eta = \frac{\mathrm{Ma}\ (\mathrm{h-hf})}{\mathrm{Cv}} \quad (3)$$

where,
η = Steam boiler efficiency
M_a = Mass of water actually evaporated into steam per kg of fuel at the working pressure
h = Specific enthalpy of steam
h_f= Specific enthalpy of feed water
Cv = calorific value of fuel
The boiler and the super-heater are considered as a single unit; thus, the boiler efficiency is regarded as the overall efficiency of the steam boiler.

2.9 Thermal Energy Potential

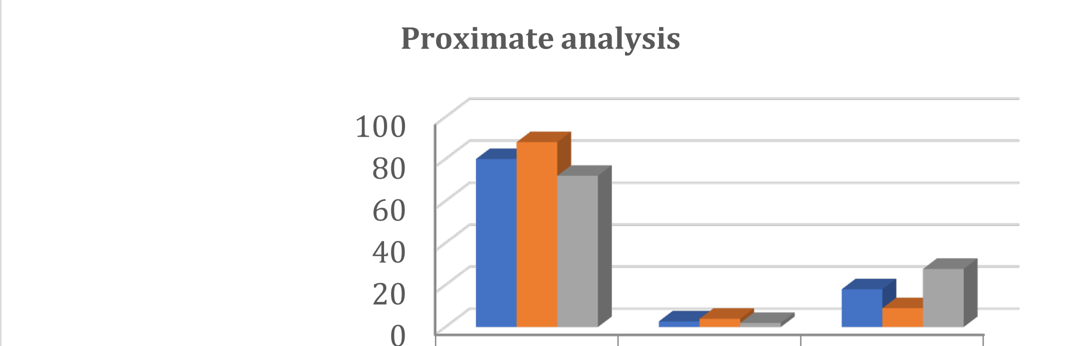
The actual quantity of thermal energy stored in each sample of wood waste per unit of time is known as the thermal energy potential. Equation (4) was utilized to ascertain it.

$$TEP = \rho \times V \times Cv \quad (4)$$

where,
TEP = Energy potential (kWth),
ρ = Density (kg/m3),
V = Rate of wood waste collected per unit time (m3/s),
Cv = Calorific value of wood waste
It was assumed that a conversion efficiency of 32% [50] converted the thermal energy potential to electrical power in kW_{el}. Therefore, $1kW_{el}$ is numerically equal to 0.32 kW_{th}.

3. Results and Discussion

Fig. 4 displays the findings of the wood waste's proximate analysis. Volatile matter is known to have a significant impact on the thermal breakdown and combustion characteristics of solid fuels [51, 52]. Therefore, the proximate analysis of the chosen wood waste cannot be disregarded to guarantee that the best ideal conditions of wood waste are used for the performance evaluation of the constructed tiny steam boiler. The findings showed that the percentage of volatile matter in the wood wastes was higher than 72%. Of the wood wastes, *Terminalia ivorensis* had the highest percentage of volatile solids at 88.05%, followed by *Cordia millenii* at 80.01% and *Lophira alata* at 72.02%. Since the larger the proportion of volatile matter, the more suitable it is for thermal conversion, as shown by [53, 54], the high values of the percentage volatile solids of the wood waste species are a good indication of better performance if utilized as a feedstock for the steam boiler. In addition, a minimum ash content in the feedstock is necessary for optimal steam boiler efficiency. According to Loo and Koppejan [52], a fuel's heating value decreases with increasing ash content. The percentage of ash content, or the projected non-combustible portion of the fuel made from wood waste, was low in this instance. *Terminalia ivorensis*, *Cordia millenii*, and *Lophira alata* were found to have ash contents of 3.91%, 2.67%, and 1.93%, respectively. The findings of the proximate analysis of the wood waste indicate that the wood samples will ignite easily with a stable flame during combustion, generating a high heating value. Similarly, the percentages of fixed carbon obtained for the wood samples were 17.98%, 8.95%, and 27.65% for *Cordia millenii, Terminalia ivorensis*, and *Lophira alata,* respectively. The results of the percentage fixed carbon agreed with the research work of Akinola and Fapetu [20].



	% Volatile Matter	% Ash Content	% Fixed Carbon
Omah (Cordia millenii)	80.01	2.67	17.98
Afara (Terminalia ivorensis)	88.05	3.91	8.95
Ekki (Lophira alata)	72.02	1.93	27.65

Fig. 4 *Proximate analysis of wood waste*

The findings of the wood wastes' percentage moisture content and calorific value are displayed in Fig. 5. A minimal percentage moisture content was achieved, according to the results, which showed values of 7.85%, 6.95%, and 7.05% for *Terminalia ivorensis, Lophira alata*, and *Cordia millenii*, respectively. Relatively low moisture content promotes thermo-chemical conversion, according to [53-56], since excessive moisture content lowers conversion system efficiency and, as a result, lowers the energy available from wood wastes during combustion, since heat would be needed to evaporate them. Additionally, the calorific values for *Cordia millenii, Terminalia ivorensis*, and *Lophira alata* are 20.01 MJ/kg, 21.22 MJ/kg, and 19.99 MJ/kg, respectively. Good energy content is indicated by the high calorific value obtained from the wood debris; these results are consistent with Huhtinen's research [55].

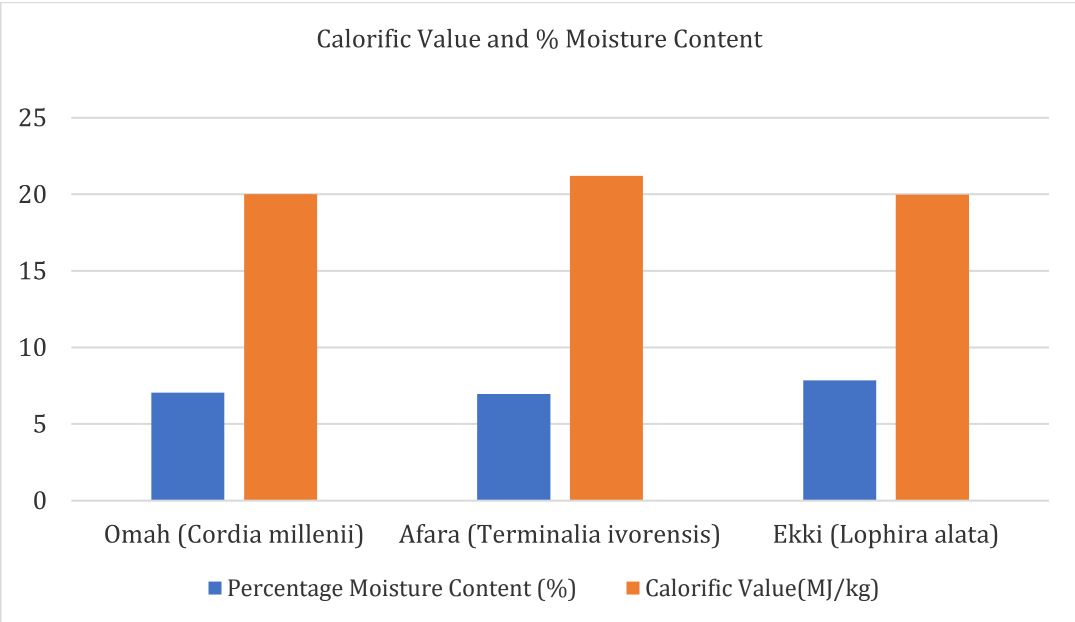


Fig. 5 *Calorific value and percentage moisture content of the wood waste*

Fig. 6 and Table 1 display the findings of the final examination of the wood waste samples as a percentage of dry weight. The findings show that of all the components present, carbon has the highest amount. This suggests that during combustion, the wood wastes' calorific value increased. For *Cordia millenii, Terminalia ivorensis*, and

Lophira alata, the percentage carbon content achieved was 59.29%, 58.99%, and 57.89%, respectively. These results were consistent with the work of Fapetu [21], which proposed a range of 50–60% for carbon content for wood biomass. Additionally, a large proportion of oxygen and hydrogen were collected, indicating the wood waste's great energy potential. Given the large proportion of carbon, hydrogen, and oxygen in the wood waste, efficient combustion should be anticipated, provided that the evaluated steam boiler is constructed correctly. High concentrations of carbon, hydrogen, and oxygen make up the majority of biomass feedstock and serve as the primary reactants in combustion processes, according to [56]. Furthermore, [57] proposed that low sulfur and nitrogen levels are necessary for adequate combustion, and the results of this investigation show that these levels are low.

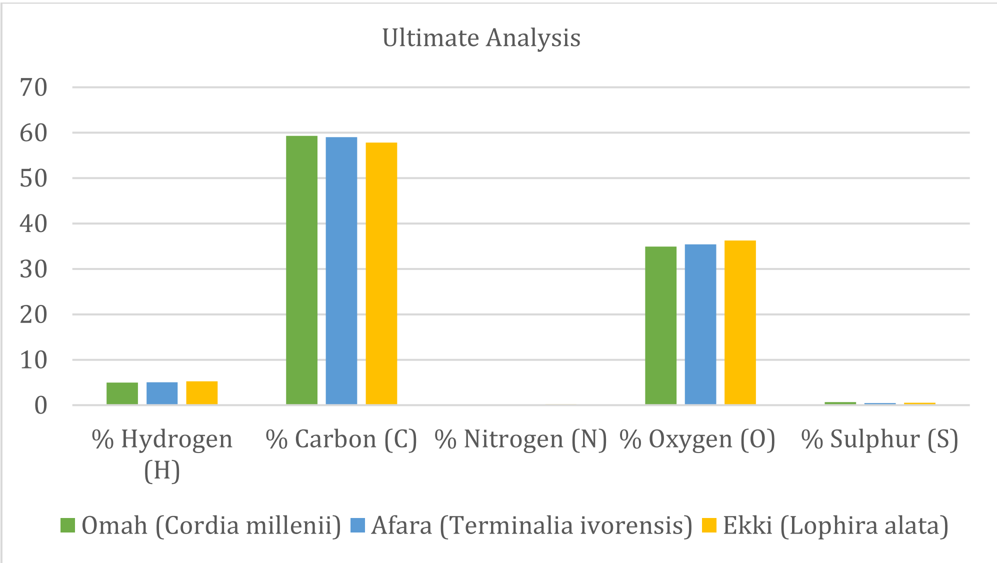


Fig. 6 *Results of ultimate analysis of wood sample*

Table 1 *Results of ultimate analysis of wood sample*

Wood Waste	% Hydrogen (H)	% Carbon (C)	% Nitrogen (N)	% Oxygen (O)	% Sulphur (S)
Omah (*Cordia millenii*)	4.99	59.29	0.12	34.95	0.65
Afara (*Terminalia ivorensis*)	5.01	58.99	0.12	35.43	0.45
Ekki (*Lophira alata*)	5.25	57.85	0.16	36.23	0.51

As shown in Fig. 7 and Table 2 are the data obtained from the analysis carried out during the performance test of the steam boiler.

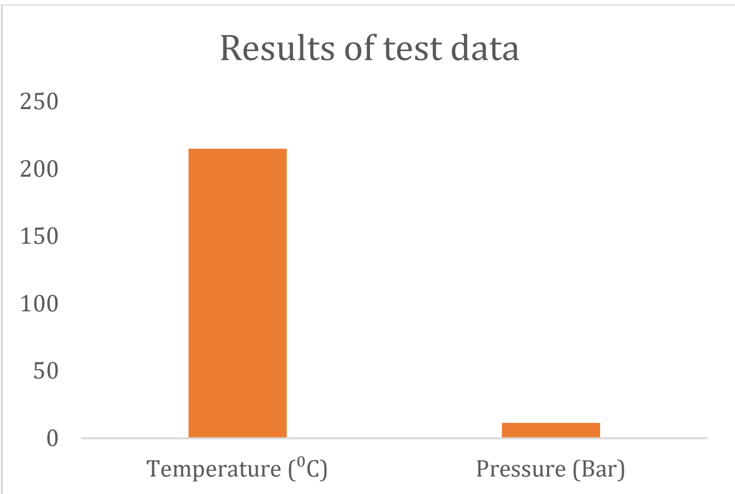


Fig. 7 *Results of performance test evaluation of steam boiler*

Table 2 *Results of performance test evaluation of steam boiler*

Parameter	Results
Temperature (^{0}C)	215
Pressure (Bar)	11.5

The boiler's efficiency was determined to be 90.33% based on the collected data. It was observed that lagging enhances heat retention in the boiler chamber. Another important element that helped achieve high boiler efficiency was the calorific value of the fuel wood. Furthermore, the boiler's flue gas and steam flow pipes were expertly welded and lagged to minimize heat losses. This was made clear by the statistics on temperature and pressure, which were recorded as 215^{o}C and 11.5 bar as depicted in Fig. 7. Using the results of the calorific value of wood waste, enthalpy of superheated steam 11.5Bar and 215^{0}C, combustion time, and mass of wood waste, it was established that 55 kW of electrical energy will be produced by burning 2 kg of wood waste in the boiler. It is crucial to note that the ash layer that forms on the surface of burning wood waste plays a significant role in regulating the rate of combustion. It does this in a useful way, giving the boiler a high power level early in the boiling process and a lower power level as the ash forms. As a result, during boiler operation, a constant energy level is maintained. Eliminating the ash layer is all that is needed to raise the power once more. The two walls should not readily conduct heat from the hot inner wall to the cold outer wall. This is because the dead air space and the wood waste are good insulators, and attaching the inner wall to the outer wall will tend to short-circuit its insulating value to the thermal conductivity of the metal. Also, grates were frequently used to improve combustion efficiency and perhaps lower pollutants. They improve air mixing with the fuel bed and the diffusion flames above by infusing air below the fuel bed, which probably improves both of their combustion. Because of this, it's critical to regularly clear the grates of ashes to ensure that airflow is not obstructed. Besides, limiting surplus air can boost performance, but if insufficient oxygen reaches the combustion chamber or if the air-fuel mixture is not optimal, it could also lead to an increase in emissions. For this reason, the combustion chamber's sides are perforated to provide sufficient airflow through the chamber. By ensuring that as little energy is lost as the steam leaves the steam drum and travels to the steam distribution manifold, the lagging of the steam pipe plays a critical part in the overall boiler efficiency.

4. Conclusion

In this study, the effectiveness of a wood waste-fueled steam boiler was evaluated. The findings showed that the wood samples utilized in this investigation are appropriate as fuel for procedures involving thermochemical conversion that produce electricity. In addition, *Terminalia ivorensis* had the greatest volatile solid percentage (88.05%), followed by wood wastes from *Cordia millenii* at 80.01% and *Lophira alata* at 72.02%. Additionally, a minimum ash percentage was discovered to be best for steam boiler efficiency, while the ash levels of *Terminalia ivorensis, Cordia millenii*, and *Lophira alata* were found to be 3.91%, 2.67%, and 1.93%, respectively. Similarly, for *Cordia millenii, Terminalia ivorensis,* and *Lophira alata,* the percentages of fixed carbon obtained for the wood samples were 17.98%, 8.95%, and 27.65%, respectively. The findings indicated that a minimum percentage moisture content was attained; *Terminalia ivorensis, Lophira alata,* and *Cordia millenii* showed values of 7.85%, 6.95%, and 7.05%, respectively. Furthermore, the calorific values of *Terminalia ivorensis, Lophira alata,* and *Cordia millenii a*re 21.22 MJ/kg, 19.99 MJ/kg, and 20.01 MJ/kg, respectively. The high calorific value of the wood waste indicates a good energy content. Since wood waste contains a significant amount of carbon, hydrogen, and oxygen, efficient combustion should be expected. Thus, *Terminalia ivorensis* wood waste sample is the best fuel for the steam boiler as compared to *Cordia millenii*, and *Lophira alata.* The electrical energy produced by burning 2 kg of wood waste and the efficiency of the steam boiler were found to be 90.33% and 55 kW, respectively.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contributions

Efe Justic Igbagbon and Ejiroghene Kelly Orhorhoro contributed equally to this work. Tega Emmanuel Erokare provided guidance and oversight.

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