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Original Research Article

Evaluation of the Performance of a Locally Fabricated Biomass Stove using Some Nigerian Woods

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ABSTRACT

In this study, a biomass stove was designed and experimentally tested to determine the boiling time of different volumes of water using six different species of wood (Mangrove wood, Mahogany, Obeche, Iroko, Celtis, Erimado). After the experimental procedure, the same species of biomass were combusted in a Computrac MAX 5000XL Wood Ash Analyzer at 180 ^oC and 600 ^oC to determine their heat retention time (HRT) and mass of wood ash. It was observed that Mangrove wood required the least time and the least mass of wood fuel, followed by Mahogany to achieve water boiling temperature of the aforementioned volumes while Celtis consumed the highest time and highest mass of wood fuels to achieve water boiling temperature of 100 ^oC. This signifies that the heating value of Mangrove Wood and Mahogany is higher than those of the other five biomass fuels investigated. It was also observed that Mangrove Wood had the least percentage of Carbon (40.2%), Potassium (6.6%), Calcium (21.3%), Zinc (0.23%) etc. in its ash content which played a vital role in the minimised smoke generated during combustion. From the analysis, Mangrove Wood had the highest HRT among the six (6) species of wood combusted at 180 ^oC, followed by Mahogany and Obeche as well as the least mass of ash followed by Mahogany and Obeche. This implies that biomass stove operated with biomass fuels like Mangrove wood, Mahogany, Obeche etc. can be environmentally friendly (in terms of less carbon emissions) for large scale consumption.

1. INTRODUCTION

Due to the increasing cost of liquefied petroleum gas (LPG) and kerosene, residents in most rural settlements find it difficult to afford them for preparing daily meals. As a result of that, firewood and charcoal (biomass) derived from forests becomes the principal energy source for cooking and heating in the rural settlements (Abd'razack et al., 2012; Ozoh et al., 2018). According to Maduka (2011), 55% of Nigerian residents use firewood and charcoal as their primary source of energy for heating and cooking at home. Ajah (2013) reported that fuel wood consumption is about 80 million cubic meters. Njenga et al. (2019) noted that wood fuel sustainability is a major challenge due to inefficient methods of converting wood into energy. Also, the use of inefficient cook stoves can contribute to wood wastage and exposure of users to risk associated with emissions from the stove. Sometimes, the combustion of these biomass fuels is done indoors with little ventilation, and substantial amounts of pollutants from the combustion process and continuous exposure of users to the emissions can increase the risk of respiratory problem in humans and animals (Sheth and Babu, 2009; Umogbai and Orkuma, 2011).

A biomass cooking stove was designed and evaluated by Odesola and Kazeem (2014) using biomass gasification principle to meet cooking energy requirement. The stove performed with an efficiency of 52-61.4% and percentage heat utilization of about 40.65%. Igboanugo and Ajieh (2017) designed and fabricated a biomass stove, which was compared to the traditional three-stone stove. Thermal efficiency of 55% was obtained from the deigned stove compared to the traditional three-stone stove which had a thermal efficiency of 18%. The design, construction and testing of an improved wood stove was carried out by Ayo (2009), and the performance test results show that the wood stove has a maximum thermal efficiency of 64.4%, power delivery of 2.52 kW, and a minimum specific fuel consumption of 0.447.

In recent times, studies have shown that some wood fuels when used in the proper medium have high heating value and less carbon emissions to satisfy the energy demand in most Nigerian settlements. Using water boiling test, Akpootu et al. (2014) carried out a comparative analysis on four (4) fuel wood stoves including Save 80, Single hole Improved wood stove, locally fabricated metal stove, traditional open fire stove. The result revealed that using 1.25 kg and 1.05 kg of fire wood, the traditional open fire stove and locally fabricated metal stove took an average of 40.66 min and 30.67 min to boil 2 liters of water at 100 ^oC, while using 0.75 kg and 0.30 kg of wood fuel in Single Hole Improved wood stove and Save 80 took an average of 28.00 min and 15.33 min to boil the same quantity of water at 100 ^oC.

Igboanugo et al. (2015) investigated the emissions from particulate matter and CO from briquette and fuel wood, and the test results were analyzed using MATLAB. The results obtained showed the burning rate of briquette fuel as 20.5 g/min and that of fuel wood as 16.8 g/min. The thermal efficiencies of briquettes and fuel wood were 14.5% and 31.1%. High thermal efficiency translates to less exposure to particulate matter (PM) and CO which reduces health problems associated with the burning of briquette and fuel wood in biomass stove. The analysis indicated that fuel wood emitted more PM while there was no significance in CO emission between the two (2) fuel feed stocks, whereas, result of paired sample indicated that both fuels emitted more PM and More CO. Sengar et al. (2015) developed a funnel shape biomass cook stove for cooking. Teak (*Tectona grandis* L. f.) and Khakro (*Butea monosperma*) wood species were selected as fuel wood, and their heating values were examined. Higher heating value of teak and khakro wood were found as 3765 kCal/kg and 3577 kCal/kg respectively. Thermal efficiency, power input, power rating and fuel consumption rate of the developed cook stove were 20.19 %, 17.76 kW, 3.55 kW and 4 kg/hr.

This study is focused on evaluation of the energy potential of some Nigerian woods in a locally designed biomass stove.

2. MATERIALS AND METHODS

2.1. Material

As shown in Table 1, the biomass stove was tested using six (6) different species of wood fuels obtained from sawmills in Benin City metropolis. As shown in Figure 1, the six samples of wood species used in this study were labeled properly to avoid mix-up of any sort.

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Table 1: Names of wood fuels used for experimental evaluation of the biomass stove

Wood fuel	Trade name	Scientific name	Other names
1.	Mangrove wood	*Rhizophora racemose*	Red mangrove; tall
2.	Mahogany (Dry zone)	*Khaya senegalensi*	Orere, Djave
3.	Obeche	*Triplochiton scleroxylon*	White-wood
4.	Iroko	*Milicia excels*	Mvule
5.	Celtis	*Celtis spp*	Esa
6.	Erimado	*Ricinodendron heudelotii*	Sanga-sanga wana

Figure 1: Samples of wood used for the analysis

2.2. Methods

Before the biomas stove was fabricated, it was initially designed using SOLIDWORKS software 2015 version. As shown in Figure 2, the biomass stove designed consisted of fuel gate which is the inlet where the biomass is fed through to the stove. Despite the high cost of stainless steel, it was used in designing the body of the biomass stove due to its unique property to withstand thermally and environmentally induced corrosion and low maintenance. As shown in Figure 3, the perforated plate which fitters the fuel ash is made from a mild steel plate of 2 cm thickness. The opening was designed to be of moderate size of about 2 cm x 2 cm, such that biomas can be fed through with ease. It has an ash tray, a steel plate and a chimney as well as a fuel gate (door) with hinges as shown in Figure 4a. The ash tray forms a base for the wood fuels as they are introduced into the stove through the fuel gate. In other words, cut pieces of biomass are placed on the ash tray prior to being introduced into the stove for combustion, and when the biomass is completely burnt, the tray is either removed or the bunt charcoal is removed while the tray is inside the stove. The purpose of the perforated plate is to allow air ingress into the combustion chamber for complete combustion to take place, which enable effective heat transfer through conduction and convection of the air molecules. It has a bore hole of 180 mm diameter which serves as base where the cooking pot is placed. Biomass are fed into and removed through the fuel gate. It also has a chimney incorporated by the side of the cylindrical stove to allow the migration of excess heat and smoke out of the combustion chamber of the stove. The chimney is like a vertical tube or hollow column used to emit environmentally polluting gaseous and solid mater, including but not limited to by-products of burning carbon or hydrogen-based fuels. In this case, it diverts the direction of theses migrating pollutants from the fuel gate directly into the atmosphere where its interaction with air becomes less harmful to the stove users.

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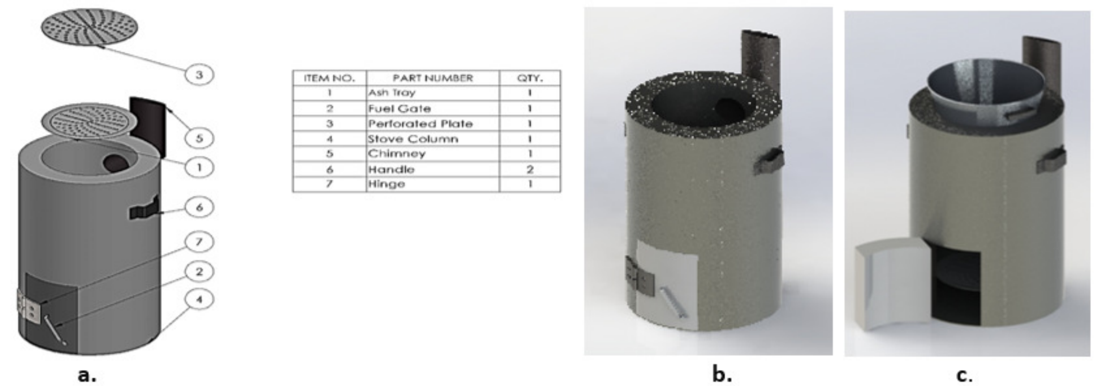

ITEM NO.	PART NUMBER	QTY.
1	Ash Tray	1
2	Fuel Gate	1
3	Perforated Plate	1
4	Stove Column	1
5	Chimney	1
6	Handle	2
7	Hinge	1

Figure 2: Assembly drawing of the biomass stove

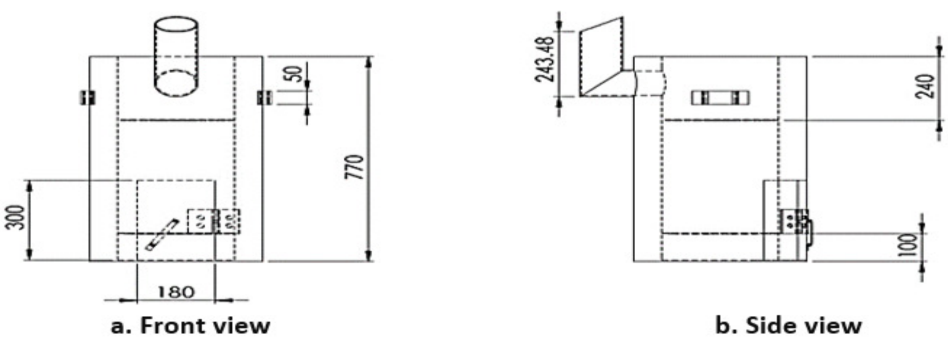

Figure 3: Orthographic view of the biomass stove

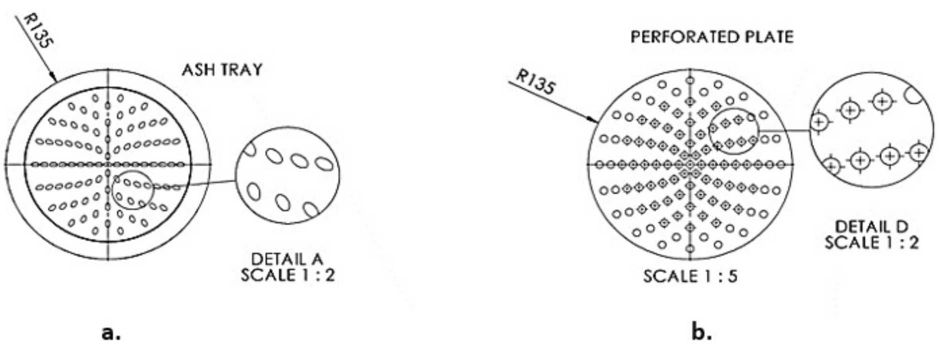

Figure 4: Ash tray and perforated plate

Materials employed in the fabrication process of the biomass stove which came with different sizes, dimensions and geometries were purchased from the open market. The fabrication process of the biomass stove involved cutting of the materials into specific sizes and joining them together through welding method. The procedures are highlighted as follows:

i. Measurement: The materials used in the fabrication process of the biomass stove were measured to required dimensions using measuring tape.
ii. Marking Out: After measuring the required dimension, white chalk was used to mark out a line on the material to indicate the areas that are meant to be cut.
iii. Cutting: The marked out parts were cut according to the dimensions specified on the working drawing (Table 2). Handheld sawing equipment was used to carry out the cutting operation.

iv. Drilling and Boring Operation: Drilling and boring operations are mainly used in making holes for temporary joints. On the other hand, boring is simply enlarging the drilled hole to the required dimension. Both machine processes were applied in fabrication of the machine especially in the parts/components like the hinges on the fuel gate where bolt and nuts were required during installation.
v. Welding: Welding involves the joining of two or more metals together and this can be achieved either by gas welding or arc welding which is the most common welding operation. After cutting of the various materials to required shapes and sizes, welding was used to joined together as shown in Figure 5.
vi. Grinding and filling operation: These methods were used to smoothen the surface of the welded and rough areas on the body of the biomass stove as well as removing unwanted parts and metals to achieve good surface finish.
vii. Finishing: After the welding operation, rough edges and entire body surface of the biomass stove was smoothened using emery paper, afterwards, the stove was painted to prevent the surface from corrosion.

Table 2: Dimensions of the locally designed biomass stove

	Parts Measured	Values
1.	Inner diameter of biomass stove	222 mm
2.	Inner diameter of biomass stove	225 mm
3.	Height of combustion chamber	226 mm
4.	Internal radius of combustion chamber	50 mm
5	Height of stove base	15 mm
6.	Height of Biomass stove	770 mm
7.	Thickness of perforated plate	2 mm
8.	Diameter of perforated plate	180 mm
9.	Height of chimney from the stove	243 mm
10.	Diameter of chimney	20 mm

a.

b.

Figure 5: Fabricated biomass stove

2.2.1. Performance evaluation

To examine the performance of the above designed biomass wood stove, water boiling test was conducted in accordance with University of California Berkeley (UCB)/Shell Foundation method which is based on ISO/IWA/VITA WBT 4.1.2 standards for determining the efficiency of wood fuel in stoves (Igboanugo et al., 2015). Also, each of the wood samples were sliced into smaller particle sizes using a short knife. The sliced particles contained a wide range of particle sizes that was not sifted. Testing conditions such as 180 ºC for the HRT and 600 ºC for the ash analysis were established prior to testing the samples. Waffle pans were prepared prior to testing to remove any film that was used to prevent the particles from sticking to the pans. The pan was placed on the Computrac MAX 5000XL analyzer with the prepared samples evenly distributed inside, and the analyzer which operated at the aforementioned temperatures was closed for the process to be observed. Ash contents obtained for each of the burnt wood fuels were analyzed using MAX 5000XL as shown in Figure 6. Orange et al. (2012) suggested that moisture content of wood fuel must be standardized for test results to be accurate. In this case, moisture content of the wood fuel could not be determined, but each of the wood specie was sliced into smaller particles and dried properly under sun for thirty (30) days to ensure that it is moisture free. Computrac MAX 5000XL ash analyzer offers a fast analysis for burnt wood ash with real-time results for solids and ash.

Figure 6: Computrac MAX 5000XL wood ash analyzer

3. RESULTS AND DISCUSSION

Operating performance of the biomass stove was evaluated in terms of the time required for a given mass of biomass (1.5 kg) to boil different volumes of water including 35, 60, 75, 95, 120, 150, 180, 250, 300 and 450 cl. Figures 7-16 are a graphical representations of the boiling Time (mins) for different quantities of water with various masses of wood fuel investigated in this study. To achieve the boiling temperature (100 ºC) of 35 cl of water using different species of wood fuels presented in Table 1, it was observed that Mangrove wood consumed the least time (2.2 min) and the least mass of wood fuel (0.4 kg) to achieve this task. To boil 60 cl of water, Mangrove wood was also observed to consumed the least time (2.6 min) and the least mass of wood fuel (0.62 kg) achieve this task. However, it took intervals of 3.17, 4.33, 5.16, 6.14, 8.18, 11.24, 13.28 min and mass of wood fuels of 0.72, 0.82, 0.93, 1.06, 1.12, 1.24 and 1.32 kg to boil 75, 95, 120, 150, 180, 250, 300 and 450 cl of water using Mangrove wood as fuel source. An increasing trend was observed in the time interval and mass of wood fuels used to achieve water boiling temperature of 100 ºC for all the aforementioned volume of water used in the experiment.

Using Mahogany as wood fuel, it took time intervals of 3.03, 3.57, 4.52, 5.49, 6.11, 7.53, 9.58, 12.47, 14.06, 20.58 min and 0.65, 0.73, 0.84, 0.93, 1.11, 1.15, 1.42, 1.64, 1.82 and 1.92 kg of wood fuel to boil 75, 95, 120, 150, 180, 250, 300 and 450 cl. Like in the case of Mangrove wood, an increasing trend was also observed in the time interval and mass of wood fuels used to achieve water boiling temperature of 100 ºC for all the aforementioned volume of water used in the experiment.

It was observed that the other species of wood such as Obeche, Iroko, Celtis and Erimado did not follow an increasing trend in the time interval and mass required to achieve water boiling temperature of 100ºC for the aforementioned volumes of water. For 35 cl of water, Iroko consumed the highest time (4.28 min) and highest mass (0.78 kg) of wood fuel to achieve water boiling temperature of 100ºC. For 60 cl of water, Celtis

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consumed the highest time (5.17 min) while Erimado took the highest mass (0.96 kg) of wood fuel to achieve water boiling temperature of 100 ºC. For 75 cl of water, Celtis consumed the highest time (4.28 min) and highest mass (0.78 kg) of wood fuel to achieve water boiling temperature of 100 ºC. For 60 cl of water, Celtis consumed the highest time (6.52 min) and highest mass (0.96 kg) of wood fuel to achieve water boiling temperature of 100 ºC. For 95 cl of water, Celtis consumed the highest time (7.49 min) and highest mass (1.36 kg) of wood fuel to achieve water boiling temperature of 100 ºC. For 120, 150, 180, 250, 300 and 450 cl of water, Celtis was also observed to consume the highest time and highest mass of wood fuels to achieve water boiling temperature of 100 ºC.

In summary, mangrove wood consumed the least time and the least mass of wood fuel, followed by Mahogany to achieve water boiling temperature of the aforementioned volumes. In almost all the experiments, it was observed that Celtis consumed the highest time and highest mass of wood fuels to achieve water boiling temperature of 100 ºC. Table 3 represents the percentage composition of different wood ash at 600 ºC.

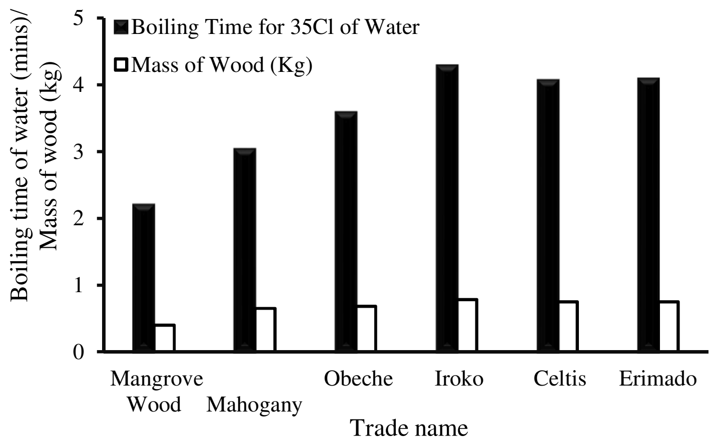

Figure 7: Boiling time of 35 cl water and mass of wood fuel

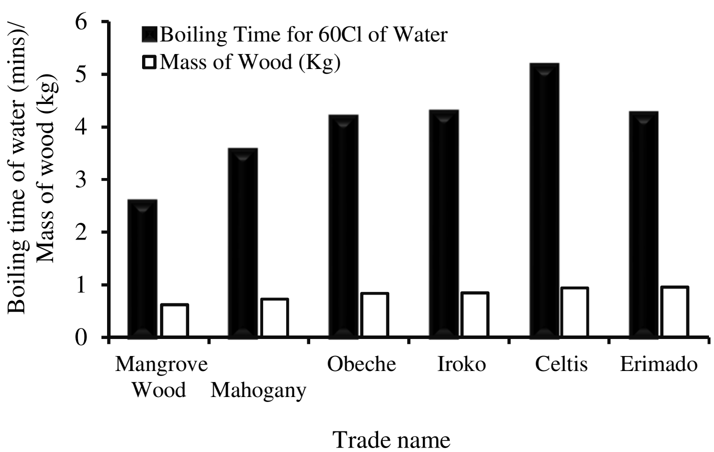

Figure 8: Boiling time of 60 cl water and mass of wood fuel

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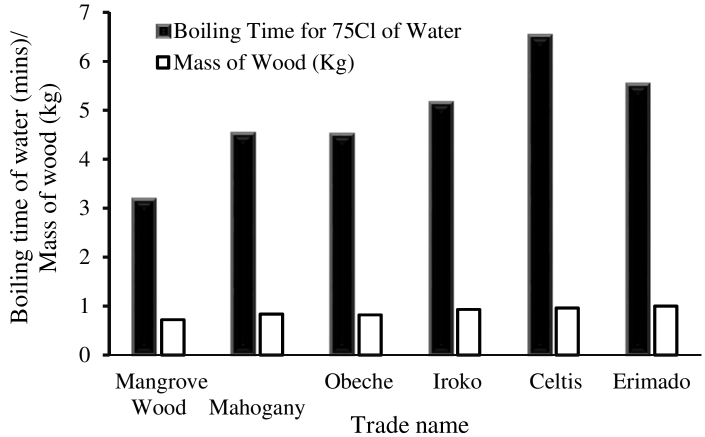

Figure 9: Boiling time of 75 cl water and mass of wood fuel

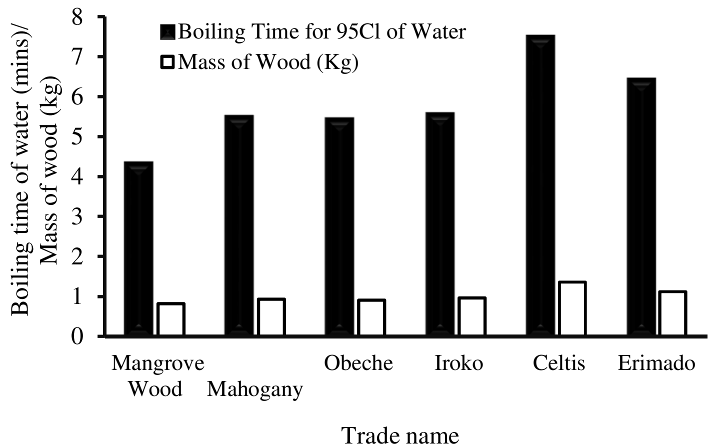

Figure 10: Boiling time of 95 cl water and mass of wood fuel

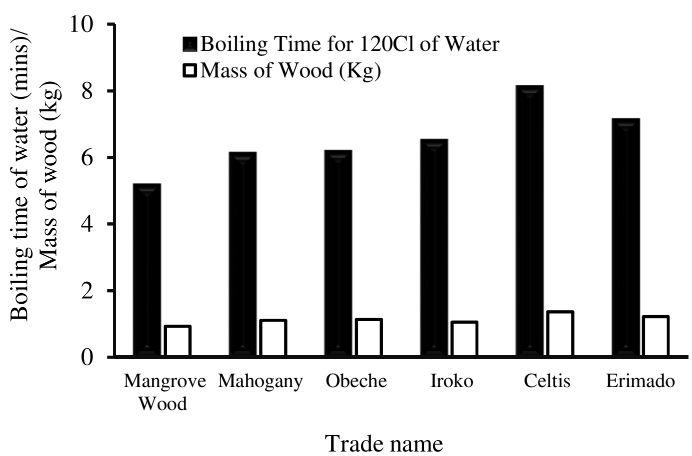

Figure 11: Boiling time of 120 cl water and mass of wood fuel

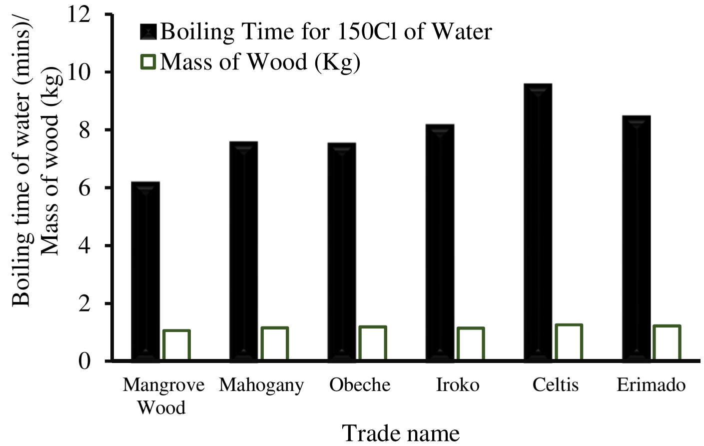

Figure 12: Boiling time of 150 cl water and mass of wood fuel

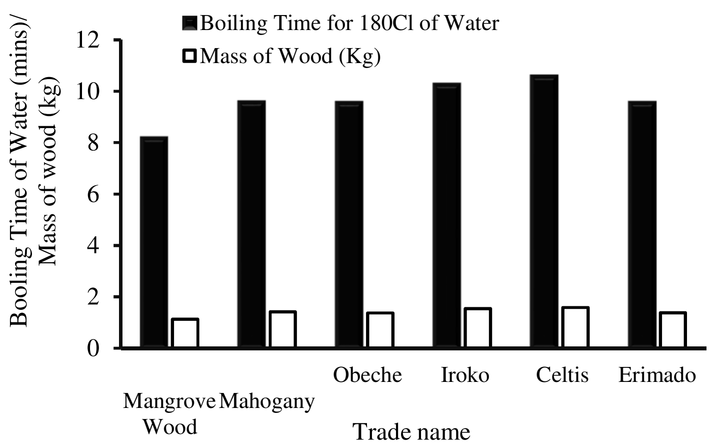

Figure 13: Boiling time of 180 cl water and mass of wood fuel

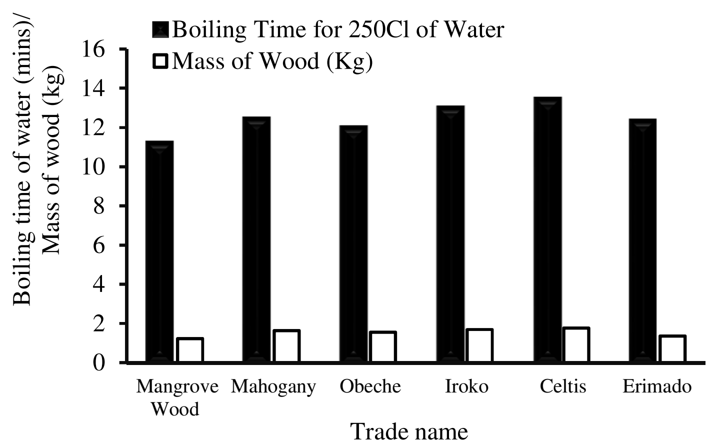

Figure 14: Boiling time of 250 cl water and mass of wood fuel

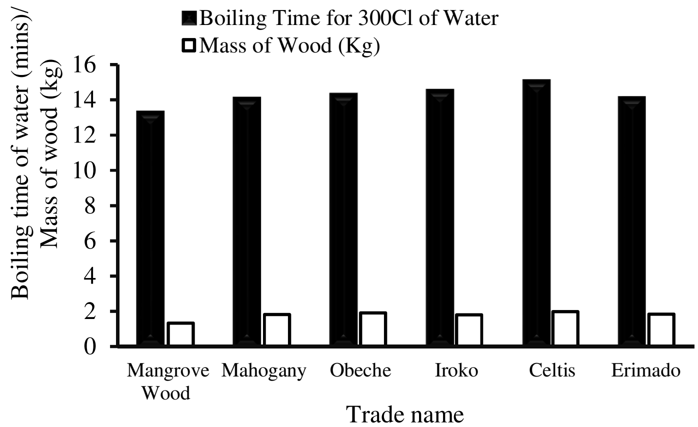

Figure 15: Boiling time of 300 cl water and mass of wood fuel

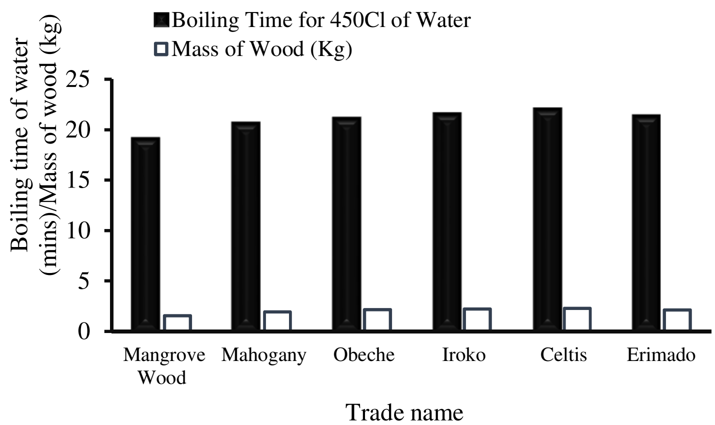

Figure 16: Boiling time of 450 cl water and mass of wood fuel

Table 3: Percentage composition of different wood ash at 600 ^oC

Elements (%)	Mangrove	Mahogany	Obeche	Iroko	Celtis	Erimado
Carbon	40.2	44.9	45.3	47.4	44.5	46.6
Potassium	6.6	9.2	7.9	8.3	8.6	8.8
Calcium	21.3	24.6	23.5	24.9	22.4	22.3
Magnesium	7.2	6.4	6.8	7.2	8.3	7.4
Manganese	2.6	3.4	3.7	4.1	2.8	2.5
Sulphur	0.34	0.42	0.67	0.31	0.53	0.46
Zinc	0.23	0.41	0.56	0.32	0.24	0.42
Copper	-	0.3	0.5	0.2	-	-
Sodium	0.12	0.14	0.8	0.11	0.13	0.7
Iron	0.01	0.02	0.06	0.03	0.05	0.02
Aluminium	-	0.02	0.01	-	0.02	-
Phosphorous	0.03	0.03	-	0.04	0.03	0.01

The percentage concentration of different elements at different wood ash temperature of 600 ^oC was determined by Computrac MAX 5000XL analyser as shown in Table 3. The major percentage of elements in the wood ash is carbon, ranging from 40.2% to 47.4% with its least ash percentage obtained from Mangrove wood and the highest percentage from Iroko. Other percentages of carbon (44.5%, 44.9, 45.3%, 46.6%) measured from the wood ash (Celtis, Mahogany, Obeche, Erimado) fell within the range of 40.2% and 47.4%. The carbon which is formed from the high temperature (600 ºC) combustion of the blended wood samples is non-metallic and tetravalent, making four electrons to form covalent chemical bond. This correlates with the report of Carson and Mumford (2004) on hazardous chemicals.

As shown in Table 3, Calcium with a chemical formula Ca was the second highest elements in terms of its percentage composition of wood ash obtained from aforementioned wood samples analysed in this study. It was observed in the range of 21.3% and 24.9%, with the least ash percentage contained in Mangrove wood and the highest percentage in Iroko. Other percentages of calcium (22.3%, 22.4%, 23.5%, 24.6%) measured from the wood ash (Erimado, Celtis, Obeche, Mahogany) fell within the range of 21.3% and 24.9%. Calcium which is a chemical element with atomic number twenty (20), is a greyish-white bivalent metallic element that was found in the ash content of the various wood fuels analysed in this study. This resulted from the high temperature combustion of wood fuel in the combustion chamber of the biomass stove (Pasanen et al., 2001).

As shown in Table 3, Potassium is another element that was observed in percentages lower than carbon and calcium. It was observed in the range of 6.6% and 9.2%, with the least ash percentage contained in Mangrove wood and the highest percentage in Mahogany. Other percentages of Potassium (7.9%, 8.3%, 8.6%, 8.8%) measured from the wood ash (Obeche, Iroko, Celtis, Erimado) fell within the range of 6.6% and 9.2%. Potassium which is one of the constituents observed in the wood ash has its own economic importance in the area of fertilizer production (Adekayode and Olojugba, 2010). The normalized concentrations of most elements, with the exception of potassium, sulfur and copper remains constant when the temperature is increasing, and are therefore retained in the ash at higher temperatures (Alfredsson, 2018). Hence, during the combustion process of the wood fuels, the normalized concentrations of potassium, sulphur, and copper initially remain constant but gradually start declining as the temperature increase. In a study on wood ash composition exposed to high furnace temperature, Mahendra et al. (1993) observed a significant decrease in potassium concentration at temperature greater than 900 ºC and decrease in sulphur content at temperature between 1000 and 1100 ºC.

As shown in Table 3, Magnesium is another element that was observed in percentages lower than carbon and calcium. It was observed in the range of 6.4% and 8.3%, with the least ash percentage contained in Mahogany and the highest percentage in Celtis. Other percentages of Magnesium (6.8%, 7.2%, 7.2%, 7.4%) measured from the wood ash (Obeche, Iroko, Mangrove wood, Erimado) fell within the range of 6.4% and 8.3%. In the reaction process, oxygen reacts with other combustion constituent to form a white powder of magnesium oxide known as magnesia and also magnesium nitride. At a temperature of 600 ºC, the presence of magnesium in the combustion chamber can reacts with oxygen to form hydrogen bubbles with a characteristic hissing (Hroncova et al., 2016). The concentrations of Manganese, Sulphur, Zinc, Copper, Sodium, Iron, Phosphorous and Aluminium was not discussed in details because the percentage of their concentrations in the ash content obtained from various wood fuels at a temperature of 600 ºC was observed at trace quantities.

Figure 17 is a graphical representation of the HRT of each biomass specie combusted at 180 ºC using Computrac MAX 5000XL Wood Ash Analyzer and the mass of wood ash from each species of wood at 600 ºC. To determine the HRT, each of the biomass was combusted at 180 ºC for twenty-two (22) minutes, afterwards, it was monitored under room temperature until it was no longer hot. From the graphical representation, Mangrove Wood had the highest HRT among the six (6) species of wood combusted at 180 ºC, followed by Mahogany Obeche etc. This signifies that the higher the HRT, the longer the residence time to sustain the duration of usage and vice versa. This agrees with the findings of Wotton et al. (2012) on flame temperature and residence time of fire in Eucalypt forest.

However, Mangrove wood among the six (6) species of wood investigated in this study produced the least mass of wood ash after combustion at 600 °C followed by Mahogany Obeche etc. For Mangrove Wood, Mahogany and Obeche which are the three (3) wood species that produced the lowest mass of wood ash, this further justifies that the said wood species has a higher capacity to sustain heat induced in them during combustion until all its constituting fibers completely combust and reduced to ash which the texture when felt by hand was characterized by smooth powdery and somewhat slippery texture. The low mass of wood ash obtained after combustion can also make it easier for disposal (Adrian et al., 2012). Iroko (biomass wood) produced the fourth (4th) highest mass in this category and the hand textural test revealed powdered material characterized by microscopic unburnt fine grain particles. Celtis and Erimado (biomass wood) produced the highest mass of wood ash, with textures characterized by unburnt coarse grain particles when felt by hand.

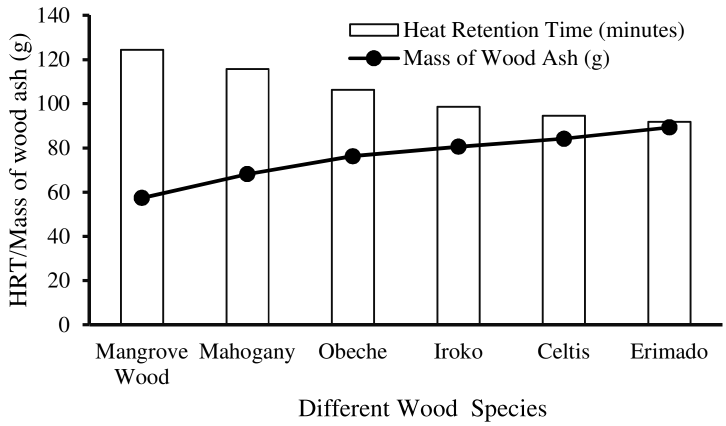

Figure 17: Plot of heat retention time and mass of wood ash

4. CONCLUSION

In this study, Biomass Stove was locally fabricated and evaluated using some Nigerian Woods to determine their energy potentials. Following the successful fabrication and testing of the biomass stove, it is concluded that biomass stove can be a viable cooking alternative particularly in rural settlements where biomass like Mangrove wood, Mahogany and Obeche are employed as a major fuel source. This is as a result of the low carbon emissions, HRT as well as lowest mass of wood ash obtained during the combustion of these biomass wood species at respective temperatures discussed in this study. Although the use of stainless steel in designing the body of the biomass stove made the fabrication process a bit expensive on a small-scale production, however, this can be compensated for in terms of cost by its long term usage, resistance to corrosion and low maintenance.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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