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Original Article

The Assessment of Combustion Performance of Improved Cookstoves in Sierra Leone

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Abstract *- Improved charcoal cookstoves are being produced indiscriminately by unlicensed local craftspeople, and their use is expanding quickly in Sierra Leone. There have not been any comprehensive or in-depth analyses of efficiency or charcoal savings on Wonder stoves and Metal stoves. In this study, the performance of two improved charcoal cookstoves — the Wonder stove and the Metal stove—was assessed. To conduct efficiency and charcoal-saving analyses, a set of charcoals from the Abura tree (mitragyna cilliata) and another set from assorted trees: Mango tree (Mangifera indica) and Matchstick tree (Aechmea gamosepala) were prepared. When Abura charcoal and other types of charcoal (assorted) were to test the efficiency of the stoves, the results obtained for the Wonder stove showed average efficiencies of 19.67% and 14.68%, respectively, while those for the Metal stove showed efficiencies of 17.79% and 14.75%. When burned charcoals were compared at the high-power phase cold start in both stoves, the Wonder stove saved 54.21% of the charcoal with a corresponding time of 4.42 minutes, while the Metal stove saved 1.40% of the charcoal with a similar time of 4.34 minutes.*

Keywords *- Wonder stove, Metal stove, Abura tree, Charcoal, Thermal efficiency.*

1. Introduction

One of the biggest problems the world is currently facing is sustainable energy, which affects every part of our life. Inaccessibility to contemporary energy services significantly negatively impacts health, restricts opportunities, and worsens the wealth gap for poor people. Recent developments from global warming, a financial meltdown, and fluctuating energy prices have only increased the complexity of people experiencing poverty [1]. Currently, over 770 million people are living in the world without electricity access [2, 3, 4, 5], most of whom are in Africa and Asia's developing countries [6, 7] and currently, 87% of people in sub-Saharan Africa do not have access to clean cooking [8] and 38% of the global population are without clean cooking facilities [9]. Similarly, a report by [10] indicates that based on a 71-country sample of 5.3 billion people, which includes 90% of nations with poor and lower middle incomes, the proportion of people whom Clean Energy Cooking Services are available is lowest in Sub-Saharan Africa (10%) and about 4 billion individuals—or approximately half of the world's population—cannot cook effectively, conveniently, reliably, safely, and inexpensively [11]. Because of limited progress in the percentage of people utilising clean cooking fuels in sub-Saharan Africa, current efforts to minimise the majority of individuals cooking with biomass are failing [12, 13].

Furthermore, connecting the remaining unserved communities, including those connecting to frail and overcrowded urban grids and displaced and difficult-to-reach populations, is problematic [14]. In all areas of the energy industry, bioenergy is an important factor in slowing climate change. Biomass supply chains and effective combustion performance are essential for bioenergy to reach its full potential. The technology offers a unique degree of flexibility in comparison to other renewable energy sources in terms of the variety of raw materials and the numerous production mechanisms, end products, and its application in the primary energy sectors of heating and food preparation [15, 16]. The reliance on biomass burning dates back to ancient times, particularly in underdeveloped countries in both Asia and Africa. Even though the world is witnessing significant urbanisation, a large portion of the population still resides in rural areas with few amenities available [17]. Reports claim that one-third of the world's population lacks access to modern cooking fuels and technologies [18, 19, 20, 21, 22, 23]. This has clear evident implications for social and economic growth [24], as well as negative health effects and gender implications [25, 26]. In Sub-Saharan, more than 80% of people use biomass fuels for cooking. By 2030, it is predicted that one billion Africans will depend on biomass resources to meet their energy demands [27]. According to some studies, only 1% of Ugandans have access to adequate cooking choices, compared to 3% and 5%, respectively, in Tanzania, 5% and 6% in Ethiopia [28]. Approximately 10% of the population has access to and consumes clean cooking fuels, ranking Kenya among the top 20 countries with the worst shortage of such fuels. At the same time, there is a surplus of electricity provided by the centralised system [29]. In Kenya, households still use the greatest proportion of biomass fuels for their basic energy needs. For rural households, this proportion rises to over 90%. Biomass fuels account for 69% of the country's primary energy needs [30, 31].

Furthermore, Bangladesh is one of the world's most densely populated countries and recently attained lower middle-income status, with over 160 million inhabitants, 64% of whom live in rural areas. It is reported that the country has made rapid strides toward electrification of all areas for which the majority of people (99%) have access to electricity, but 77% of Bangladeshis still lack access to clean cooking [32]. Biomass combustion in conventional cookstoves is still one of the most common ways of cooking across the majority of rural areas of emerging nations, particularly in Sub-Saharan Africa and elsewhere.

Biomass provides more than 80% of energy use in Sierra Leone [33, 34], where there are 7,541,641 people [35], an increase of around 6% from the results of the latest general population and housing census in 2015. In 2013, less than 13% of the people had access to power from the grid. Sierra Leone's electricity sub-sector is now experiencing difficulties [36]. Efficiency and accessibility are constrained by the distribution and transmission network's high technical losses. Low power quality results from the infrastructure being overburdened by illegal users, further exacerbating these problems. Additionally, thieves have systematically been vandalising the transformers and distribution cables, further compounding issues for the power utility company. Meanwhile, the production and use of sustainable power from hydro, solar, biomass, and other clean energy sources have slowed down. In both urban and rural contexts, wood fuel is the primary biomass energy source used for regular cooking and crafting tasks, with charcoal coming in second nationwide [37]. The second-largest energy source, at around 13%, is imported petroleum products. The remaining energy is provided by on- and off-grid electricity within main towns. In the rural parts of Sierra Leone, the production and trading of charcoal have grown significantly over the previous ten years [38]. It was a minor fuel in urban areas in the 1980s and 1990s. However, it steadily replaced fuelwood and has become the fuel of choice for the vast majority of city dwellers because it is economical to all socioeconomic strata and the only available choice to the numerous low-paid city workers; it is considered more effective than firewood; it burns with a relatively very small quantity of smoke and offers less of a fire danger (liked by most property owners); and it has a greater calorific value and is easier to transport. [39]. In Sierra Leone, the household sector accounts for the majority of energy production and consumption. Thin leftover plastics and Kerosene are mostly used for lighting biomass, such as fuelwood and charcoal within the urban settings; mulch and some other dried grasses, as well as dried wastes from palm oil production, are used as tinder for cooking and other artisans' works in rural communities [40].

Charcoal is a dependable, practical, and affordable energy source used for cooking in many households in Sierra Leone, even those considered the upper class. In many African countries, the majority of urban households rely (at least in part) on charcoal for their daily energy requirements [41]. The need for charcoal is constantly rising as a result of rising urbanisation and population, and the sector's economic impact is significant. Thousands of people rely on charcoal as their primary source of income in most African countries [42]. The increasing anthropogenic impact on plant cover is due to people's reliance on solid fuels. Inefficient charcoal burning practices and the use of ineffective wood or charcoal cooking stoves worsen the situation. Inefficient stoves have numerous environmental, health, and economic consequences for homes [43].

Stoves that are inefficient or ineffective consume far more firewood or charcoal than is required for the same level of consumption. Even worse is the fact that most people depend on wood fuels, thereby causing environmental issues as a result of the indiscriminate exploitation of timber. When forests are cleared in an unregulated manner, the recycling process of Greenhouse gases is greatly reduced. Emissions from the burning of biomass in an inefficient way can also add to greenhouse gas emissions, thereby worsening the global warming situation [44]. Furthermore, improved efficient and clean cookstoves are a significant advancement for the environment and public health. Utilizing such improved cookstoves results in better fuel combustion and greater heat transfer, reducing fuel demand, improving women's and children's health and lowering cooking expenses [45]. The Wonder stove and Metal stove are the two most popular and commonly used improved charcoal cookstoves in Sierra Leone. The performance of various models and designs of improved cookstoves varies substantially [46, 47]. This could result from variations in the designed components and fuel type. Under the International Workshop Agreement process of the International Standards Organization (ISO), a set of interim international norms for stove performance was created [48].

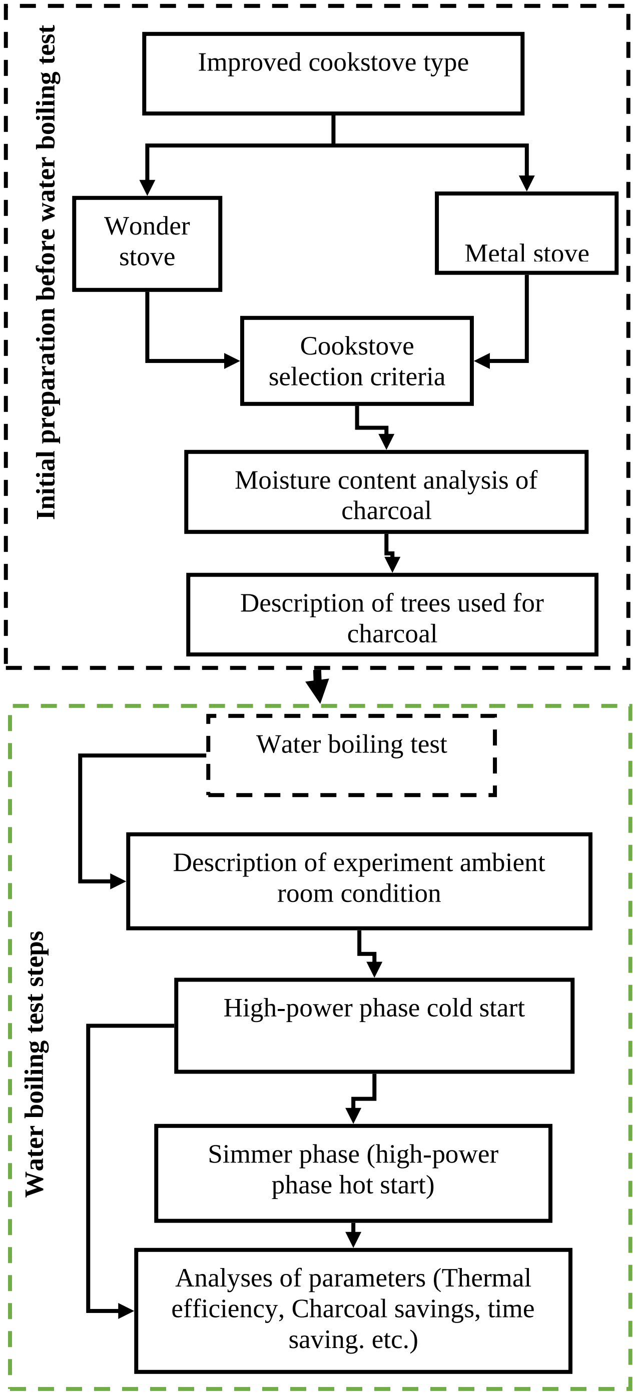

Fig. 1 Framework of methodology

Efficiency, pollution, and safety are just a few areas this framework offers for measuring and categorising performance. Several studies are underway to evaluate the applicability of both the Wonder and Metal charcoal cookstoves in terms of their overall energy metrics and emission metrics. An experimental investigation on energy analysis using particular charcoal products from the three species of trees—the Abura tree (Mitragyna cilliata), Mango tree (Mangifera indica), and Matchstick tree (Aechmea gamosepala)—that Sierra Leone's charcoal producers use most frequently and extensively to produce charcoal for commercial uses—was conducted on the Wonder stove and Metal stove, respectively analysis.

2. Materials and Methods

Fig. 1 illustrates the fundamental structure of the methodology used to conduct the water boiling test experiment to evaluate stoves efficiencies.

2.1. Improved Cookstove Type

In Sub-Saharan Africa, there are a lot of newly developed improved cookstoves with widely varying internal combustion performances [49, 50, 51]. To minimise any disparities in climatic and environmental circumstances, the identified improved charcoal cookstoves have all been purchased within Sierra Leone and transferred to the testing location. The Wonder stove and Metal stove, frequently used in rural and urban households, are shown in Figs. 2 and 3.

Figure 2: depicts the front and top views of a Wonder stove. The Wonder stove's combustion chamber and walls are lined with ceramic. The chamber comprises 24 unevenly spaced holes with almost equal 10mm diameters. To protect the ceramic liner and to allow for air entry into the combustion chamber, fixed support is provided for the installation of the cooking pot. The Wonder stove has an ashtray that can be removed and emptied underneath the combustion chamber.

(a) **(b)**

Fig. 2 Wonder stove (a) Front view (b) Top view

Fig. 3 depicts the front and top views of a metal stove, which has four additional holes drilled into its wall to accommodate the insertion of two metal rods for supporting cooking vessels and nine asymmetrical square holes in the combustion chamber. Additionally, ash removal is allowed below the combustion chamber.

(a) **(b)**

Fig. 3 Metal stove (a) Front view (b) Top view

Table 1. Cross-sectional designs need sufficient samples for each group to evaluate progress over traditional stoves

Estimating the Coefficient of Variance														
1.3	**1.2**	**1.1**	**1**	**0.9**	**0.8**	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**	**0.1**		
2653	2261	1900	1570	1272	1005	769	565	393	251	142	633	16	**10%**	**The discernible change in means**
663	565	475	393	381	251	193	142	98	63	36	16	4	**20%**	
295	251	211	175	142	112	86	63	44	28	16	7	2	**30%**	
166	142	119	98	80	63	48	36	25	16	9	4	1	**40%**	
106	91	76	63	51	40	31	23	16	10	6	3	1	**50%**	
74	63	53	44	36	28	22	16	11	7	4	2	1	**60%**	
54	46	39	32	26	21	16	12	8	5	3	2	1	**70%**	
42	36	30	25	20	16	12	10	6	4	2	1	0	**80%**	
33	28	24	20	16	13	10	7	5	3	2	1	0	**90%**	
27	23	19	16	13	10	8	6	4	3	2	1	0	**100%**	

Source: Edwards et al., 2007

2.2. Cookstove Selection Criteria

Many criteria for choosing an improved charcoal cook stove, such as [52] claims that in order for a cookstove to be called an improved cookstove, particulate matter with an aerodynamic diameter smaller than 2.5 micrometres (PM<2.5µm) must be reduced by more than 50% (≥50%) during the water boiling test, be movable, created or made in only one place, and not involve reassembly. Researchers [53] also agreed with the aforementioned standards or criteria. The study's selection of the improved cookstoves adhered to the methodology from [54], which suggests three approaches: alter the intended observable disparity or distinction, alter the coefficient of variation (COV - minor variability) and alter the overall shape or style of the cookstove. In Table 1, the total sample size is just 10 per set or group when the variability is 90%, and the coefficient of variation (COV) is 0.7. Considering 60% or 70% as a conservative option makes sense if the optimised or improved cookstove is running properly and few other nearby sources produce equivalent or similar pollution. Unfortunately, in real-world circumstances, the coefficient of variation (COV) can often be fairly high, similar to the figure of 0.7 in the preceding example. Additionally, the primary topic pertaining to the selection of observable variance partially depends on the purpose of the research endeavour. It may be reasonable to limit the sample size in this case to two (2) since, in our opinion, the chosen improved cookstoves did not meet their objectives, especially if the overall condition of indoor air was not decreased to this degree. Additionally, 30% may be appropriate for some users if the improved cookstove can cut pollutants in the air by up to 30% while simultaneously offering benefits like significant reductions in fuel consumption and short trial water boiling times. Therefore, it is crucial to choose the sample size up front.

2.3 Cookstove Testing Procedures

The mandatory procedure mainly consists of two stages of water boiling testing for improved cook stoves, namely the high-power phase's cold start and the high-power phase's hot start, as well as two other voluntary testing phases, namely the kitchen performance test or assessment and the control cooking test or assessment [55, 56, 57]. To determine the parameters, the 2016 Gold Standard Advanced Cookstove Methodologies Guidebook, GS Simplified, AMS II. G, and TPDDTEC [58], studies of firepower, efficiency, and energy output were used. Therefore, the section on stove assessment techniques included a summary of the justifications and calculating procedures used, emphasising the distinctions between the present method and the earlier one. Two test stages of the water boiling assessments, namely the high-power phase cold start (HPCS) and the simmer phase - high-power hot start (HPHS), were performed on the stoves (Wonder stove and Metal stove) [55], with a few rare exceptions, the control cooking test and kitchen performance testing were not used to assess the firepower and efficiency of the stoves. However, some testing tools, such as standard pots and a digital weighing scale for water boiling tests, were completely employed [60] [61] [62].’

2.4. Moisture Content Analysis

With the advent of a grain moisture tester, the moisture content of the two different sets of charcoals was computed on a dry weight basis using the formula below [63]:

$$\mathrm{mc}_{db} = \frac{m_{brd} - m_{ard}}{m_{ard}} \times 100 \quad (1)$$

Where,

mc_{db} is the percentage moisture content on a dry basis,

m_{brd} is the mass (g) of dry charcoal before re-drying and m_{ard} is the mass (g) of dry charcoal after re-dying in the sun for 96 hours at a temperature between 29℃ - 33℃, respectively.

2.5. Description of Tree used for Charcoal Production

Three sets of trees were used to produce two sets of charcoal. One type of charcoal used in the study was obtained from the Abura tree (mitragyna cilliata) in a local peat bog, with all wood knots removed before the production of charcoal for experiments. The second batch of charcoal was produced from two varieties of trees: The mango tree (Mangifera indica) and the Matchstick tree

(Aechmea gamosepala) beside the Abura tree using different local peat bogs constructed for that purpose. The choice of those trees, especially the Abura tree, was made due to the cost of each charcoal from those trees on the local market. Since the Abura tree is assumed by its producers to stay much longer in the charcoal stove than the others or is thought superior, it is typically produced and sold separately.

2.6. Procedures of the Water Boiling Test Used

The Water Boiling Test (WBT) simulates the cooking process in a simplified manner [64, 65]. Its purpose is to assess how efficiently a cookstove uses fuel to transfer heat in a cooking pot and the amount of emissions generated while cooking [66]. In summary, the water boiling test is important when testing improved cookstoves as it quantifies their efficiency, fuel savings, environmental impact, and user experience and helps promote their widespread adoption [67, 68, 69]. It serves as a valuable tool for stove manufacturers, researchers, and policymakers to evaluate and compare various cookstove models' performance accurately. The study's water boiling test consists of two stages that occur immediately after each test run on each of the tested stoves. The descriptions of the techniques employed are provided below.

2.6.1. Experimental Ambient-Room Conditions Description

Because relative humidity and temperature are important factors in evaluating improved cookstove performance, laboratory air quality checks were performed before each experiment to account for temperature, water vapour, and local boiling point using a RISEPRO 4 Channel, cup anemometer and a K-type Digital Thermocouple (-200°C – 1372°C).

2.6.2. High-Power Phase Cold Start

The air temperature parameters of the experiment room readings (temperature and pressure) were taken and recorded. The heating of 2.5 litres of distilled water to a temperature of 100°C was done with a measured quantity of tinder and charcoal. Following that, the weight of the pot with water following boiling was weighed and recorded, as well as the residual charcoal. On each improved charcoal cookstove, each test was repeated ten times and averaged

2.6.3. Simmering Test –High-Power Phase Hot Start

Initial data for the simmering test high-power phase of the experiment were taken from all parameters measured at the end of the HPCS. Using a spatula to control the fire in the combustion chamber until the temperature fall below 96°C but above 85°C [70]. For roughly 45 minutes, this temperature will be held. The main reason for this part of the experiment is that most of the toughest or hardest foods in Africa (including locally dried beans) can be cooked within this temperature range in less than 45 minutes [71, 72]

2.6.4. Mass of Charcoal Burnt

The difference between the pre-weighed pile of charcoal and the leftover pile at the end of the experiment was used to account for the amount of charcoal burned to bring a known volume of water to a boiling temperature. The following equation was used to carry out the analysis [73].

$$\boldsymbol{m_c = m_{cb} - m_{ca}} \tag{2}$$

Where,

m_c is the mass (g) of charcoal burnt,

m_{cb} is the mass (g) of pre-weigh charcoal before the test, and m_{ca} is the mass (g) of charcoal after the test.

Alternatively, the quantity of charcoal burnt can also be obtained from the relation [74]:

$$\boldsymbol{m_c = m_{ccb} - m_{cca}} \tag{3}$$

Where,

m_{ccb} is the mass (g) of the charcoal plus container before the test, and m_{cca} is the mass (g) of the charcoal plus container after the test.

2.6.5. Mass of Vaporized Water

The quantity of water lost through evaporation was calculated by taking the difference in the mass of the pot with water after the test from the mass of the pre-weighed pot with water before the start of the test. The linear equation is given by [75]:

$$m_{vw} = m_{ipw} - m_{fpw} \tag{4}$$

Where,

m_{vw} is the mass (g) of water vaporized, m_{ipw} is the initial mass (g) of the pre-weighed pot with water and m_{fpw} is the final mass (g) of the pot with water after the test.

2.6.6. Mass of Remaining Water

The amount of water that remained after the pot had heated up to a boiling point was computed by deducting the mass of the empty pot from the ultimate mass of the pot with water after the test. The following equations are connected to and modelled by the linear function [76]:

$$m_{rw} = m_{fpw} - m_{ep} \tag{5}$$

Where,

m_{rw} is the mass (g) of the remaining water, m_{fpw} is the final mass (g) of the pot with water, and m_{ep} is the mass (g) of the empty pot.

2.6.7. Time to Complete One Phase of the Test

The time required to complete one test was determined using the relation [77]:

$$\Delta t_c = t_f - t_i \tag{5}$$

Where,

Δt_c is the time (minutes) taken to complete one test, t_f

is the time (minutes) recorded when water reaches 100℃, and t_i is the initial time (minutes) recorded at the start of the fire.

2.6.8. Temperature Difference

The difference in temperature between the water in the pot at its initial temperature and the water in the pot at its boiling point was determined using the following formula [78]:

$$\Delta T = T_f - T_i \tag{6}$$

Where,

ΔT is the temperature difference (℃), T_f, the temperature reading at boiling (final), and T_i (℃) the initial temperatures of water in the pot.

2.6.9. Estimation of Fire Power

The ratio of the energy present in the charcoal burned in completing one test per unit of time was determined by the formula [79]:

$$F_p = \frac{m_c \times LHV}{60(t_c - t_i)} \tag{7}$$

Where,

F_p is the firepower (W), LHV is the lower heating value of charcoal, m_c and is the mass (g) of charcoal burnt. t_c is the final time reading (recorded), and t_i is the initial time recorded Since t_c and t_i are mostly in minutes, and they require to be changed to seconds.

2.6.10. Thermal Efficiency

The ratio of the sum of energy absorption by water in the testing pot, the absorption of energy by steam, to energy generated by the burning charcoal. However, water behaves differently in the experiment's high-power and low-power phases, and a specific formula is used to calculate the energy absorbed by water and vapour [80].

$$\eta_T = \left(\frac{m_{rw} \times C_w \times \Delta T + m_{vw} \times l_w}{m_c \times LHV}\right) \times 100 \tag{8}$$

Where,

η_T is the thermal efficiency (%) required to heat water to a vapour state, m_{rw} is the mass (g) of the remaining water after the test, m_c is the mass (g) of charcoal burnt, ΔT is the temperature difference (℃), m_{vw} is the mass (g) of vaporized water during the test, and LHV is the lower heating value of charcoal.

2.6.11. Charcoal Saving

The amount of charcoal used for a particular stove was calculated using the difference in charcoal mass between the task before the experiment and after the experiment results. A comparison metric that indicates the amount of charcoal saved when using a wonder stove instead of a metal stove for a particular heating operation is shown below [81].

$$C_s = \frac{m_m - m_w}{m_w} \times 100 \tag{9}$$

Where,

C_s is the charcoal savings expressed in %, m_w is the mass (g) of charcoal burnet in Wonder stove, and m_m is the mass (g) of charcoal burnt in a Metal stove.

2.6.12. Time-Saving

The time difference between the stove with the highest calculated average efficiency with the one with the calculated lower average efficiency performing similar tests under the same environmental conditions is expressed as follows:

$$\Delta t_i = t_h - t_l \tag{10}$$

Where,

Δt_i is the time saved (min), $i = 1, 2, 3 \ldots$ is the corresponding number of tests. t_h and t_l are respectively the corresponding time taken by the effective stove and the time taken by the lower effective stove using the various charcoals as fuels.

3. Results and Discussions

For the two primary tests that were ((Specifically, hot and cold starts for high-power phases), OriginPro software was used to do all statistical analyses and evaluations of the two improved charcoal cookstoves.

Table 2**:** summarises the assessments of the Wonder stove's efficiency using the Paired Sample t-Test at the high-power phase cold start of the experiment.

The statistics showed that the population means of both Abura and assorted charcoal (the Null Hypothesis) are substantially different from the test difference mean at 0.05 level of confidence and 9 Degrees of Freedom.

The Null Hypothesis is therefore disproved. That is the statistic (5.66) and P-value (3.10×10^{-4}) from the t-test table show that the two means differ significantly from one another, indicating that the two forms of charcoal have different efficiency when used in the same stove.

According to the average efficiency in the Wonder stove, Abura charcoal outperformed assorted charcoal.

The efficiency of the stove was 19.68% on average when Abura charcoal was used as fuel, compared to 14.68% when assorted charcoal was used.

As a result, Abura charcoal performed 5% better in the same Wonder stove than assorted charcoal. When both efficiencies were considered, the stove's average efficiency was 17.18%. The results obtained in this work are similar to those described in the literatures:11% and 26.92% [82].

Table 2. Efficiency studies for the wonder stove using abura charcoal and other types of charcoal as fuels

Paired sample t-Test					
	N	Mean	SD	SEM	Median
Abura Charcoal	10	19.68	2.50	0.79	16.40
Assorted Charcoal		14.68	0.65	0.21	14.64
Difference		5.00	2.80	0.88	4.57
Overall	20	17.18	3.12	0.70	16.22
Test statistics					
statistics		DF		Prob>|t|	
5.66		9		3.10×10^{-4}	

Table 3. Analysis of the Metal Stove's efficiency at cold start high power phase using abura charcoal and assorted charcoal

Paired Sample t Test					
	N	Mean	SD	SEM	Median
Abura charcoal (%)	10	17.79	1.14	0.36	18.17
Assorted charcoal (%)		15.75	0.73	0.23	15.71
Difference		2.05	1.18	0.37	2.38
Overall	20	16.77	1.40	0.31	16.73
Test Statistics					
statistics		DF		Prob>|t|	
5.49		9		3.83×10^{-4}	

Table 4. Efficiency studies of the wonder stove using abura and assorted types of charcoal at the hot start, high-power phase

Paired Sample t Test					
	N	Mean	SD	SEM	Midian
Abura charcoal (%)	10	9.62	2.16	0.68	8.62
Assorted charcoal (%)		7.32	0.32	0.10	7.26
Difference		2.30	2.28	0.72	1.53
Overall	20	8.47	1.91	0.43	7.72
Test Statistics					
statistics			DF		Prob>|t|
3.19			9		0.01

Whereas in table 3, using the Paired Sample t-Test, displayed the analyses of the metal stove's efficiency when treated to the same quantity and quality of charcoal from the Abura tree and assorted trees at the cold start high power phase. As a result, the population means (the Null Hypothesis) are significantly different from the test difference mean at the 0.05 level of confidence and 9 degrees of freedom (Alternative Hypothesis). The null hypothesis is therefore disproved. That is, the statistic (5.49) and P-value (3.83×10^{-4}) from the t-test table showed that the two means differ significantly from one another, indicating that the two forms of charcoal have different efficiency for the same metal stove. The average efficiencies for both Charcoals are 17.79% and 15.75%, respectively, with a difference of 2.05%. The average efficiency after taking into account both efficiencies was 16.77% for the Metal stove. The average efficiency after taking into account both efficiencies was 16.77% for the Metal stove. These findings are analogous to those made by the researchers [83] after conducting a water boiling test on two types of stoves: Plancha and open fire stoves.

Additionally, Table 4 displays the Wonder stove's efficiency evaluations throughout the high-power phase hot start at the simmer test. The difference between population means (the Null Hypothesis), and the test difference means it is statistically different at the 0.05 level of confidence and 9 degrees of freedom. That is, the statistic (3.19) and the corresponding p-value (0.01) show that the two charcoal types have different efficiency levels for the same stove throughout the simmer test phase. Both Abura and Assorted charcoal had average efficiency rates of 9.62% and 7.32%, respectively, with a difference of 2.32%. As a result, Abura charcoal outperformed assorted charcoal.

In Table 5, according to analyses of Metal stove efficiency, the difference between the population means (the Null Hypothesis), and the test difference means is not statistically different at the 0.05 level of confidence and 9 degrees of freedom. Meanwhile, the difference between the averaged efficiencies calculated was 0.243%, which is statistically negligible or insignificant.

Table 5. Evaluations of the metal stove's performance using abura and assorted types of charcoal at the hot start, high-power phase

<table>
<tr><th colspan="6">Paired Sample t Test</th></tr>
<tr><td></td><td>N</td><td>Mean</td><td>SD</td><td>Sum</td><td>Min</td></tr>
<tr><td>Abura charcoal</td><td rowspan="3">10</td><td>7.72</td><td>0.76</td><td>0.24</td><td>7.97</td></tr>
<tr><td>Assorted charcoal</td><td>7.96</td><td>0.54</td><td>0.17</td><td>7.85</td></tr>
<tr><td>Difference</td><td>-0.24</td><td>0.99</td><td>0.31</td><td>-0.07</td></tr>
<tr><td>Overall</td><td>20</td><td>7.84</td><td>0.65</td><td>0.15</td><td>7.97</td></tr>
<tr><td colspan="6">Test Statistics</td></tr>
<tr><td colspan="2">t statistic</td><td colspan="2">DF</td><td colspan="2">Prob>|t|</td></tr>
<tr><td colspan="2">-0.78</td><td colspan="2">9</td><td colspan="2">0.46</td></tr>
</table>

Table 6. Analysis of the mass of varied charcoal burned in the sonder stove with time at high-power phase cold start

Descriptive Statistics							
	N	Mean	SD	Sum	Min	Median	Max
Time taken to boil 2.5L of H_2O (min)	10	24.8	0.74685	248	23.7	24.95	25.8
Abura charcoal burnt (g)		465.6	64.08	4656	380	462.5	555
Time taken to boil 2.5L of H_2O(min)		29.22	0.84	292.2	27.9	29.35	30.2
Assorted charcoal burnt (g)		702.9	43.18	7029	640	705	770

Table 7. Analysis of different charcoal burned in metal stoves with time at high-power phase cold start

Descriptive statistics							
	N	Mean	SD	Sum	Min	Median	Max
Time taken to boil 2.5L of H_2O (min)	10	26.97	1.11	269.7	25.2	26.9	28.8
Abura charcoal burnt		546.7	33.87	5467	500	552	590
Time taken to boil 2.5L H_2O (min)		31.31	1.03	313.1	29.5	31.25	32.4
Assorted charcoal burnt		536.8	21.25	5368	500	536	570

Table 8. Analysis of different charcoal burnt amounts in the wonder stove at the simmering phase

Descriptive statistics							
	N	Mean	SD	Sum	Min	Median	Max
Simmer time (min)	10	45	0	450	45	45	45
Abura charcoal (g)		736.8	130.31	7368	493	790	865
Assorted charcoal burnt (g)		874.5	33.51	8745	839	870	940

When using Abura charcoal, the Wonder stove's efficiency ranged from 16.40 to 24.25%, and when using assorted charcoals, it ranged from 13.81 to 16.04%. For metal stoves, the efficiency ranged from 15.12% to 18.87% when using Abura charcoal and from 15.09% to 17.02% when using assorted charcoal. When compared to the efficiencies of other improved cookstoves provided by other authors or researchers, the efficiencies obtained were: 25.11% to 27.44% [84]; 12% to 27% [85]; 14% to 21% [86] and 18%, 25%, 28%, 32% and 35% were also reported by [87], respectively.

The analyses of the mass of the various charcoals used in the Wonder stove to heat 2.5 litres of water to the boiling point are shown in Table 6: at the high-power phase cold start.

This shows that to heat 2.5 litres of water to a boiling temperature, 465.6 g of Abura charcoal on average were consumed in 24.8 minutes, and 702.9 g of assorted charcoal on average were consumed in 29.22minutes on average bases. The minimum and maximum time spent on all the experiments were 23.7 minutes and 25.8 minutes for the Abura charcoal, with a minimum and maximum amount of charcoal of 380 g and 555g, respectively. Whilst it took a minimum of 27.9 minutes and a maximum of 30.2 minutes to boil 2.5 litres of water for the tests to be completed with the assorted charcoal in the Wonder stove at high power phase cold start. The minimum and maximum amounts of assorted charcoal consumed were 640 g and 770 g, respectively.

Table 7 shows that using different charcoals at cold start high power phase, it took an average of 26.97 and 31.31 minutes and 546.7 g and 536.8 g of charcoal, respectively, to heat 2.5 litres of water to boil in the metal stove. For Metal Stoves, the minimum and maximum estimates for the amount of time and charcoal consumed were 25.2 minutes, 28.8 minutes, 500g, and 590g, respectively, and 29.5 minutes, 32.4 minutes, 500 g, and 570g.

Table 9. Analysis of various charcoal burnt in metal stove with respect to time at a simmering phase

Descriptive statistics							
	N	Mean	SD	Sum	Min	Median	Max
Time taken to boil 2.5L H_2O (min)	10	45	0	450	45	45	45
Abura charcoal burnt (g)		736.7	80.72	7367	641	723.5	890
Assorted charcoal burnt (g)		809.4	50.13	8094	726	818	890

Table 10. Analysis of abura charcoal saved in wonder stove with respect to time at cold start high power phase

Descriptive statistics							
	N	Mean	SD	Sum	Min	Median	Max
Time saved (min)	10	4.42	1.2934	44.2	2.1	4.65	6.4
Charcoal saved in Wonder stove (%)		54.21	27.70	542.13	15.32	47.34	97.44

Table 11. Analysis of the time at high power phase cold start for abura charcoal saved in a metal stove

Descriptive statistics							
	N	Mean	SD	Sum	Min	Median	Max
Time saved	10	4.34	1.22	43.4	2.5	4.8	5.9
%Charcoal saved		1.40	8.23	14.00	-10.78	1.27	12.28

Table 12. Percentage analysis of abura charcoal saved in wonder stove with respect to time at a simmer - high power phase hot start

Descriptive statistics							
	N	Mean	SD	Sum	Min	Median	Max
Time saved (min)	10	45	0	450	45	45	45
Charcoal saved in Wonder stove (%)		23.08	28.00	230.84	-0.35	8.85	80.93

Table 13. Analysis of abura charcoal saved in metal stove with respect to time at a simmer - high power phase hot start

Descriptive statistics							
	N	Mean	SD	Sum	Min	Median	Max
Time saved	10	45	0	450	45	45	45
%Charcoal saved		10.95	13.24	109.45	-10.12	11.70	38.85

Additionally, Table 8 revealed that 736.8g and 874.5g of Abura and Assorted charcoals were used on average within 45 minutes of the experiment's simmer test phase in the Wonder stove.

Table 9: demonstrates that 736.7g and 809.4g, respectively, were utilised on average at a simmer for 45 minutes. Abura charcoal's minimum and maximum burn weights were 450g and 890g, respectively, whereas the mixed charcoals were 809.4g and 890g. However, the minimum and highest amounts of charcoal burnt on each stove at simmer were: 493g, 865g; Abura charcoal, 839g, 940; assorted charcoal for Wonder stove, 641g, 890g; Abura charcoal and 726g, and 890g assorted charcoal for the Metal stove. Furthermore, the percentage of charcoal saved in the Wonder Stove during the test's cold start and high-power phase is shown in Table 10's descriptive statistics. An average of 4.42 minutes and 54.213% of the charcoal's mass were saved.

Table 11: shows that in an average of 4.34 minutes, 1.40% of the average mass of charcoal was saved when a metal stove was used. The charcoal saved has approximated minimum and maximum values of -10.78% and 12.28%, indicating that the high-power phase hot start does not result in significant noticeable reductions.

According to Table 12, only 23.08% of the charcoal was conserved throughout the simmer phase of the test, on average, in 45 minutes, with a 28% standard deviation. The savings at simmer compared to the cold start high power phase is minimal.

Similar results were found in Table 13, which indicates that only 10.95% of the charcoal was saved in the metal stove throughout the simmer test's hot start, high power phase on average over 45 minutes. This suggests that the Wonder stove also performed better with Abura charcoal in terms of time and charcoal savings. These outcomes, once more, are comparable to those attained by [88] during the water boiling test and field experiments on Injera cooking stoves.

The energy metrics for both stoves using the different types of charcoal used in the experiment are summarised in Tables 14 and 15, respectively. Meanwhile, 9.33kW and 11.95kW were the average fire powers for Abura charcoal and assorted charcoal in the Wonder stove. For the Metal stove, the average fire powers were determined to be 10.07kW for Abura charcoal and 12.25kW for the assorted types of charcoal.

In summary, evaluating an improved cookstove's efficiency offers important information about its effects on the environment, human health, the economy, and society. This knowledge aids in promoting the use of healthier cooking methods and advances broader development goals. Several researchers believe measuring improved cookstove efficiency is an excellent idea for making fact-based decisions [89, 90].

4. Conclusion

Using charcoal fuel only from the Abura tree and other trees, two typical improved cookstoves (Wonder stove and Metal stove) frequently used in Sierra Leone were tested for efficiency and charcoal saving. The efficiencies attained through this effort are generally comparable to those documented in the literature. As a result, the Wonder stove fared better in efficiency testing than the two other kinds of charcoal products, making it the better option.

An overview of the energy metrics for the two improved cookstoves is shown in Tables 13 and 14. (Wonder stove and Metal stove). Thus, the Wonder stove outperformed the two distinct types of charcoal products in efficiency tests, making it a preferable choice.

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Table 14. Summary of energy metrics for wonder stove

	High-power phase Cold start										Simmer - hot start high power phase					
	Abura Charcoal			Assorted Charcoal			Efficiency		Savings			Charcoal burnt		Efficiency		Savings
Unit	Min	g	kW	Min	g	kW	%	%	min	%	min	g		%		%
	Time taken to heat 2.5L of H_2O to boiling Temp	Mass of charcoal burnt	Firepower	Time taken to heat 2.5L of H_2O to boiling Temperature	Mass of charcoal burnt	Firepower	Abura charcoal	Assorted charcoal	Time saved	Charcoal Saved	Time taken to Simmer	Abura charcoal burnt	Assorted charcoal burnt	Abura charcoal	Assorted charcoal	Charcoal saved
N=10	25.2	455	8.97	28.5	640	11.15	21.58	16.04	3.3	40.66	45	680	940	10.81	7.87	38.24
	25.5	540	10.52	30.1	700	11.55	19.77	14.49	4.6	29.63	45	700	900	10.79	6.84	28.57
	24.5	555	11.25	29.4	640	10.81	16.77	15.15	4.9	15.32	45	852	849	8.54	7.23	-0.35
	25.8	470	9.05	27.9	670	11.93	18.53	14.68	2.1	42.55	45	800	839	8.61	7.19	4.88
	23.7	533	11.17	30.1	700	11.55	16.40	14.96	6.4	31.33	45	813	840	8.09	7.58	3.32
	23.8	493	10.29	29.3	750	12.71	22.25	13.81	5.5	52.13	45	493	892	13.19	7.06	80.93
	24.1	380	7.83	28.4	719	12.57	20.66	13.89	4.3	89.21	45	780	880	8.63	6.99	12.82
	25.1	400	7.92	29.8	730	12.17	24.25	14.21	4.7	82.50	45	545	860	12.67	7.28	57.80
	25.5	440	8.57	28.5	710	12.37	18.17	14.61	3	61.36	45	840	845	8.53	7.57	0.60
	24.8	390	7.81	30.2	770	12.66	18.42	14.92	5.4	97.44	45	865	900	6.36	7.58	4.05
Total	248	4656	93.37	292.2	7029	119.48	196.79	146.77	44.2	542.13	450	7368	8745	96.22	73.19	230.84
Average	24.8	465.6	9.34	29.22	702.9	11.95	19.68	14.68	4.42	54.21	45	736.8	874.5	9.62	7.32	23.08

Table 15. Summary of energy metrics of metal stove

	high-power phase Cold start										Simmer - hot start high-power phase.					
	Abura Charcoal			Assorted Charcoal			Efficiency		Savings		Time	Charcoal burnt		Efficiency		Savings
Unit	Min	g	kW	min	g	kW	%		min	%	Min	g	g	%		%
	Time taken to heat 2.5L of H_2O to boiling	Mass of Charcoal Burnt	Firepower	Time taken to heat 2.5L of H_2O to boiling	Mass of Charcoal Burnt	Fire Power	Abura Charcoal	Assorted Charcoal	Time Saved	Charcoal Saved	Time taken to Simmer	Mass of Abura Charcoal burnt	Assorted charcoal burnt	Abura Charcoal	Assorted Charcoal	Charcoal Saved
N=10	26.5	500	9.37	29.5	520	13.13	17.18	15.09	3	-4	45	730	836	7.52	7.54	14.52
	27.8	590	10.54	31.1	540	12.78	15.12	15.11	3.3	8.47	45	890	840	6.48	7.59	-5.62
	27.1	503	9.22	32.2	550	12.80	18.87	14.63	5.1	-9.34	45	641	890	8.58	7.30	38.85
	28.8	567	9.78	31.3	520	11.58	17.92	15.49	2.5	8.29	45	717	850	8.21	7.43	18.55
	26.7	550	10.23	32.4	532	11.34	18.27	15.76	5.7	3.27	45	749	838	7.99	7.70	11.88
	28	570	10.11	31.2	500	11.86	18.21	15.73	3.2	12.28	45	730	800	7.95	8.00	9.59
	26.4	582	10.95	32.3	525	12.15	18.13	15.70	5.9	9.79	45	704	788	8.13	8.20	11.93
	25.2	552	10.88	30	556	12.75	16.89	16.35	4.8	-0.72	45	860	773	6.29	8.40	-10.12
	27.6	552	9.93	32.4	570	11.96	18.90	16.57	4.8	-3.26	45	695	753	8.31	8.60	8.35
	25.6	501	9.72	30.7	555	12.13	18.44	17.03	5.1	-10.78	45	651	726	7.74	8.87	11.52
Total	269.7	5467	100.73	313.1	5368	122.48	177.91	157.46	43.4	14.00	450	7367	8094	77.20	79.63	109.45
Average	26.97	546.7	10.07	31.31	536.8	12.25	17.79	15.746	4.34	1.40	45	736.7	809.4	7.72	7.96	10.95