New Energy Exploitation and Application
https://ojs.ukscip.com/index.php/neea

Article

A Comparative Analysis of Selected Improved Biomass Cookstoves' Temperature Profiles Using the Testo 310 Flue Gas Analyzer

Umar Museheeh Lahai [1,2,*], **Eric Antwi Ofosu** [1] and **Samuel Gyamfi** [1]

[1] Department of Renewable Energy Engineering, School of Energy, University of Energy and Natural Resources, Sunyani, P. O Box 214, Ghana

[2] Department of Mechanical Engineering, Faculty of Engineering, Milton Margai Technical University, Freetown, Sierra Leone

[*] Correspondence: umarmlahai@gmail.com

Received: 16 May 2025; **Revised:** 23 June 2025; **Accepted:** 7 July 2025; **Published:** 21 July 2025

Abstract: One of the major challenges facing the energy sectors in practically all developing countries worldwide is clean cooking. In Sierra Leone, only 1% of the population has access to clean cooking, making it one of the worst among the developing countries with clean cooking problems. Many people are switching to improved biomass cookstoves (IBCs), but the unprecedented production of charcoal-based IBCs and varied designs, particularly ceramic linings, make it difficult for users to choose the right size. The study surveyed major IBC production and sales centres in Sierra Leone's western regions between 2021 and 2023, examining temperature profiles of the metal stove (MS) and wonder stove (WS). The data showed that an average of 3352 MS and 1833 WS were produced and sold between 2021 to 2023. A water boiling test was adopted for IBCs testing and Testo 310 flue gas analyzer was used to track the temperature profiles of the chosen IBCs. The findings suggest that WS could be able to generate and retain heat more quickly and sustainably than MS. Additionally, the recorded temperatures and timings of all IBCs were also subjected to a systematic correlational analysis. A simulation of the various temperatures and times was also plotted to ascertain the temperature-time graph differences. These results are relevant and could aid in the analysis of IBC emissions and thermal efficiency. Thus, the results of the study could be utilized to offer policy recommendations for IBC production and sales centres in Sierra Leone and other developing countries.

Keywords: Charcoal; Charcoal Energy Density; Clean Cooking; Correlational Analysis; Energy; Thermal Efficiency

1. Introduction

The world is experiencing a severe energy crisis, with developing countries all over the world being impacted by incredibly high and unstable energy prices, especially for fossil fuels. Many developing countries may be priced out of the energy market by rising energy prices, which would have a substantial effect on the most vulnerable citizens. The energy crisis cannot be unconnected from the COVID-19 outbreak and the conflict between Russia and Ukraine [1,2]. Furthermore, governments in developing countries are under tremendous pressure as a result of disturbances to the global energy market. However, using renewable energy alone is still insufficient for Africa to industrialize and experience robust economic growth [3]. This does not call into question the necessity of the energy transition, which is a major force behind climate resilience and sustainable development. Due to Africa's excessive reliance on fossil fuels, practically all of its residents are at risk of negative consequences from unpredictable swings in energy costs. The cost-of-living crisis is being exacerbated by rising energy prices, which are also perpetuating the vicious cycle of tight household budgets and rising energy poverty.

Sustainable Development Goal Seven (SDG7) encourages initiatives to transition to greener fuels and stoves that burn healthier. But in almost every developing country in the world, over 85% of the population finds it difficult to access clean cooking facilities due to the growing cost of energy and the technologies associated with it. This situation is getting worse every day across Africa due to the growing demand for energy and a surge in population. Nearly 90% of households in sub-Saharan Africa (SSA) remain dependent on biomass as their primary source of energy for cooking and daily activities, either fully or partially [4,5]. In addition to the fact that access to clean cooking is quite costly, this indicates energy poverty in the subregion. However, several studies on improved biomass cookstoves (IBCs) have been compelled and prompted by the persistent and ongoing usage of biomass as the key cooking fuel in poor or developing countries, particularly in SSA. Some of these studies have found that many developing countries around the world, particularly those in SSA, have found promise in IBCs, which replace traditional approaches to cooking with solid fuels like wood and charcoal. A report indicates that between 80% to 90% of the population in sub-Saharan Africa (SSA) use solid fuels like wood, charcoal and animal dung for their everyday cooking and crafts, primarily in IBCs [6]. Furthermore, according to some research works done in Sierra Leone on a few IBCs, which adopted the water boiling test (WBT) to carry out the computation of the various thermal efficiencies, and emissions of selected IBCs, the results showed great potential for IBCs used. Thus, all the selected IBCs were significantly better than traditional versions of cooking stoves in terms of increased efficiency, reduced emissions, and fuel savings [7,8]. Furthermore, the research made an important step in ascertaining the various IBCs' thermal efficiencies. However, neither the analysis of the temperature profiles of IBCs nor the relationship between temperature and time were critically analyzed over the selected IBCs. Thus, these aspects of the thermodynamic systems are compelling and crucial for the development and assessment of every IBC. Furthermore, some researchers have proved that faster cooking times can result from higher temperatures [9–11], which are achievable in IBCs. This is because most solid food can be heated more rapidly and uniformly due to the improved heat transfer efficiency in IBCs. The majority of IBC research in SSA has concentrated on IBC combustion performance [12,13], with little or no attention paid to the IBC temperature profile investigations.

Almost all IBCs in SSA are made of metal casing, and the majority of them also have ceramic or clay linings in the combustion chambers, which provide effective charcoal burning and temperature conservation, making them more efficient than the traditional three-stone fire stoves [8]. However, obtaining considerably greater thermal efficiency from these IBCs necessitates a careful balance, and low temperature may be one crucial factor that throws the equilibrium off. Additionally, most research has focused on IBCs that burn wood exclusively, rather than IBCs that depend on charcoal as fuel. This is justified by the fact that wood is easy to handle and prepare for laboratory and field testing for greenhouse gas emissions, thermal efficiency and other pollutants [14]. Hence, the intensive labour and time-consuming nature of charcoal production at the local level may be the cause of this unbalanced approach.

Charcoal is produced when raw or dry wood or other organic materials carbonize without oxygen. In SSA, charcoal is mostly produced from peat (mostly rectangular shape) with controlled oxygen. However, in some instances, it is produced in kilns that are furnished with regulated and restricted volumes of air, in chambers that contain different gases, or in airtight ovens or retorts [15]. Its energy density is a crucial factor in its use as a fuel source for IBCs. Research by Hwangdee, Jansiri, Sudajan, et al. [16] revealed that different charcoals produced from particular raw hardwoods had an approximate energy density ranging from 189 kg/m^3 to 560 kg/m^3. This demonstrates that the energy density of charcoal produced from the same tree does not have constant values. Furthermore, these figures confirmed that raw wood had a lower energy density than charcoal. Accordingly, the bulk density of charcoal, which varies according to the type of wood and the carbonization procedure, determines its energy density by volume. Hence, charcoal needs a specific temperature range to ignite and keep up burning. Researchers [17] have defined the self-ignition of charcoal as a runaway heat brought on by internally exothermic processes; that is, the system is considered capable of self-heating to ignite if the internal temperature rises to a point where thermal runaway occurs. The ignition temperature of charcoal can be greatly influenced by the moisture content of the charcoal and the amount of carbon in the wood that carbonizes to charcoal [17,18]. When the ignition temperature is reached, the charcoal begins to burn, producing heat and gases that sustain the combustion process. Nevertheless, the majority of IBC research conducted in SSA did not take into account examining the corresponding temperature patterns.

Fewer studies have focused on examining the thermal efficiency and emissions including temperature profiles of IBC combustion chambers, such as the work of Barpatra, et al. [19] who used ANSYS Fluent software to simulate the combus-tion chambers and determine the air and temperature within the combustion chamber of a natural draft biomass cookstove. Additionally, researchers [20] examined a three-dimensional porous stove using innovative ceramic foam to validate numerical models. The surface temperatures and pertinent experimental findings were compared. These researchers demonstrated the importance of assessing the solid-gas temperature profiles and the heat trans-mission properties of the selected improved biomass cookstoves. The fact that the temperature profile influences almost every aspect of IBC performance, including robustness, greenhouse gas emissions, thermal efficiency, se-curity, and customer experience, makes it an essential diagnostic and design tool [21]. Also, it has been claimed that temperature profiles have been utilized to calculate the minimal fuel needed for an acceptable heating cycle in blast furnace stoves' thermal regenerator systems [22]. For a precise assessment of charcoal requirements, it is critical to comprehend the temperature profile of IBCs. Also, better thermal profiles are frequently associated with less charcoal use, which lessens deforestation and saves users' time. This is one of the strongest arguments for conducting this research, as efforts to design and influence IBC would be blind and less effective without it. Fur-thermore, ore emissions of carbon monoxide, particulate matter ($PM_{2.5}$), and other pollutants result from partial combustion at reduced temperatures. Therefore, cleaner combustion, better indoor air quality, and lower health risks have been proposed by the hotter and more predictable temperature profile. IBC construction materials need to be able to tolerate high temperatures without deteriorating, and knowing the temperature profile guarantees the right material selection, which could increase IBC's lifespan. Thus, scientifically analysing the temperature profiles of these IBCs using particular charcoal produced from carefully chosen trees can be crucial to comprehending how solid fuels, such as charcoal, burn in IBCs. The outcome of the analysis could be quite useful for analyzing IBCs' emissions and the thermal efficiency of IBCs at various country levels. This will assist in developing policy guidelines for designers of IBC combustion chambers and production companies or private producers to enhance their choices of high-temperature-resistant materials.

The energy sector in Sierra Leone faces numerous challenges, including poor transmission and distribution infrastructures, limited access to electricity, insufficient generation capacity, high electricity costs due to reliance on fossil fuels and imports, and a lack of funding and investment. These challenges make it extremely difficult for the general public to have access to clean cooking solutions. As a result, the population's only choice is to use the IBCs as a tool to leverage their regular cooking activities. Furthermore, in Sierra Leone, clean cooking presents certain challenges. This is because both rural and urban populations have limited access to electricity. It has been reported that just around 1% of people in Sierra Leone have access to clean cooking, and even those who have access to the national grid connection rarely use it because of how expensive it is [23]. This explains why many middle-class and lower-class workers in Sierra Leone have been unable to afford liquefied petroleum gas (LPG) for their homes because of its high price. Thus, the option for more than 90% of homes in Sierra Leone's rural and urban areas is to rely on IBCs, which are considered promising by the public. In Sierra Leone, two unique IBCs with a single or double combustion chamber are in extensive use (i.e. metal stove and wonder stove). Producers and sellers of IBCs in four major production and sales points/communities were given a simple questionnaire. The purpose of the questionnaire was to determine the average minimum and maximum number of IBCs produced and sold to the general public for the years 2021–2023, inclusive. Only IBC producers and sellers with at least ten years of production and sales experience and who are headquartered in the Western Area of Freetown, Sierra Leone, were given the questionnaires for the assessment. Over the past two decades, there has been an increase in the widespread and unchecked production of IBCs (metal stoves and wonder stoves) throughout Sierra Leone [7]. The majority of Sierra Leonean artisans and welders now consider the design and fabrication of these IBCs to be a business breakthrough. IBCs are constantly in greater demand. As a result, the primary fuel for these IBCs, charcoal, is being produced at an exponential rate. Therefore, it is necessary to objectively examine the temperature profiles of the two most used IBCs in Sierra Leone: the Wonder Stove (WS) and the Metal Stove (MS).

2. Materials and Methods

In general, there are two ways to evaluate the temperature profiles and emissions from IBCs, that is the chamber technique (CT) and the hood technique (HT) [24,25]. These methods are also suitable for assessing temperature profiles of IBCs alone. In this research, the HT was chosen because the instruments are portable, less expensive, and can be used with pots of varying sizes for IBC temperature profile testing. Additionally, the water boiling test (WBT) was chosen over the control cooking tests (CCT) and the kitchen performance test (KPT). The reason is that WBT will act as a simulation for KPT and CCT and quicker and the experiment can be repeated as much as possible. Sutar et al. (2015) [26] support this approach, stating that laboratory studies of IBC performance, including emissions and other parameters, have a comparative benefit over field studies. This is because the researcher can regulate specific factors including fuel types, moisture content, and atmospheric conditions.

2.1. Description of Wonder Stove (WS)

The term "Wonder stove" (WS) refers to a well-known kind of IBC with a single or double combustion chamber found in Sierra Leoneans homes. Typically, it is between 20 and 65 cm high on average. Its combustion chamber usually has an exterior metal covering and a ceramic liner with asymmetrical round holes. The producers of these kinds of IBCs have complete control over the steel metal casing's thickness, which ranges from 1 mm to 2.5 mm. Although producers can produce different sizes of IBCs, this is often done per customer specifications at varying prices. For this research, the kind of IBC obtained was among those produced for commercial purposes. The front and top views of the WS are shown in **Figure 1**.

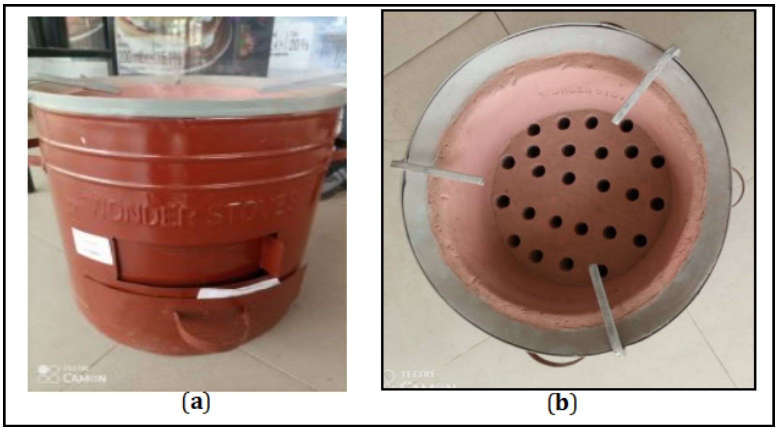

Figure 1. (**a**) WS front view; (**b**) WS top view.

2.2. Description of Metal Stove (MS)

The metal stove (MS) structure is similar to the WS, except that MS is without a ceramic liner in the combustion chamber. The MS is entirely composed of metallic steel plates ranging in thickness from 1 mm to 2.5 mm. The metal thickness is completely up to the designer and producer. Its height varies from 20 cm to 65 cm. In addition, the MS combustion chamber has irregular rectangular apertures that allow incomplete combusted biomass to sink below the combustion chamber. **Figure 2** depicts the front and top views of MS.

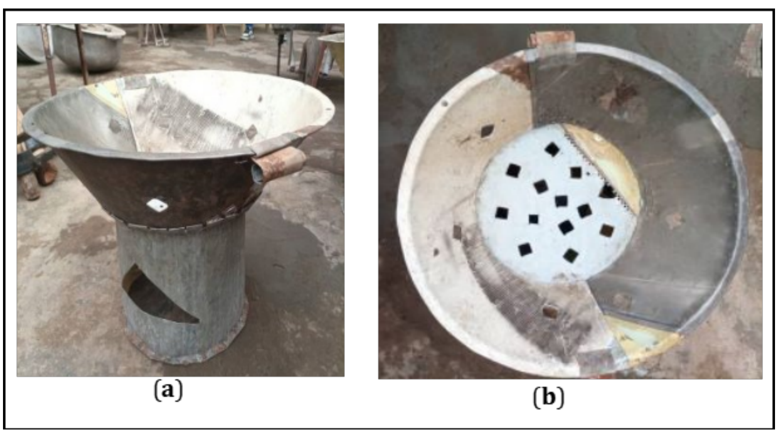

Figure 2. (**a**) MS front view; (**b**) MS top view.

2.3. Fuel Selection for Improved Biomass Cookstove (IBC)

The fuel selection methodology used was adapted from the study conducted in Sierra Leone [7]. The charcoal was produced from carefully selected trees [abura tree (*Mitragyna ciliata*), assorted trees: mango (*Mangifera indica*), matchstick (*Alstonia macrophylla*)] that are commonly used in Sierra Leone for charcoal production, and the availability of feedstocks were part of the basis for their selection. The charcoal was produced from the same tree to prevent major differences in carbon and moisture contents, which are essential for biomass combustion. For this reason, only charcoal was used in both IBCs during the experiment. In other words, producing charcoal from different trees may alter the firepower and change in temperature in each IBC. Water boiling tests were conducted in each IBC using ten piles of 5 kg of abura charcoal and other assorted charcoal, and the results were computed using the equation below.

$$m_c = m_{cb} - m_{ca} \tag{1}$$

where:
m_c = mass (g) of charcoal burned at cold start high power phase,
m_{cb} = mass (g) of pre-weigh charcoal before the start of the test, and
m_{ca} = mass (g) of charcoal after the cold start high power phase of the test.
The following formula was used to get the average mass of the burned charcoal:

$$\overline{m} = \left(\sum_{k=1}^{n} m_{ci}\right) \div n \tag{2}$$

where:
$\overline{m}$ = average mass of burnt charcoal,
m_{ci} = mass of charcoal burnt per test per stove,
$i = 1, 2, 3, \ldots$
$k = n$ denotes the total number of experiments performed per cookstove.

2.4. Temperature sensor in IBC

The temperature sensor for IBC is an electronic instrument that measures and stores temperature over time. It can transform temperature over time into an electronic graph, which can be stored for further study. The biomass temperature profile describes the way the temperature varies over time in various IBC components. The best way to keep an eye on the IBC temperature profile is to assign a similar task to each of the IBCs using similar fuels. A Testo 310 flue gas digital sensor and a thermocouple were used to monitor the temperatures of both IBCs. The Testo 310 flue gas thermocouple was adjusted, and the tip was positioned 2.5 cm from the bottom of the pot (a typical water boiling pot that holds 2.5 litres of water), to monitor the temperature until the water reached the boiling point. Furthermore, the sensor needs to be calibrated since precise temperature readings depend heavily on the sensor's calibration. The sensors are then positioned directly in the hood, just above the pot. Additionally, the ambient temperature must be measured and noted in each test. Every time a test is conducted, 2.5 litres of water must be used at the start and 2.5 litres of water for repeated tests to ensure consistent testing. Also, a consistent fuel load (charcoal) must be used for the IBC testing to start. The experiments were repeated ten (10) times and the averaged the results. The temperature readings were recorded along with the times throughout the tests.

2.5. Water Boiling Test (WBT)

The water boiling test (WBT) procedures were used to monitor and record the growing temperatures of the 2.5 litres of water during an experiment at the high-power cold start using the Testo 310 flue gas analyzer. The researchers [27] advocated using distilled water throughout the experimental trials. This is because contaminants can raise water's boiling point. Thus, affecting the temperature profile monitoring. The temperatures were recorded at minute intervals. The test was run ten times in each IBC to reduce error or variation. Before each test begins, a background temperature and humidity reading are made and documented. The results from both WS and MS were then analyzed using OriginPro software.

2.6. Temperature Simulation Tool

OriginPo software (viot2D) was used to simulate and analyze the temperatures recorded over time during the WBT experiments. Prior to the temperature-time simulation, the observed ambient temperatures were logged and removed from the final data.

3. Results and Discussions

3.1. Analysis of MS and WS Produced between 2021 and 2023

A simple questionnaire was distributed to selected MS and WS producers/sellers in Freetown, Sierra Leone's western region, to determine the minimum and maximum range of targeted IBCs that are produced and sold annually. IBC producers and sellers with more than 10 years of experience were the target of the poll. As stated below, the poll focused on the average number of IBCs (MS and WS) produced between 2021 and 2023 inclusive. The IBC producers and sellers were obliged to provide an estimated minimum and maximum range of quantities of the types of IBCs produced and sold annually for the period 2021 to 2023. Although the majority of IBC producers and sellers did not routinely track their IBC sales and production, they were able to provide an average minimum and maximum range over three years. The different ranges (min and max) for each IBC type to the production community are listed in **Table 1**.

Between 2021 to 2023, the average quantity of MS and WS produced and sold was 3352 and 1833, respectively. There was roughly 45.32% more MS produced and sold annually than WS when the production and sales figures were compared. This indicates that metal stoves (MS) are more produced and sold per year than wonder stoves (WS). The costs in **Table 1** vary from one production and sales centre to the next. This could be because the closer the production and sales centre is to the capital city, Freetown, the more the cost of both IBCs increases. However, the cost of WS is always significantly higher than that of MS in all the production and sales centres. The thickness of the metals used to make the WS and the amount of labour and money needed to make the ceramic that lines the combustion chambers have a substantial effect on the WS's sales price in addition to the city's vicinity. These findings are extremely important for the growth of the two identified IBCs and the production and sales of charcoal in Sierra Leone's agriculture sector and the Ministry of Energy.

Table 1. Estimated costs (in Leones) and quantity of IBCs by sales location and community.

Producer/Sales Location/Community	Types of IBC	Ranges of IBCs Production/Sales per Year			Estimated Current Cost of IBC (Leones)	Average Range Values of IBCs from 2021–2023			IBC Production and Sales Range Averages for 2021–2023		
		2021	2022	2023		2021	2022	2023	Average	Total Average MS	Total Average WS
Waterloo	MS	600–1500	450–2500	600–1000	70	1050	1475	800	1108	3352	1833
	WS	400–900	300–700	250–750	120	650	500	500	550		
Freetown (Ferry Junction)	MS	200–1500	300–890	400–1200	120	950	595	800	782		
	WS	150–600	200–700	250–650	250	375	450	450	425		
Grafton	MS	400–1400	450–900	400–1000	80	900	675	700	758		
	WS	200–650	300–800	100–500	150	425	550	300	425		
Leicester-International Military Assistance & Training Team (IMATT)	MS	400–800	300–1000	600–1300	90	600	650	950	733		
	WS	150–500	250–600	300–550	150	325	550	425	433		

3.2. Variations in Temperature Caused by the Use of Different Charcoals in Wonder Stove

Improved biomass cookstoves (IBCs) like wonder stoves (WS) are made to be healthier and more effective than conventional cookstoves (three–stone fire cookstoves). How IBCs' temperature variations are handled is a crucial component of their efficiency. A better-insulated design is a common feature of WS, which helps to preserve the heat inside the stove and transfer it more evenly. According to the following researchers [28, 29], this assertion is true. This may result in fewer temperature fluctuations and a more stable cooking environment. Also, some

IBCs incorporate attributes like movable burners or air vents that enable more accurate temperature control. For kitchen operations that call for specific temperatures, like baking or simmering, this can be very crucial. In general, WSs are created to offer a more constant and manageable cooking environment, which can make cooking simpler and more effective. **Figure 3** compares the temperatures of two different charcoal products used in Wonder cookstoves (WS) to test the boiling time of water. Before lighting the fire, the temperature of the WS and the water in the pot were both measured and recorded at 26°C at a time of 0.0 seconds. The temperature began to fluctuate at time 2 minutes, which may have been caused by differences in the stove's firepower and the moisture content of the various charcoals used in the tests. The performance of the stove is significantly influenced by the type of charcoal. Assorted charcoal and abura charcoal both had average moisture contents of 5.8% and 5%, respectively. A very slight change in moisture content can slow the combustion process, which will negatively impact the stove's ability to burn charcoal. Thus, having negative effects on temperature profiles. When Abura charcoal was lit, the temperature changed by 2 °C over the course of 2 minutes, whereas the assorted charcoal only added 1 °C to the temperature. After 4 minutes, the water on the stove reached a trajectory temperature of 34 °C and 31 °C, respectively. After 21 minutes of testing with abura charcoal, the temperature of the water in the pot reaches the point of simmering (i.e., 85 °C) and finally reaches boiling at an average time of 24.8 minutes. Additionally, when assorted types of charcoal are used, the temperature reaches the simmering point in 22 minutes and the boiling point in 29.22 minutes. There appears to be a positive correlation between temperature and time in both instances where both abura and assorted charcoals were utilized. The temperature-time graphs, however, show that when abura charcoal is used in WS, the temperature-time graph in this case is higher than when assorted charcoal is used in WS. Therefore, in WS, abura charcoal outperformed the assorted charcoals.

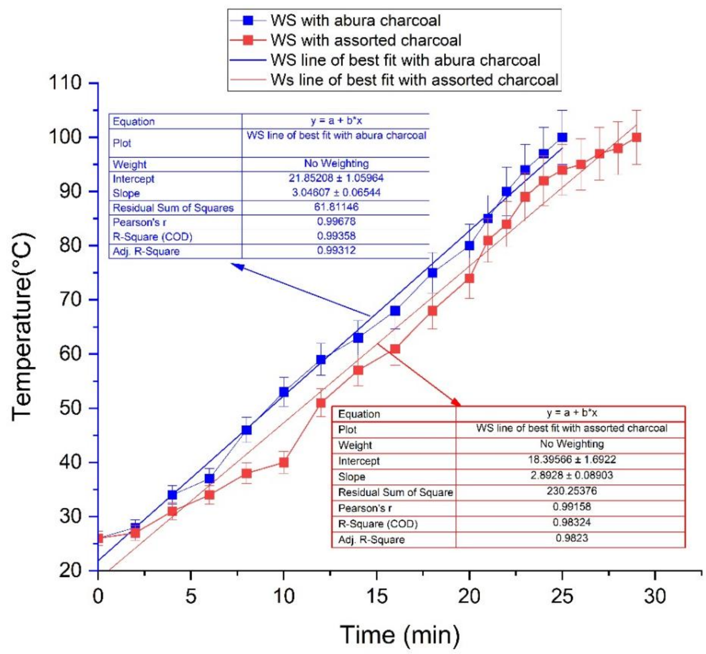

Figure 3. Wonder stove temperature-time graphs when both abura and assorted charcoals.

When evaluating two IBCs for a water boiling test, time savings can be a key consideration. IBCs are made to burn fuel more efficiently, emit fewer pollutants, and perform better during cooking, all of which can shorten cooking times. First, the efficiency of the cooking process is directly impacted by time savings. Due to their inefficient construction and high fuel consumption, traditional biomass cookstoves frequently take a long time to bring water to a boil. IBCs, on the other hand, are designed to maximise heat transfer and minimise heat loss, leading to shorter boiling periods. IBCs increase overall thermal efficiency by decreasing the time it takes for water to reach boiling, allowing users to save significant time in their daily routines. Additionally, time saves aid in resource preservation. IBCs are made to ensure that more of the heat generated is used for cooking rather than being lost, which maximizes fuel economy. In comparison to conventional three–stone fire biomass cookstoves, this indicates that less fuel is needed to get the same cooking outcomes. WS aids in the preservation of priceless natural resources like charcoal or other biomass fuels by lowering the amount of fuel required and cutting the boiling time.

In conclusion, time savings are crucial when contrasting two IBCs and performing a water boiling test. They improve the effectiveness of cooking, save resources, give people more power, and are essential in emergencies. Improved cookstoves reduce the time it takes for water to boil, which not only enhances the cooking experience but also has a significant impact on people's daily lives and the sustainability of communities.

3.3. Temperature Difference Versus Time Graph for Wonder Stove

The temperature difference versus time graph for a water boiling test on WS typically displays two distinct phases:

a. The Phase of Ignition and Preheating: During this period, the improved cookstove is lit and given some time to preheat before reaching a steady operating temperature. The temperature difference between the water and the stove is rather minor and can vary slightly during this stage as the stove heats up.

b. Boiling Phase: 2.5 litres of water is poured into the pot, and the boiling process starts, once the stove has attained a constant operating temperature. In this stage, the temperature difference between the water and the stove will steadily rise until it reaches its maximum. The efficiency of the stove, as well as the pot's size and volume, will determine how quickly the temperature rises. To guarantee that the 2.5 litres of water is boiled fast and effectively, the stove should ideally be able to sustain a high-temperature difference for a prolonged amount of time.

The wonder stove (WS) was subjected to water boiling tests with abura charcoal and assorted types of charcoal. The variation in temperature versus time graph for the WS water boiling test should, in general, show a sharp rise during the boiling phase, demonstrating that the WS can quickly and efficiently bring the 2.5 litres of water to the boiling point, which is followed by a gradual decline during the cool-down phase. The goal was to track the temperature profiles throughout the process and ascertain how effective these charcoals were in this WS (how long it takes to raise 2.5 litres of water to a boil). The temperature graphs are shown in **Figure 4**, and the shaded area denotes the area with the temperature difference. Because the Wonder stove and the water used in the water boiling test were both measured at the same temperature, 26 °C, both graphs did not begin at the origin. This also indicates the intercept on the temperature axis. It might be evident from the start of the experiment that when abura charcoal is used in the WS, the temperature rises steadily until the boiling point is reached in 24.8 minutes with abura charcoal and 29.22 minutes with assorted types of charcoal. This shows that the WS performed more quickly with abura charcoal during the water boiling test than it did with assorted charcoal, with a significant time difference of 4.42 minutes. As a result, the faster the temperature rises, the shorter the time required to complete the task.

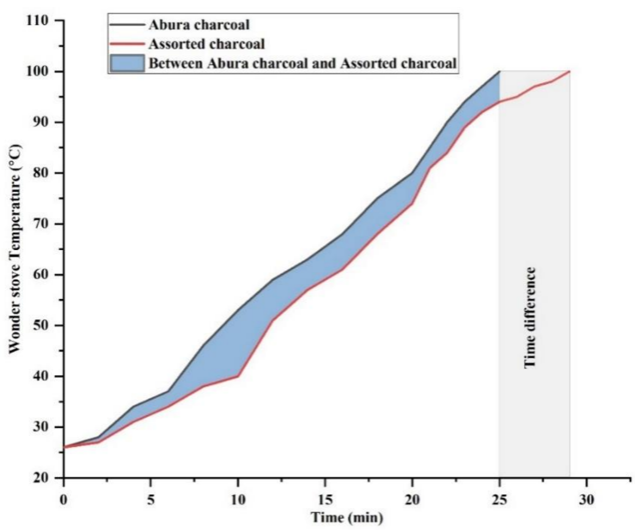

Figure 4. Wonder stove temperature difference-time graph.

Figure 5 displays the temperature sensor curve after 2.5 litres of water were heated to a boiling point in WS. These sensor graphs illustrate that even a very small increase in temperature or a temperature variation can be evident and pollutants can be sensor, regardless of the types of charcoal products utilized. Pollutants were visible in the WS when both types of charcoal were used, with a high concentration of emissions appearing two minutes after the fire started and twenty to twenty-four minutes before the water boiled.

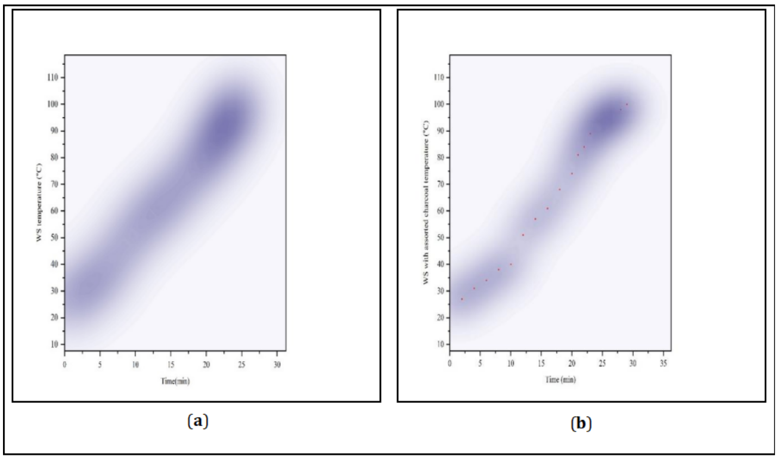

Figure 5. Temperature sensor time graphs in WS. (**a**) abura charcoal, (**b**) assorted charcoal.

Figure 6 displays the two charcoals' simulated temperature curves (voigt2D-OriginPro software) when they are utilized in WS. After placing the charcoal inside the WS and lighting it with a tinder produced from the same wood that produced the charcoal, it takes some time for the WS temperature to rise. It is essential to simulate both sets of temperatures and time recorded during the WBT using abura and assorted types of charcoal to help WS designers and producers forecast how heat would move through a WS system. An important part of the WS's lighting is the primary air intake that passes through it. The upper portion of the WS is where this occurs. But after the WS is lit, the mechanical blower serves as the secondary air intake. After ten minutes, the temperature changes sharply and continues until the 2.5 litres of water boil. This is an indicator that the stove hood's mechanical blower is controlling the temperature within the WS combustion chamber. This is shown by the simulated graphs at time 0.0 seconds. Because of this, IBC designers and producers will be able to identify potential overheating issues or temperature drops early in the design process, enhance thermal management strategies, and make the necessary adjustments to ensure WS performance and dependability across a range of temperature ranges. This could reduce the need for testing iterations and physical prototypes, which eventually saves time and money. Additionally, it is crucial to take into account the fuel's moisture content and fuel loading in each type of IBC because these factors could significantly alter the temperature during the WBT.

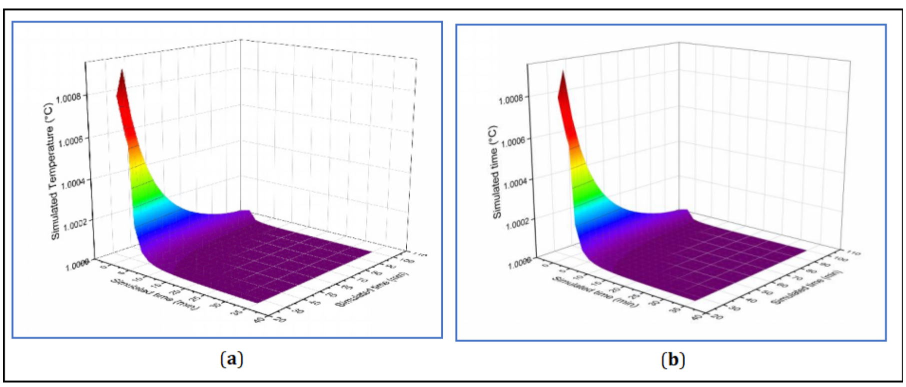

Figure 6. Simulated temperature-time graphs in WS. (**a**) abura charcoal, (**b**) assorted charcoal.

3.4. Variations In Temperature Caused by the Use of Various Charcoals in the Metal Stove

Figure 7 depicts a graph of metal stove temperature versus time when various charcoals were used in metal stove (MS). Again, the graph does not begin at the origin because the temperature of the stove and the water used to experiment were both 26 °C. A small difference in temperature of about 1 °C was seen after 2 minutes of the test. This pattern continues, with only a slight temperature change, until 14 minutes have passed. At that point, the metal stove's temperature drastically changed until the 24-minute mark. When abura charcoal was used, the time it took to boil water was measured at 27 minutes, whereas the time it took to boil water when using assorted charcoal was measured at 31 minutes. The water boiling test revealed a difference in time of 4.4 minutes. Additionally, this outcome shows that the metal stove outperformed abura charcoal more than the assorted types.

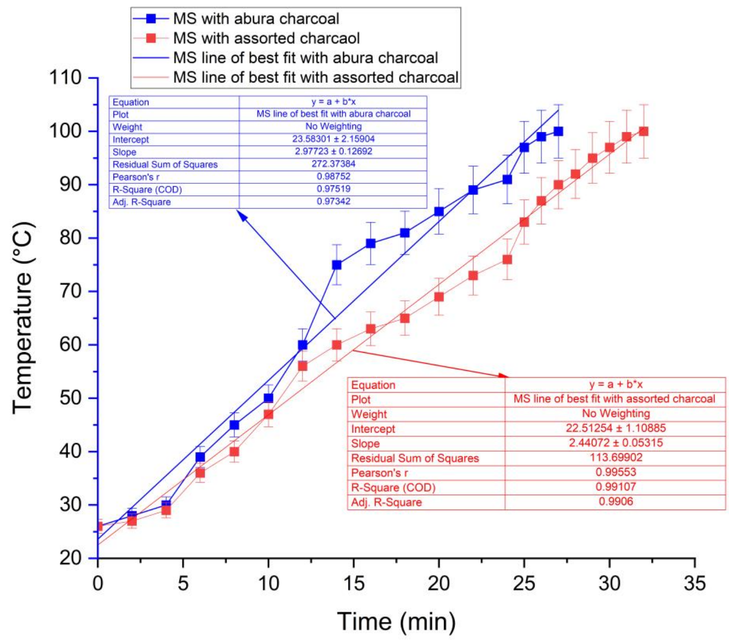

Figure 7. Metal stove temperature-Time graphs when both types of charcoal products are used.

Figure 8 depicts the graphs of the MS temperature versus the time required to complete the water boiling test on 2.5 litres of water. Prior to the experiment, the temperatures of the MS and the water were measured, and it was discovered that both were 26 °C. After 8 minutes into the test, the temperature of the MS rose quickly with abura charcoal while it rose more slowly with assorted charcoal in the same MS. The temperature difference enclosed between the curves is represented by the shaded region shown in the graph. The water boiling test, on the other hand, lasted 27 minutes with abura charcoal and 31 minutes with assorted charcoals. The test time difference, or time saved, was discovered to be 4.3 minutes. This time difference indicates that the MS significantly improved with abura charcoal than with assorted charcoals.

Figure 9 depicts the combined temperature-time graph of the Wonder stove (WS) and Metal stove (MS) fitted with best-fit lines. At time 0.00 seconds, shortly before the experiment started, it was discovered that the WS's water temperature was 26 °C. As a result, the graph crossed the temperature axis at this point. As the fire temperature and heat in the stove rise, the water's temperature rises as well until it reaches the boiling point. Regular temperature and time readings were obtained and recorded. The intersection on the temperature axis and slope of the line of best fit on the scatter plot of the temperature-time graph was found to be 21.85±1.06 and 3.05+0.07 respectively. There was only a slight deviation of the points from the line of best fit, as indicated by the residual sum of squares of the temperature and time data, which was calculated to be 61.81. The correlation coefficient was calculated to be 0.997. According to this graph, there is a significant relationship between water temperature in a WS and how long it takes to reach boiling. Even though the water used to conduct the WBT on both stoves was the same temperature at the exact moment when the timer was 0.00 seconds. A change in water temperature occurs just after a shorter period. This pattern continued until the water started to boil. The temperature-time graph and line of best fit are shown on the graph (in red) in **Figure 9**. According to the graph, the intercept was calculated to be 18.40 ± 1.69 and the slope to be 2.89 + 0.089. It has been noted, nonetheless, that not all data falls along the line of greatest fit. Some of it lies both below and above the best-fit line. This inaccuracy or error is a type of prediction known as a residual [30]. As a result, the residual sum of squares was calculated to be 61.81.

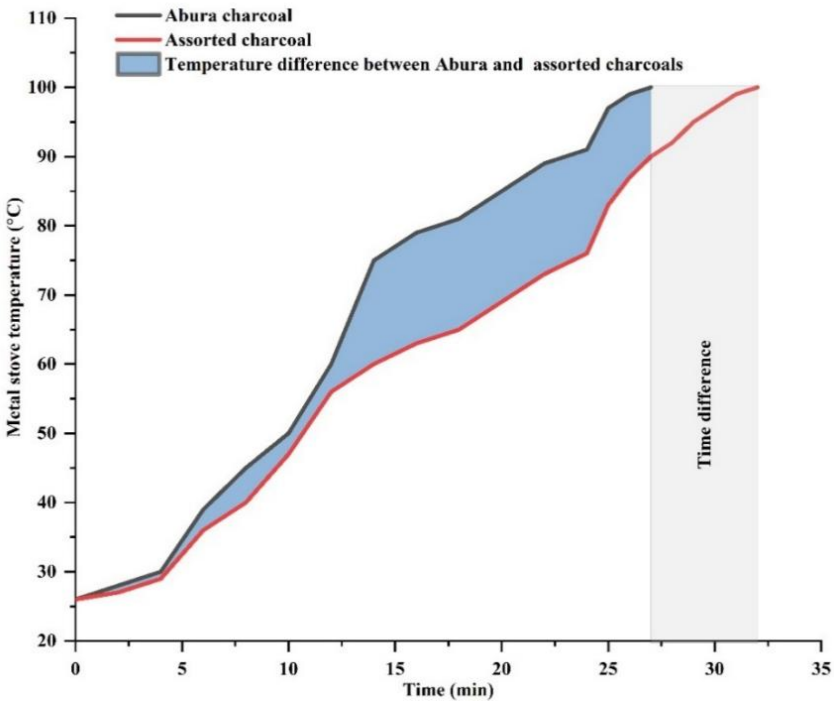

Figure 8. Metal stove temperature difference-time graph.

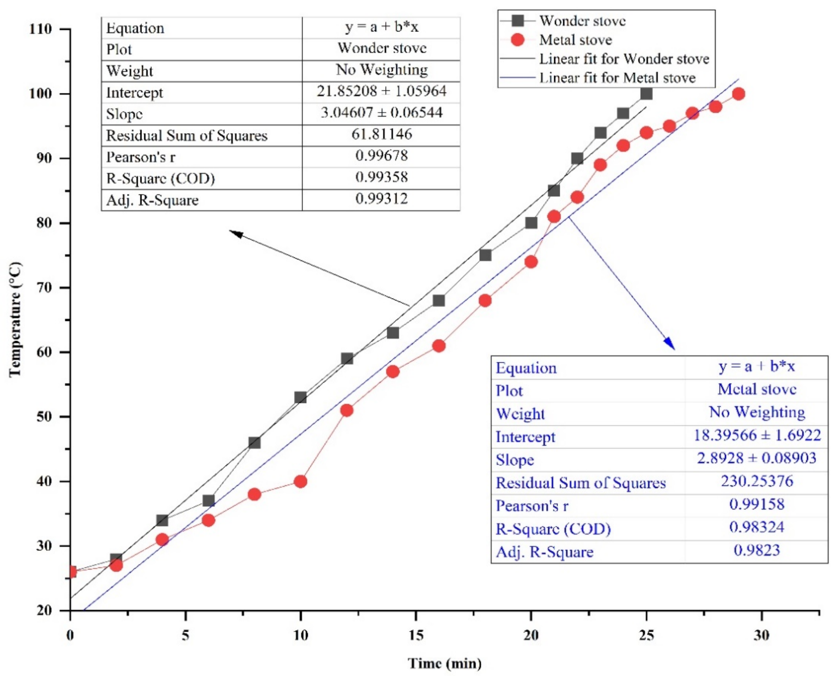

Figure 9. Relationship between Temperature with Time in a Wonder Stove and a Metal Stove.

The MS temperature-sensor time graphs are shown in **Figure 10** following the use of several charcoal products to bring 2.5 litres of water to a boil. Again, these graphs showed that even a slight temperature change would result in pollutants, and when both types of charcoals are employed in MS, pollutants are apparent even after two minutes, and emissions appear to have higher concentrations at the water boiling point in both cases.

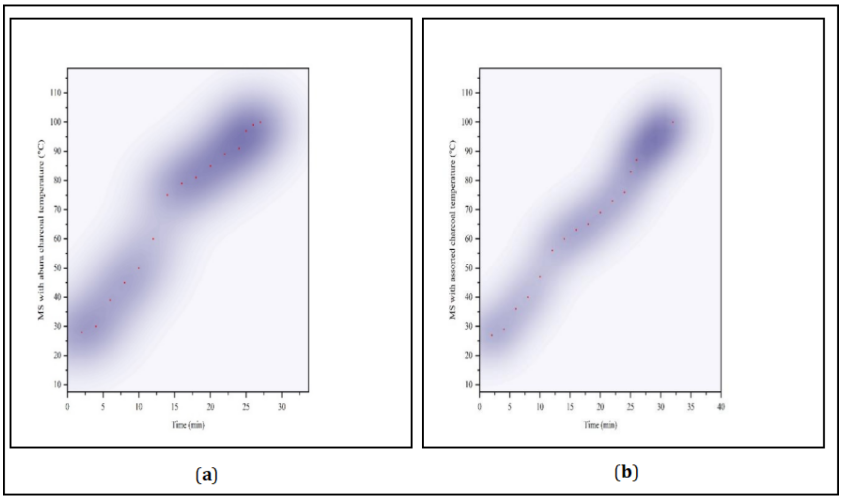

Figure 10. Temperature sensor time graphs in MS. (**a**) abura charcoal, (**b**) assorted charcoal.

Figure 11 displays the MS temperature curves that were simulated using both abura and assorted types of charcoal. The opening side of the stove hood, which lets air into the MS's combustion chamber, is the main source of airflow to the stove. The mechanical blower, on the other hand, provides the secondary airflow, allowing air to pass via baffles in the dilution tunnel controller. As a result, the fire may spread swiftly throughout the MS combustion chamber. The profiles demonstrated that the temperature distribution in the chamber spread across the combustion chamber's surface when the MS was lit. For both types of charcoals, there is a temperature trajectory (high-temperature gradients) as time goes on, say after ten minutes. Until the 2.5 litres hit the boiling point. Once more, the MS designers and producers will be prompted by these simulated temperature curves to make informed decisions about the type of metal and thickness they need to use when employing charcoals as fuels. Therefore, in MS designs, the type of metal and thickness are crucial.

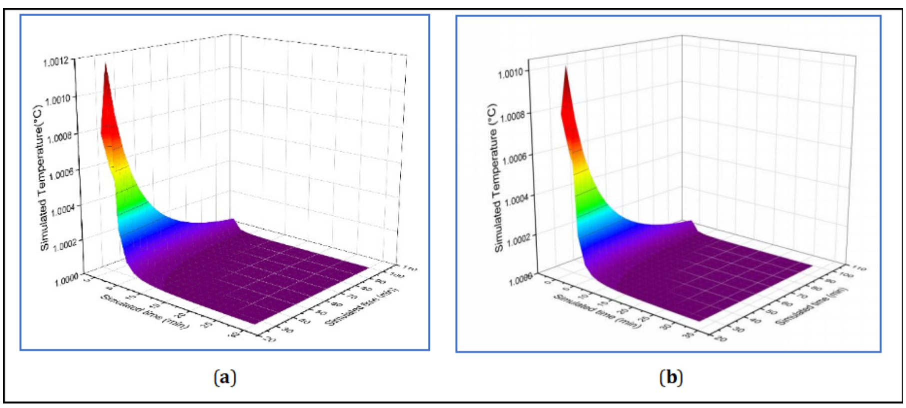

Figure 11. Simulated temperature-time graphs in MS. (**a**) abura charcoal, (**b**) assorted charcoal.

3.4.1. Descriptive Statistics for Charcoal Burned in Wonder Stove

Table 2 provides detailed information on the abura and assorted types of charcoal that were burned during the water boiling test at the high-power phase cold start (HPPCS). Repeated experiments were conducted using 2.5 litres of water, and the amount of charcoal burned was averaged in both cases of the types of charcoal utilized.

To bring 2.5 litres of water to a boiling temperature in WS, 448.2 g (on average) of abura charcoal was usually required, whereas 614.8 g (on average) of assorted charcoal was required to bring the same quantity of water to a boiling temperature. However, the minimum and maximum amounts of abura charcoal that were burned in the entire experiment in WS on average were 389 g and 520 g, whereas, the minimum and maximum quantities of assorted charcoal that were respectively burned in WS were 579 g and 697 g.

Table 2. A descriptive statistics of the two types of charcoal burned in Wonder Stove.

IBC & Charcoal Types	Descriptive Statistics								t Statistics		
	No. Test	Mean (g)	SD (g)	Sum (g)	Min (g)	Median (g)	Max (g)	SEM	t-Statistic	DF	Prob-|t|
WS with abura charcoal at HPPCS	N = 10	448.2	40.66	4482	389	452.5	520	12.86	34.86	9	< 0.0001
WS with assorted charcoal at HPPCS		614.8	35.51	6148	579	600	697	11.23	54.75	9	< 0.0001

3.4.2. Descriptive Statistics for Charcoal Burned in Metal Stove

Table 3 presents descriptive statistics regarding the amounts of different types of charcoal that are burned in metal stoves. The average quantity of charcoal used to raise 2.5 litres of water to a boiling temperature was 579 g of abura charcoal, while 662 g of assorted types of charcoal were used to bring the same quantity of water to a boiling temperature. Additionally, the minimum and maximum quantities of abura charcoal burned in MS at high-power phase cold start (HPPCS) were 518 g and 624 g, respectively, but the minimum and maximum quantities of assorted charcoal burned when using mixed charcoal were 599 g and 701 g, respectively.

Table 3. Descriptive statistics of charcoal burned in Metal Stove at HPPCS.

IBC & Charcoal Types	Descriptive Statistics								t Statistics		
	No. Test	Mean	SD	Sum	Min	Median	Max	SEM	t-Statistic	DF	Prob-|t|
MS with abura charcoal at HPPCS	N = 10	579	29.11	5790	518	583	624	9.2	62.90	9	< 0.0001
MS with assorted charcoal at HPPCS		662	31.27	6620	599	664.5	701	9.88	66.96	9	< 0.0001

4. Conclusions

This study is essential to the development of Sierra Leone's two IBC types, wonder stove and metal stove. According to the survey, a substantial quantity of wonder stoves and metal stoves are regularly produced and marketed in Freetown's urban and rural areas. This research was focused solely on brand-new IBCs that were produced and marketed within the stated timeframe. Overall, however, the most widely used IBCs in Sierra Leone have been found and have undergone temperature profile monitoring and testing that may help ascertain the different IBCs' thermal efficiency and emissions monitoring. The government of Sierra Leone can prioritize policy recommendations on the development of these two identified IBCs based on the insights this research has offered. Thus, it facilitates the collection of national data on improved biomass cookstoves and the testing of each IBC for thermal efficiency and other pollutants. The IBC figures may be subject to changes over time as the city's population grows due to the number of residential houses being built and employment migration. However, it is important to keep in mind that the study considered only IBC production and sales facilities that were established over ten years within the Waterloo community, IMATT and the Ferry Junction. The findings in this research may differ from subsequent studies that may be considering IBC establishments and sales points that have existed for less than a decade and may consider even the entire community around Freetown. Additionally, such an experiment might be conducted in other nearby nations, however, the outcomes might differ because of climatic change and the availability of comparable charcoal materials.

IBCs' designs and other external features have been the subject of several studies, but investigations of their temperature profiles have received less attention. Intending to generate renewed perspectives for IBC design research, this study has concentrated on temperature profile evaluations of the chosen MS and WS in Sierra Leone.

Regardless of the different types of charcoal used to perform the WBT, this study showed that temperature and time had a strong positive correlation in each IBC. The correlation coefficients that were determined measure the strength and direction of correlations between important performance parameters in a WBT. This helps ensure that the cookstove functions efficiently and consistently, driving both technical advances and legislative decisions regarding clean cooking technology. Additionally, as this study's literature has demonstrated, fuel selection may be a major factor in determining the efficiency and firepower of any IBC performance, especially when looking at the temperature profile. Therefore, it becomes logical to think about doing more research on the kinds and quantities of emissions that are generated during temperature profiling [31]. The IBC temperature profiles presented in this study can be used to enlighten numerous further studies relating to the chemistry of burning charcoals which are made from various woods. A thorough correlational investigation between temperature and time has been carried out using the selected charcoals and IBCs. These findings can provide insight into the distribution of temperatures inside each IBC's combustion chamber. Thus, both WS and MS results showed good potential for further research and its replication in the subregion.

Author Contributions

Conceptualization, U.M.L.; methodology, U.M.L.; software, U.M.L.; validation, E.A.O. and S.G.; formal analysis, U.M.L., E.A.O. and S.G.; investigation, U.M.L., E.A.O. and S.G.; resources, U.M.L., S.G. and E.A.O.; data curation, U M Land; writing—original draft preparation, U.M.L.; writing—review and editing, E.A.O. and S.G.; visualization, U.M.L.; supervision, E.A.O. and S.G.; project administration, U.M.L.; funding acquisition, E.A.O. and S.G.. All authors have read and agreed to the published version of the manuscript.

Funding

This study was entirely funded by the World Bank Group via the Regional Centre for Energy and Environmental Sustainability (RCEES) at the University of Energy and Natural Resources, Sunyani, Ghana.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

All data provided in the research study can be accessed by contacting the corresponding author.

Acknowledgments

The authors would like to thank all of their colleagues for their valuable suggestions and the hard-working lab staff for always being available. Additionally, the authors would like to express their gratitude to the World Bank Group for financing this work.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Global Impact of War in Ukraine: Energy Crisis. Available online: https://unctad.org/publication/global-impact-war-ukraine-energy-crisis (accessed on 19 January 2025).
2. World Energy Outlook 2024. Available online: https://www.iea.org/reports/world-energy-outlook-2024 (accessed on 28 December 2024).
3. Berahab, R. The Energy Crisis of 2021 and its Implications for Africa. Available online: https://www.policycenter.ma/publications/energy-crisis-2021-and-its-implications-africa (accessed on 10 December 2024).

4. Stritzke, S.; Sakyi-Nyarko, C.; Bisaga, I.; et al. Results-Based Financing (RBF) for Modern Energy Cooking Solutions: An Effective Driver for Innovation and Scale? *Energies* **2021**, *14*, 4559.
5. Wright, C.; Sathre, R.; Buluswar, S. The global challenge of clean cooking systems. *Food Security* **2020**, *12*, 1219–1240.
6. Meng, T.; Florkowski, W.J.; Sarpong, D.B.; et al. Cooking Fuel Usage in Sub-Saharan Urban Households. *Energies* **2021**, *14*, 4629.
7. Lahai, U.M.; Antwi, E.O.; Gyamfi, S.; et al. Assessment of Post-Combustion CO_2, CO and $PM_{2.5}$ Levels from Selected Improved Biomass Cookstoves in Sierra Leone. *SSRG Int. J. Mech. Eng.* **2024**, *11*, 48–69.
8. Lahai, U.M.; Ofosu, E.A.; Gyamfi, S.; et al. The Assessment of Combustion Performance of Improved Cookstoves in Sierra Leone. *Int. J. Eng. Trends Technol.* **2023**, *71*, 196–211.
9. Alvarez-Ramirez, J.; Vernon-Carter, E.J.; Carrillo-Navas, H.; et al. Effects of cooking temperature and time on the color, morphology, crystallinity, thermal properties, starch-lipid complexes formation and rheological properties of roux. *LWT* **2018**, *91*, 203–212.
10. Gebreegziabher, Z.; Beyene, A.D.; Bluffstone, R.; et al. Fuel savings, cooking time and user satisfaction with improved biomass cookstoves: Evidence from controlled cooking tests in Ethiopia. *Res. Energy Econ.* **2018**, *52*, 173–185.
11. Ayub, H.R.; Ambusso, W.J.; Manene, F.M. A Review of Cooking Systems and Energy Efficiencies. *American J. Energy Eng.* **2021**, *9*, 1–7.
12. Njenga, M.; Gitau, J.K.; Njenga, M.; et al. Innovative biomass cooking approaches for sub-Saharan Africa. *African J. Food, Agric. Nutr. Dev.* **2019**, *19*, 14066–14087.
13. Kaputo, K.; Mwanza, M.; Talai, S. A Review of Improved Cooker Stove Utilization Levels, Challenges and Benefits in Sub-Saharan Africa. *J. Energy Res. Rev.* **2023**, *14*, 9–25.
14. L'Orange, C.; DeFoort, M.; Willson, B. Influence of testing parameters on biomass stove performance and development of an improved testing protocol. *Energy Sustain. Dev.* **2012**, *16*, 3–12.
15. Demirbas, A.; Ahmad, W.; Alamoudi, R.; et al. Sustainable charcoal production from biomass. *Energy Sources, Part A* **2016**, *38*, 1882–1889.
16. Hwangdee, P.; Jansiri, C.; Sudajan, S.; et al. Physical Characteristics and Energy Content of Biomass Charcoal Powder. *Int. J. Renew. Energy Res.* **2021**, *11*, 158–169.
17. Wolters, F.C.; Pagni, P.J.; Frost, T.R.; et al. Size Constraints on Self Ignition of Charcoal Briquets. *Fire Saf. Sci.* **2003**, *7*, 593–604.
18. Ajayeoba, A.O.; Fajobi, M.O.; Adebiyi, K.A.; et al. Safety assessment of charcoal usage and effects of common charcoal ignition aiders on combustion indices. *Sci. Rep.* **2022**, *12*, 16940.
19. Barpatra Gohain, R.J.; Dutta, P.P. A Numerical and Experimental Performance Assessments of an Improved Natural Draft Biomass Cook Stove. *Combust. Sci. Technol.* **2024**, 1–28.
20. Zhou, H.; Wang, G.; Tu, H.; et al. Combustion Temperature in a Three-Dimensional Porous Stove with a High-Fidelity Structure. *Therm. Eng.* **2023**, *233*, 121108.
21. Mengsi, D.; Pengxin, Z.; Hanyu, Y.; et al. Directions to improve the thermal efficiency of household biomass cookstoves: A review. *Energy Build.* **2023**, *278*, 112625.
22. Muske, K.R.; Howse, J.W.; Hansen, G.A.; et al. Temperature Profile Estimation for a Thermal Regenerator. In *Proceedings of the 38th IEEE Conference on Decision and Control*, Phoenix, AZ, USA, 7–10 December 1999.
23. Policy recommendations for clean cooking access in Freetown, Sierra Leone. Available online: https://iclei.org/e-library/policy-recommendations-for-clean-cooking-access-in-freetown-sierra-leone/ (accessed on 18 February 2025).
24. Ballard-Tremeer, G.; Jawurek, H.H. The "hood method" of Measuring Emissions of Rural Cooking Devices. *Biomass Energy* **1999**, *16*, 341–345.
25. Bhattacharya, S.C.; Albina, D.O.; Salam, P.A. Emission factors of wood and charcoal-fired cookstoves. *Biomass Bioenergy* **2002**, *23*, 453–469.
26. Sutar, K.B.; Kohli, S.; Ravi, M.R.; et al. Biomass cookstoves: A review of technical aspects. *Renew. Sustain. Energy Rev.* **2015**, *41*, 1128–1166.
27. Lahai, U.M.; Antwi, E.O.; Gyamfi, S.; et al. Technical Considerations for the Design and Selection of Improved Cookstoves: A Review. *Int. J. Eng. Trends Technol.* **2022**, *70*, 439–449.
28. Kehirsagar, M.P.; Kalamkar, V.R. A comprehensive review on biomass cookstoves and a systematic approach for modern cookstove design. *Renew. Sustain. Energy Rev.* **2014**, *30*, 580–603.
29. Still, D.; Bentson, S.; Li, H. Results of Laboratory Testing of 15 Cookstove Designs in Accordance with the ISO/IWA Tiers of Performance. *EcoHealth* **2015**, *12*, 12–24.

30. NumPy Ninja. Available online: https://www.numpyninjaacademy.com (accessed on 18 November 2022).
31. Memon, S.A.; Jaiswal, M.S.; Jain, Y.; et al. A comprehensive review and a systematic approach to enhance the performance of improved cookstove (ICS). *J. Thermal Anal. Calorim.* **2020**, *141*, 2253–2263.