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Original Article

Assessment of Post-Combustion CO_2, CO and $PM_{2.5}$ Levels from Selected Improved Biomass Cookstoves in Sierra Leone

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Abstract - *Cooking with solid fuels like charcoal is prevalent among households in Sierra Leone. These have resulted in significant release of emissions of carbon dioxide (CO_2), carbon monoxide (CO), and particulate matter whose aerodynamic diameter is less than or equal 2.5 μm ($PM_{2.5}$). The study conducted a Water Boiling Test (WBT experiment on Wonder and Metal stoves, using charcoal from selected trees: abura (Mitragyna stipulosa) and mixed trees, Mango (Mangifera indica), and Matchstick (Aechmea gamosepala). During every phase of the WBT, the pollutants released by two sets of charcoals in two improved cookstoves were calculated. The High-Power Phase Cold Start (HPPCS) of the WBT indicated that when Abura charcoal was used as fuel, the average emission factors of CO_2, CO, and $PM_{2.5}$ were computed for the Wonder stove as: $2.58g/kg$, $0.12g/kg$, $307.47\mu g/kg$ and for the metal stove as, $3.64g/kg$, $0.19g/kg$, $446.56\ \mu g/kg$. Furthermore, the emission above factors were computed with assorted charcoal for the wonder stove as $4.59g/kg$, $0.119g/kg$, $411.17\mu g/kg$ and for the metal stove as $5.07g/kg$, $0.15g/kg$, $503.28\mu g/kg$. The emission factors were also computed throughout the simmer phases of the WBT for both Wonder and Metal stoves. The research provides guidelines for the next environmental assessments and intervention initiatives in Sub-Saharan Africa.*

Keywords - *Carbon atom concentration, Charcoal, Emissions, Emission factors, Emission metrics*.

1. Introduction

According to recent projections, by 2030, only 77% of the world's population will have access to environmentally friendly cooking energy and technologies, and 1.9 billion people will continue to use outdated, inefficient stoves to cook with solid fuels like wood, charcoal, coal, agricultural wastes and kerosene [1]. By extending the projection over 2030 and taking into consideration a surge in population within the developing countries, the current pattern under the status quo predicts that by 2050, 2.3 billion people in 91 low- and middle-income countries-45 of the 47 Sub-Saharan African countries are included-will still lack access to clean cooking energy. Statistics have shown that if the present conditions keep going, in 2030, Sub-Saharan Africa will be home to almost 60% of the people who lack access to clean cooking energy, with very little change anticipated by 2050. As a result, household duties, including craft activities, will be performed using subpar technologies and inefficient fuels. However, the use of ineffective, harmful fuels and technologies poses a health risk. It is a significant cause of illnesses and fatalities, especially for women and children in low- and middle-income countries [2]. This makes using polluting fuels for cooking one of the main factors in the environment that causes disease [3]. In 2020, air pollution from homes was thought to be the cause of 3.2 million annual deaths, including approximately 7.41% of deaths among children below the age of five [1]. In Sub-Saharan Africa and some parts of Asia, most individuals suffer from exposure to household air pollution. This is because the majority of people who are dependent on solid fuels for cooking live in Africa and Asia [4]. Meanwhile, the increase in energy prices on the global market in recent years has caused middle-class earners in sub-Saharan African countries to be unable to afford to purchase sustainable, clean cooking energy [5]. Consequently, over the past two years, the use of improved biomass cookstoves with solid fuels has gradually and progressively increased throughout the sub-Saharan African countries. This directly affects both the environment and the health of its

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users, making it necessary for every country to reexamine the emissions produced by the use of improved biomass cookstoves.

Improvements to biomass cookstoves have received much more attention and effort over the past two decades, especially in developing countries. These advancements are crucial because 3 billion people still use open fires or improved biomass cookstoves, which burn wood, charcoal, and other solid fuels, to prepare their meals [1]. This has also spurred a great deal of research towards improved biomass cookstove designs and fabrication, as well as environmental emission levels. Although biomass cookstoves can emit a wide range of emissions when they burn wood, charcoal, or other solid fuels, it has been reported that the amount of emissions is highly influenced by the amount of Carbon and moisture in the wood used to produce charcoal [6]. Assessing the most harmful substances, such as carbon dioxide (CO_2), which has contributed to an increase in respiratory illnesses in households and the national depletion of the ozone layer, is crucial. Therefore, it is intrinsically important to concentrate on the primary emissions, which include Carbon dioxide (CO_2), Carbon monoxide (CO), and fine particulate matter whose diameter is less than or equal to 2.5 micrometres [$PM_{2.5}$ ($PM \leq 2.5\mu m$)].

The investigation to determine the CO_2, CO and $PM_{2.5}$ emissions produced by improved biomass cookstoves at various country levels are inherently paramount and for a variety of vital reasons. Furthermore, significant amounts of indoor air pollution, frequently brought on by inefficient improved biomass cookstoves, may trigger respiratory conditions and other health issues, particularly in women and children who spend much time in kitchens and close to either open fires or the improved biomass cookstoves [7]. In addition, a study carried out by Yun et al., 2020 [8] discovered that emissions from cooking have greatly contributed to both air pollution and the release of greenhouse gases. Meanwhile, several countries have ratified international pacts meant to cut greenhouse gas emissions and enhance air quality. This means that quantifying improved biomass cookstove emissions CO_2 CO $PM_{2.5}$ helps a country report on how well it is doing in fulfilling its obligations under these international agreements. Subsequently, this will also help to ensure that the advantages of improved biomass stoves are divided fairly across various populations, especially vulnerable groups like women and marginalised neighbourhoods or communities. It is crucial to comprehend and account for the emissions from improved biomass cookstoves at country levels.

2. Energy Situation in Sierra Leone

Sierra Leone's energy sector faces considerable hurdles. The country is struggling and has almost failed to adequately supply its population's energy demands, leading to restricted access to dependable and inexpensive energy for many inhabitants [9]. Sierra Leone is a country that mainly relies on hydroelectric power, with small significant dams (installed capacity ≈56MW) producing electricity [10]. On the other hand, frequent power outages and an unstable power supply have been caused by poor maintenance and ageing infrastructure. Furthermore, due to the country's substantial reliance on hydropower, it is susceptible to changes in rainfall patterns, which affects the supply of electricity during droughts. It is estimated that just 15% of Sierra Leone's population, including 2.5% of those living in rural areas, have access to the country's electricity supply [11]. The lack of access to the national electricity grid, especially in rural regions, forces residents to use costly and ineffective alternatives like diesel generators. The Sierra Leonean government is aware of how critical it is to improve the nation's energy infrastructure. Private investment has been sought, and alternative energy sources, including solar and wind power, are being promoted [12]. Diversifying the energy mix and reducing reliance on hydroelectricity are the goals. However, due to capacity and financial constraints and limitations, development in these areas has been gradual. The reasonable cost of energy presents problems for Sierra Leone as well. Since energy is somewhat expensive, many homes and businesses find it challenging to afford dependable power. This impedes economic growth and reduces prospects for power productivity and growth. For many households in Sierra Leone, finding clean cooking options continues to be a major difficulty. The lack of a clean, sufficient, affordable, and sustainable electric energy supply is a problem that is affecting the entire country [13]. Wood and charcoal dominate electricity usage in Sierra Leone, accounting for more than 80% of it [12].

In Sierra Leone, wood fuel is the main source of biomass energy, followed by charcoal [14], and more than 80% of people use basic improved biomass cookstoves at home, commonly known as Wonder Stove (WS) and Metal Stove (MS). As a result, it is imperative to determine how much CO_2 CO, $PM_{2.5}$ is released into the air as a result of those improved biomass cookstove usages (WS and MS). In conclusion, quantifying the emissions from those aforementioned improved biomass cookstoves at a national scale is crucial for determining how they will affect our society, the environment, and public health. Furthermore, knowing the quantities of CO_2 CO and $PM_{2.5}$ would aid in forming policy choices, encourage sustainability, and aid in the fight against air pollution and climate change on a worldwide scale.

3. Materials and Methods

3.1. Description of Wonder Stove (WS) and Metal Stove (MS)

Figure 1 depicts a typical Wonder Stove (WS) from the upper and end views. This improved biomass cookstove is common and mostly used in Sierra Leone. More than 80% of different residences in urban and peri-urban areas normally use these stoves with charcoal. It has a ceramic combustion chamber lined with around 25 unevenly spaced holes that are 10 mm in diameter and can be used to let incombustible fall below the combustion chamber.

Figure 2 shows the end and upper views of the Metal Stove (MS), an improved biomass cookstove used in Sierra Leone. It is constructed from steel plates that are 1.5 mm thick. There are thirteen unsymmetrical holes in the combustion chamber, each around 12 mm to 15mm in diameter. Six additional unsymmetrical holes, each with a diameter of 15 mm, are located near one another on the wall of the combustion chamber and are made of steel plates of the same thickness as the combustion chamber. These six holes, which are on opposite sides above the combustion chamber and are about 70mm to 80 mm above it, are used to put three horizontal steel rods, primarily 10 mm in diameter, that are used for cooking vessel stands.

(a) (b)

Fig. 1 Wonder Stove (WS) (a) Upper view, and (b) End view.

(a) (b)

Fig. 2 Metal Stove (a) End view, and (b) Upper view.

3.2. Fuel Selection Criteria

Throughout the experiment, only charcoal was used as fuel to prevent significant variations in energy and carbon contents. The first quantity of charcoal was produced from a particular species of tree (abura tree, mitragyna stipulosa). The other set of charcoal came from two different species of trees, including the Mango (Mangifera indica) and the Matchstick (Aechmea gamosepala). The same species of trees that were used to make charcoal were also used to make tinder. These trees are the most popular and widely used trees by Sierra Leone's charcoal producers.

3.3. Measurement of Emissions Levels

The methods applied here were based on the methods of Omar et al. (2007) [15] and Chowdhury et al. (2007) [16]; they recommended that emissions measurements be made at one-minute intervals, with the caveat that improved charcoal cookstove heights be kept at 0.5m from the hood, with the exception that a CO_2 digital combustion analyser (Testo 310 Residential combustion analyser) was used to carry out analyses on emissions including CO, CO_2 and $PM_{2.5}$. Furthermore, OriginPro software was used to carry out the statistical analyses on all emission metrics determined. In addition, variations in particle size distribution with rising humidity may cause the concentration of $PM_{2.5}$ to be overestimated. As opposed to the correction factor formula utilized in the research done by [17], the Testo 310 instrument, as shown in Figure 1, is employed to correct the effects of the relative humidity.

Fig. 3 Testo 310 Instrument for CO_2, CO, and $PM_{2.5}$ monitoring

3.4. Carbon Atom Concentration

Carbon atom concentration in the experiment is the average carbon atom concentration in the dilution tunnel, which accounts for the carbon atoms present in CO_2, CO, and $PM_{2.5}$. Hence, they are related by the following:

$$CC_c = CO_{2_{carbon,c}} + CO_{carbon,c} + PM_{carbon,c} \tag{1}$$

Where,

CC_c is the total carbon atom concentration (ppm),

$CO_{2_{carbon,c}}$, $CO_{carbon,c}$, and $PM_{carbon,c}$ are respectively the various carbon concentrations of CO_2, CO, and PM.

3.5. Carbon Dioxide Concentration

Because CO_2 it can be found in both outdoor and indoor air, it is crucial to evaluate the air quality before starting the test and to take and record frequent measurements. Hence, the CO_2 measurement is the average ambient CO_2 concentration that has been taken and deducted from the average value observed during the test. The following formula was used to calculate the amount of CO_2 in the experiment, and it is as follows:

$$Q_{CO2_a} = Q_{CO2_f} - Q_{CO2_i} \quad (2)$$

Where,

Q_{CO2_a} is the CO_2 concentration measured (ppm), Q_{CO2_i} and Q_{CO2_f} are the initial and final readings of CO_2 (ppm) concentrations.

3.6. Total Mass of Concentration of Carbon

This is the real carbon mass concentration captured in the dilution tunnel, and it is determined using the formula below:

$$T_{C_c} = \frac{CC_c \times 12 \times P_{atm} \times 10^{-6}}{R \times (\Delta T + 273.15)} \quad (3)$$

Where,

T_{C_c}, is the total mass concentration of Carbon (g),

ΔT, is the temperature difference (℃),

CC_c, has its usual meaning from equation (1)

R, is the universal gas constant, equals $0.008314 kPam^3/molK$ and P_{atm} is the atmospheric pressure (kPa).

3.7. Carbon Monoxide Concentration

This is the mean ambient CO concentration, which has been deducted from the average value observed during the test. Hence, it is related by the equation:

$$Q_{CO_a} = Q_{CO_f} - Q_{CO_i} \quad (4)$$

Where,

Q_{CO_a}, is the actual amount of CO (ppm) concentration measured,

Q_{CO_f} and Q_{CO_i} are the final and initial readings of CO (ppm) concentrations.

3.8. Estimation of $PM_{2.5}$

This is the average ambient $PM_{2.5}$concentration, which has been deducted from the average density $PM_{2.5}$ obtained during the test, and they are related by:

$$Q_{PM_{2.5}{}_a} = Q_{PM_{2.5}{}_f} - Q_{PM_{2.5}{}_i} \quad (5)$$

Where,

$Q_{PM_{2.5}{}_a}$, is the reading concentration of $PM_{2.5}$ accounted for and $Q_{PM_{2.5}{}_f}$, and $Q_{PM_{2.5}{}_i}$ are respectively the final and ambient readings of $PM_{2.5}$ concentrations.

Since $Q_{PM_{2.5}{}_a}$ it is measured in $\mu g/m^3$, it must be converted to ppm before substituting into equation (5). Hence $Q_{PM_{2.5}{}_a}$ can now be obtained from the equation

$$Q_{PM_{2.5}{}_{a,ppm}} = \left(\frac{Q_{PM_{2.5}{}_a} \times R \times (\Delta T + 273.15)}{15 \times P_{atm}}\right) \quad (6)$$

Where, $Q_{PM_{2.5}{}_{a,ppm}}$ is the actual value of $PM_{2.5}$ now measured (ppm), R, P_{atm} and ΔT has its usual meanings from equation (3). Furthermore, equation (1) will now become:

$$CC_c = Q_{CO2_a} + Q_{CO_a} + Q_{PM_{2.5}{}_{a,ppm}} \quad (7)$$

Where the symbols have their usual meanings from Equations (1),(2),(4), and (5), respectively.

3.9. Hood Flowrate Measurement

The airflow rate of a kitchen stove hood is the volume of air drawn through it in a given amount of time. The usual unit of measurement for this airflow rate is a cubic meter per minute (m^3/min). The more air the stove hood can flow and the higher its airflow rate rating, the better it is at extracting smoke, steam, and other cooking wastes from the kitchen. The flow rate of a stove hood is an important consideration when selecting a hood for kitchen activities, as it directly affects the hood's ability to remove contaminants from the air. A higher flow rate is generally better for larger kitchens or for kitchens that produce a lot of smoke or steam, while a lower flow rate may be sufficient for smaller kitchens or for kitchens where cooking is less frequent or intense. It is important to note that the flow rate of a stove hood can also be affected by the length and configuration of the ductwork that connects the hood to the outside of the home. A longer or more convoluted ductwork can increase resistance to airflow, reducing the effective flow rate of the hood. The amount of charcoal-burnt gases that a mechanical device captures each minute is determined by the following relationship:

$$Q_h = 2cv_a y^2 \quad (8)$$

Where,

Q_h, is the hood flowrate (m^3/min),

c, is the circumference of the hood (m),

v_a, is the average capturing velocity (m/min) of the burnt gases, and y (m) is the distance between the table and the exhaust hood $(y \leq 1.2)$.

3.10. Total Exhaust Flow

This is the volume of flow of burnt gases exiting the exhaust hood.

$$V_c = Q_h \times \frac{\Delta t_c}{60} \quad (9)$$

Where,

V_e, is the total amount of volume (m^3) of gases exiting the hood,

Δt_c, is the time (min) required to complete one test, and

Q_h, has its usual meaning from equation (8).

3.11. Estimated Mass of Charcoal Burnt from Emissions

This is the approximation of charcoal burnt based on overall carbon mass gathered in the emission hood, and it is related by:

$$m_e = T_{C_c} \times \frac{V_c}{CharcoalfracC} \quad (10)$$

Where
m_e (g_{chal}) is the estimated mass of charcoal burnt from emission and
V_c has its usual meaning from equation (9).

3.12. Carbon Dioxide Emission Factor

This is the amount of CO_2 emissions per kilogram of charcoal burned on average. The proportion of Concentration of CO_2 carbon content is used to compute it, and the equation relates it:

$$EF_{CO2,c} = \frac{Q_{CO2_a}}{CC_c} \times \frac{44}{12} \times fuelFracC \times 1000 \quad (11)$$

Where,
$EF_{CO2,c}$ is the emission factor of CO_2 $(g/kgCharcoal)$,
$CC_c$and Q_{CO2_a} have their usual meanings from equation (7) and equation (2), respectively.

3.13. Carbon Monoxide Emission Factor

The CO emission factor is the average amount of CO released per kilogram of charcoal burned. It was calculated in the same way as $EF_{CO2,c}$ and only it uses CO's molecular weight instead, as related below:

$$EF_{CO,c} = \frac{Q_{CO_a}}{CC_c} \times \frac{28}{12} \times fuelFracC \times 1000 \quad (12)$$

Where,
$EF_{CO,c}$ is the emission factor of CO $(g/kgCharcoal)$,
CC_c and Q_{CO_a} have their usual meanings from equation (7) and equation (4)

3.14. Particulate Matter Emission Factor

This is the $PM_{2.5}$ emissions per kilogram of charcoal used on average, and it is calculated by using the formula:

$$EF_{PM_{2.5},c} = \frac{Q_{PM_{2.5}a} \times charcoal\ fracC \times 1000}{T_{C_c} \times 1000000} \quad (13)$$

Where:
$EF_{PM_{2.5},c}$ is the emission factor of $PM_{2.5}$ $(g/kgCharcoal)$,
$Q_{PM_{2.5}a}$ and T_{C_c} have their usual meanings from equation (5) and equation (3).

3.15. Mass of Carbon Dioxide Produced

This is the total sum of Carbon dioxide released during the experiment. It is calculated using the formula.

$$m_{CO_2} = EF_{CO2,c} \times m_e \times \frac{1}{1000} \quad (14)$$

Where:
m_{CO_2} is the mass of CO_2 (g) produced,
m_e (g_{chal}) is the estimated mass of charcoal burnt from emission, and $EF_{CO2,c}$ is the emission factor of CO_2 $(g/kgCharcoal)$.

3.16. Mass of Carbon Monoxide Produced

It is the total amount CO released during the test, and it is related to the equation:

$$m_{CO} = EF_{CO,c} \times m_e \times \frac{1}{1000} \quad (15)$$

Where:
m_{CO} is the mass of CO released (g),
m_e, and $EF_{CO,c}$ have their usual meanings from equation (12).

3.17. Mass of $PM_{2.5}$ Produced

This is the total amount $PM_{2.5}$ produced during the testing period and is determined by:

$$m_{PM_{2.5}} = EF_{PM_{2.5},c} \times m_e \times \frac{1}{1000} \quad (16)$$

Where:
$m_{PM_{2.5}}$ is the mass produced (g),
m_e and $EF_{PM_{2.5},c}$ have their usual meanings from Equations (10) and (13), respectively.

4. Results and Discussions

4.1. Wonder Stove Emissions Metrics

More efficient cookstoves are designed to produce fewer emissions when cooking than traditional stoves. The amount of emissions from improved cookstoves varies depending on the type of stove and fuel utilised. Improved cookstoves produce fewer harmful pollutants, such as carbon monoxide and particulate matter, than conventional stoves do. If they utilise cleaner-burning fuels, they might also emit less carbon dioxide and other greenhouse pollutants. Improved cookstoves, however, still have the potential to emit some emissions, especially if they are not used correctly or if the fuel is of low quality. Although they are often lower than those from conventional stoves, emissions from improved cookstoves can still have a substantial impact on health and contribute to both interior and outdoor air pollution.

Figure 4, depicts the experiment's HPPCS's average carbon atom concentration. Even though the same improved cookstove was used to experiment, the findings indicate that, at this point in the experiment, there has been a substantial change in the concentration of carbon atoms, with a difference of about 39.78%. Around 192.75 ppm of Carbon present when abura charcoal was used, and 269.44 ppm were present when mixed charcoal was utilised. As a result, Abura Charcoal (AC) is much more advantageous since its carbon atom concentration is substantially lower than that of other mixed types of charcoal.

The typical amount of pollutants flown from the Wonder Stove (WS) to the hood is shown in Figure 5 for the HPPCS. However, when both types of charcoal are used, the volume of emissions flown is not noticeably different. In the hood, assorted or mixed charcoal emits 19.46% more volume than the AC.

Figure 6 shows the mass of charcoal burned, as calculated from the concentration of carbon atoms. Abura Charcoal (AC) utilised at a high-power phase cold start generates $0.9g$ real charcoal mass from a total average carbon atom concentration of, $192.75\,ppm$, while mixed charcoal used at an HPPCS yields $1.57g$ a total average carbon atom concentration of $269.44\,ppm$. Once more, these findings show that WS outperformed mixed charcoal while using AC.

Improved cookstoves like WS take less fuel to carry out water boiling tests, which lowers the amount of CO_2 emissions that are generated. Several factors, such as the type of stove, the type of charcoal used, the cooking duration, and the cooking temperature, affect how much CO_2 is produced when using a WS. However, compared to conventional stoves, using improved cookstoves can generally reduce CO_2 emissions by up to 50% [18]. It is crucial to keep in mind that this is only an estimate and that the exact quantity CO_2 produced can change depending on several variables. A crucial defence in the fight against climate change, the WS may considerably cut carbon emissions and enhance indoor air quality. Hence, the mass CO_2 was calculated using the typical carbon atom concentration.

Figure 7 displays the various CO_2 masses in relation to the various assorted charcoal used during the HPPCS $2.58g$ of CO_2 was generated using Abura charcoal when the average carbon atom level was $192.75\,ppm$, and $4.59g$ of CO_2 was produced similarly when the average carbon atom content was $269.44\,ppm$. The researchers Martin and Thomas, 2011 [19] found that different types of trees had varying carbon levels, which may account for the difference in CO_2 in these results. Abura charcoal (AC) consequently provided the WS with a benefit over assorted or mixed charcoal.

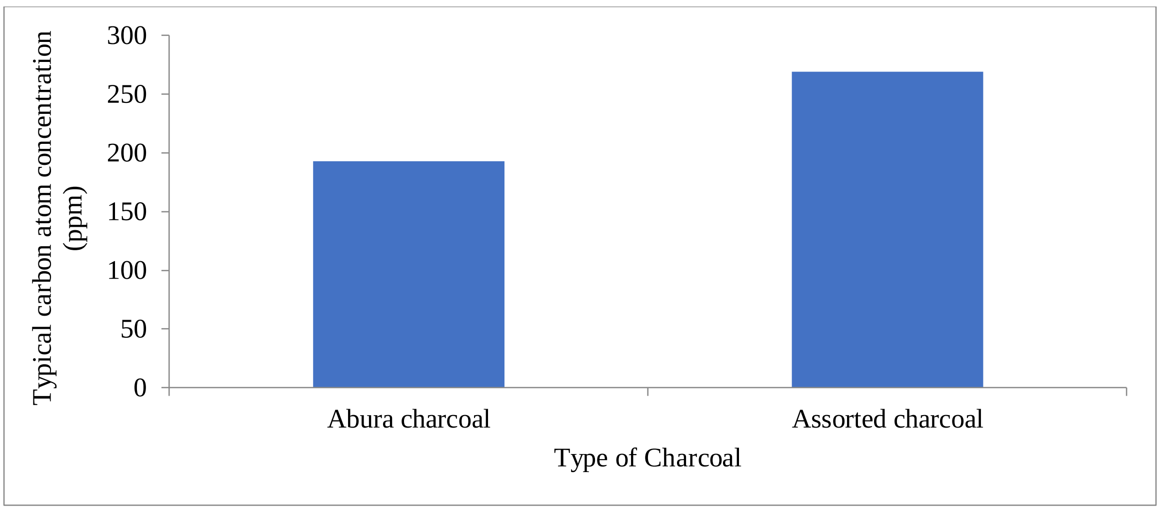

Fig. 4 Carbon atom concentration during HPPCS of the WBT when WS is used

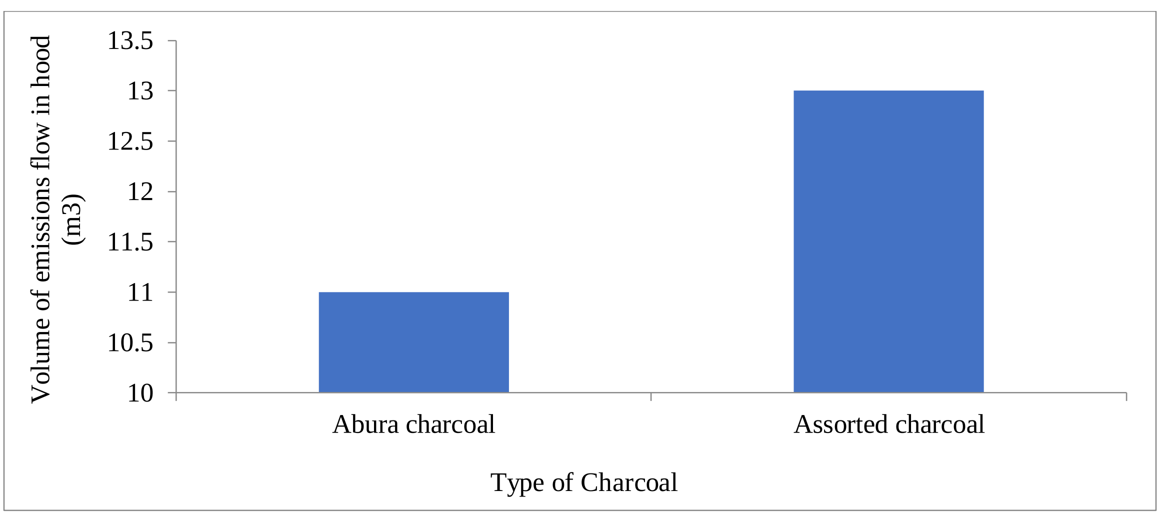

Fig. 5 Average amount of emissions when WS is used during the WBT's HPPCS

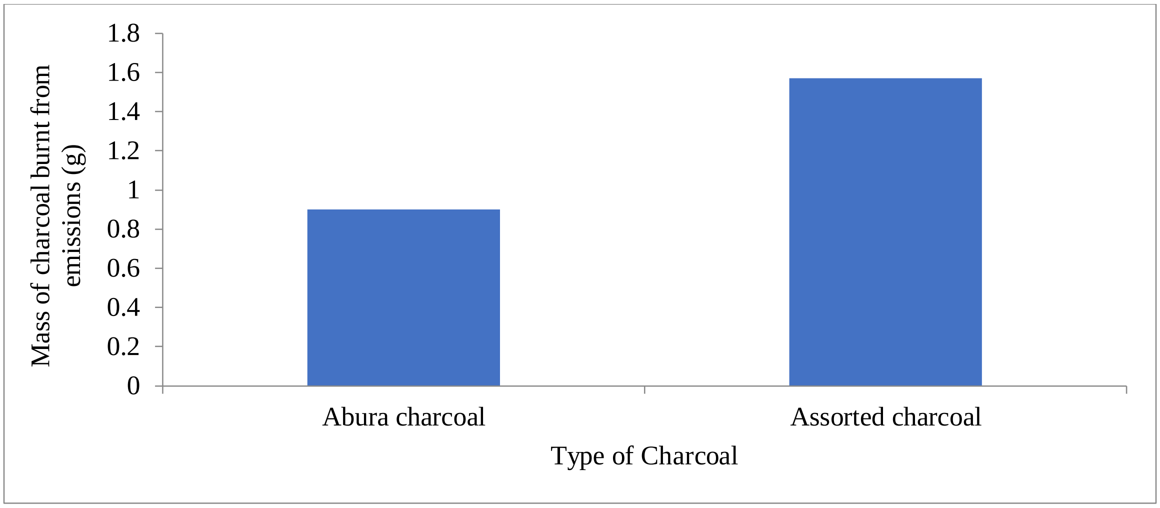

Fig. 6 Mass of charcoal burnt from emissions in WS at HPPCS of the WBT

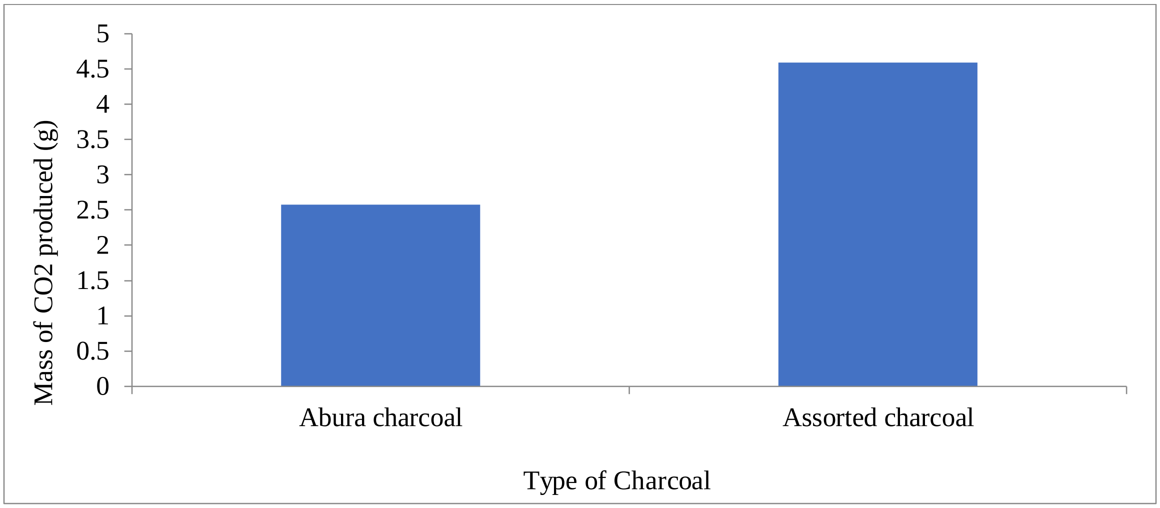

Fig. 7 Mass of CO_2 in wonder stove at cold start high power phase of WBT

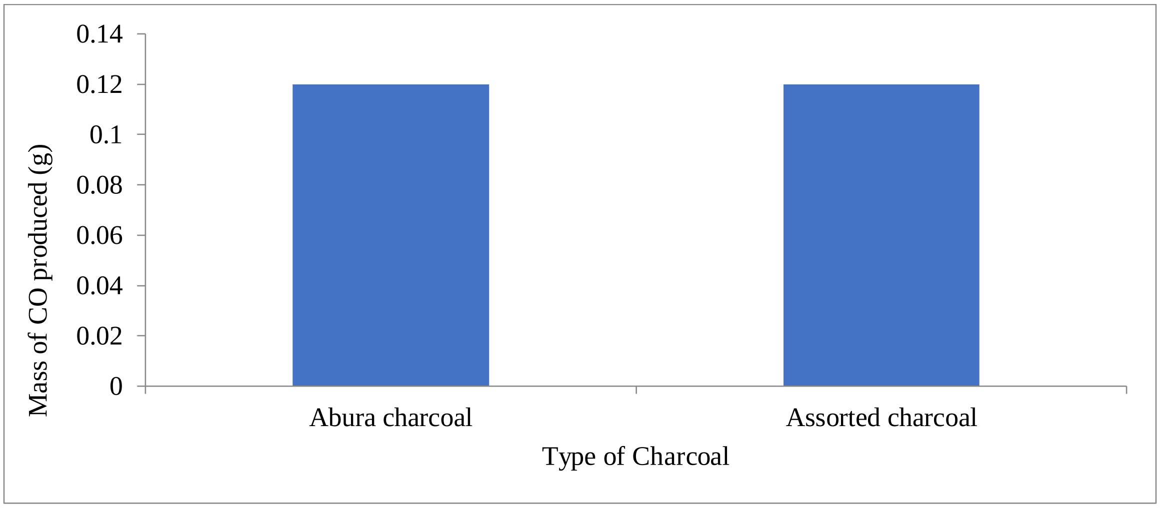

Fig. 8 Average mass of CO in Wonder Stove at cold start high-power phase of the WBT

Several variables, including the type of stove, the fuel being burnt, the amount of water being tested, and the laboratory's ventilation, can affect how much CO is generated when a Wonder Stove is utilised. Compared to conventional three-fired-stone stoves, WS is made to burn fuel more effectively and cleanly, which can lower the emissions of CO other pollutants. The World Health Organization (WHO) claims that modern cookstoves can cut carbon monoxide emissions from conventional stoves by up to 50% [20].

However, it is challenging to estimate the precise quantity CO that an improved cookstove will emit without knowing specifics about the stove and the circumstances in which it will be utilised. A Wonder Stove (WS) should typically emit much less CO when used properly than a conventional stove, which can assist in improving indoor air quality and lower the health concerns related to carbon monoxide exposure. The amount of CO emitted in the WS when using both abura and assorted or mixed charcoals was found to be $0.12g$ and $0.119g$, respectively.

When abura charcoal and assorted or mixed types of charcoal are used to heat 2.5 litres of water to boiling, the progression of the CO_2 CO ratio is shown in Figure 8.

According to the findings, the CO_2 CO ratios for abura charcoal and other assorted or mixed charcoals are 21 and 38.6, respectively. This shows that CO_2 and CO levels can change depending on the fuel utilised and not only the type of improved cookstove used.

In Figure 10, the mass of $PM_{2.5}$ the WS and assorted or mixed charcoal was calculated and estimated to be $307.49\mu g$ and $411.17\mu g$, respectively. However, the assorted or mixed charcoal emits. $103.68\mu g$ There is more $PM_{2.5}$ than AC, and it is a statistically significant difference.

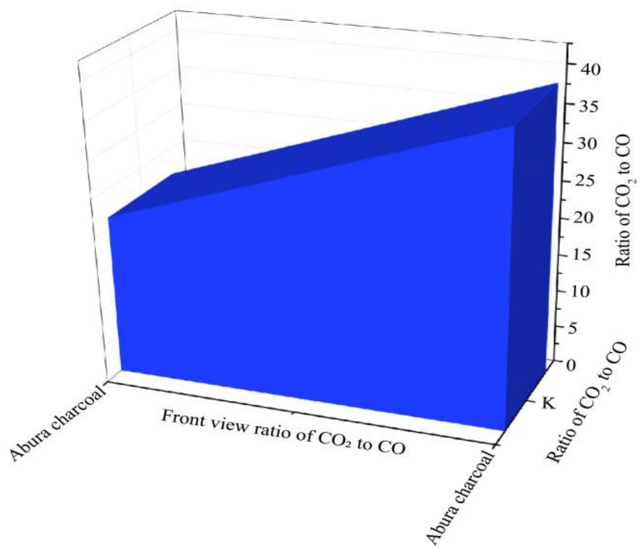

Fig. 9 Mass ratio of CO_2 to CO at the WS's HPPCS of the WBT

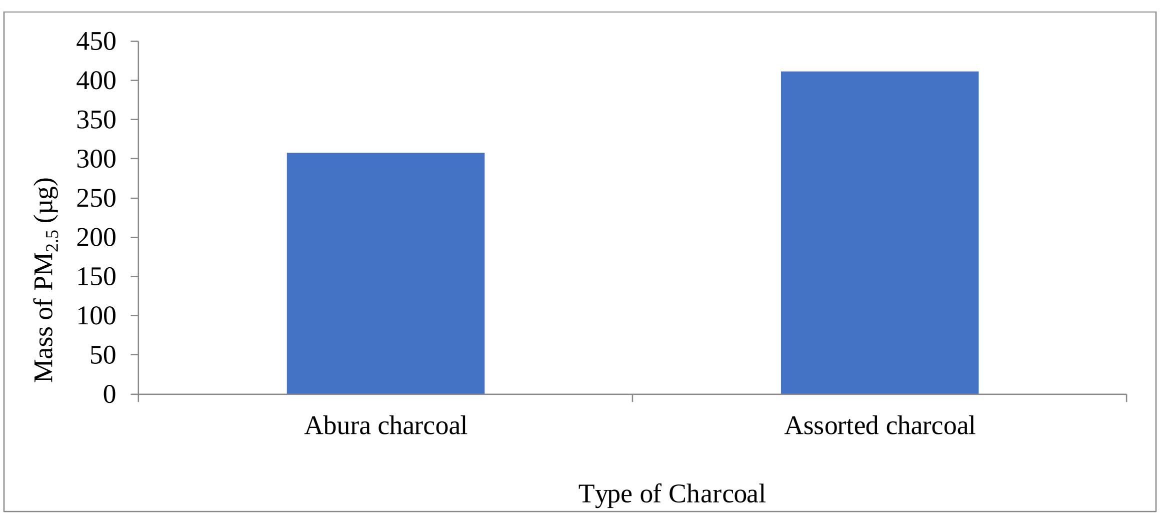

Fig. 10 Mass of $PM_{2.5}$ in WS at HPPCS of the WBT

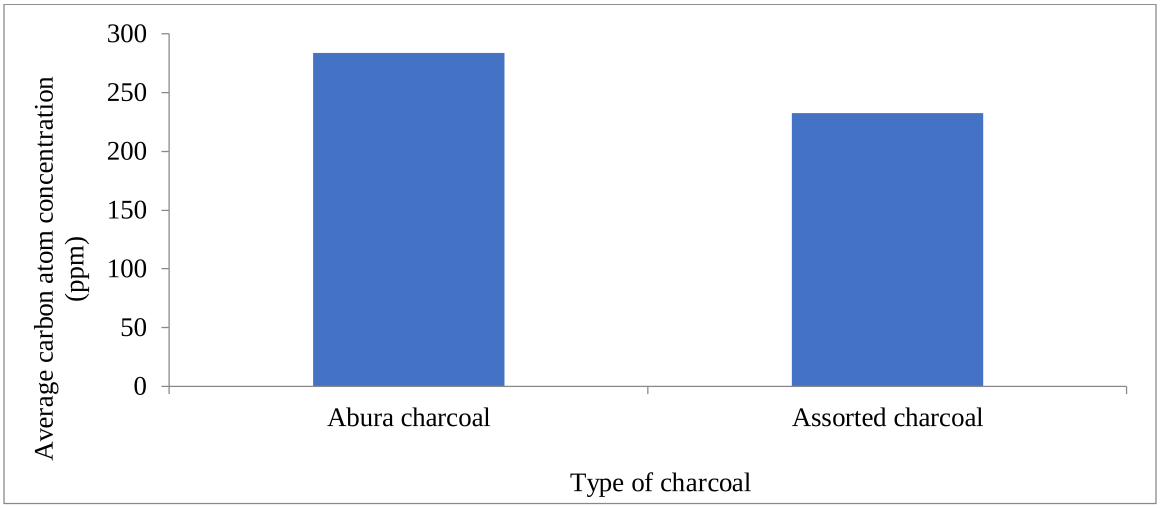

Fig. 11 Typical carbon atom concentration at simmer of the WBT when WS is used

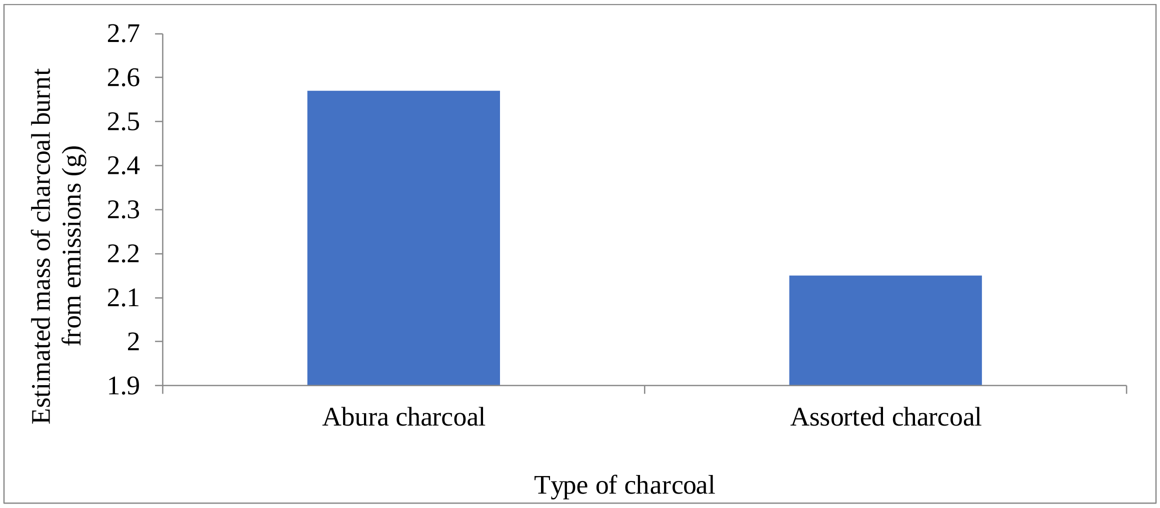

Fig. 12 Average mass of charcoal burnt from emissions at a simmer in the WS of the WBT

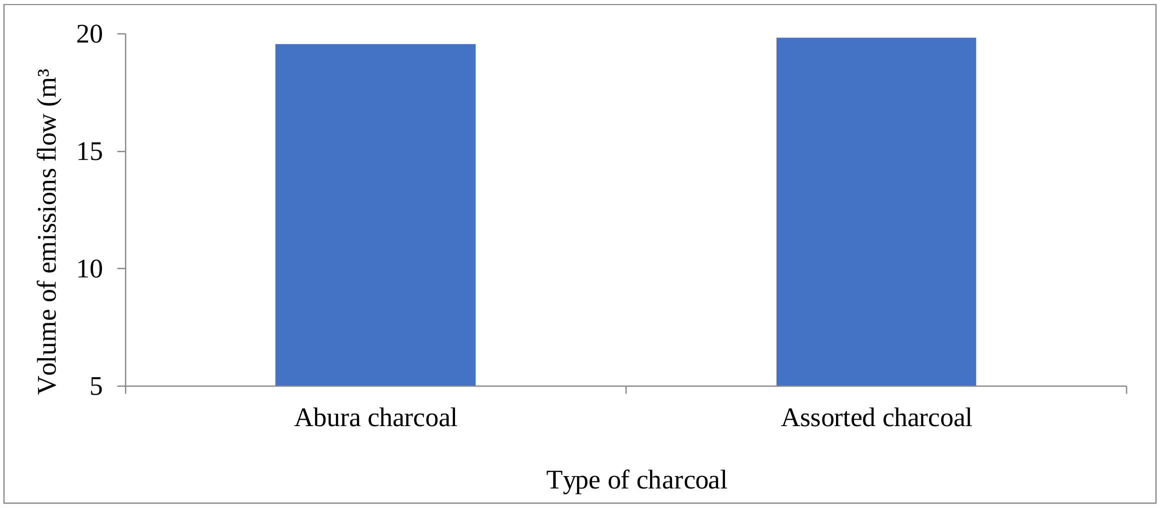

Fig. 13 Average volume of emissions produced by a WS at a simmering phase

Compared to conventional stoves, improved cookstoves are made to burn wood, charcoal, or other solid fuels more effectively. As a result, fewer emissions of particulate matter, black Carbon, and other contaminants that may be detrimental to the environment and human health are produced. All fuels, including wood and charcoal, contain carbon atoms, which when burned, release CO_2. By burning fuel more effectively and reducing the amount of CO_2 released per unit of fuel used, improved cookstoves like Wonder Stove can contribute to lowering the concentration of carbon atoms in the atmosphere. Wonder Stove cannot always completely remove carbon emissions; it is crucial to remember this. Despite having a lower atmospheric carbon dioxide concentration than conventional stoves, they nonetheless contribute to carbon emissions and climate change.

Figure 11 shows the carbon atom concentration at simmer, and it shows that the Wonder stove's carbon atom concentration is 283.56ppm for Abura charcoal and 232.52ppm assorted charcoal, respectively. Using these findings, it can be seen that Abura charcoal produces 51.04ppm more carbon atoms than the other types of charcoal.

The quantity of charcoal burned from emissions in a Wonder Stove (WS) depends on several variables, including the stove's quality, how often and how long it is used, and the type of fuel you use. However, improved cookstoves are made to burn fuel more effectively, which means that very little solid fuel is required compared to conventional stoves to create the same amount of heat.

Due to its effectiveness, less charcoal is burned, and fewer emissions are emitted into the atmosphere. In comparison to conventional stoves, improved cookstoves can typically cut charcoal consumption by up to 50%. This decrease in charcoal consumption results in lower emissions of hazardous pollutants including CO_2 and $PM_{2.5}$. It is vital to keep in mind that the actual amount of charcoal burned by emissions from an improved cookstove will depend on several variables and can be challenging to measure precisely without special equipment.

Nonetheless, it is well acknowledged that using improved cookstoves is an efficient strategy to decrease the usage of charcoal and alleviate the harmful effects of cooking emissions. Figure 12 displays the mass of carbon output measured in the Wonder cooker when both charcoals were used to conduct the water boiling test during the experiment's cold start high power phase. When Abura charcoal was utilised, the mass of charcoal burnt from emission was calculated at $2.57\ g$ and $2.15\ g$ when assorted or mixed charcoal was burnt.

The amount of smoke and pollutants discharged into the air during cooking is reduced with improved cookstoves. They can thereby substantially lower the amount of emissions produced by conventional stoves. Many variables, including the stove's unique design, the fuel utilised, and the user's cooking habits, might affect the precise volume of emissions flow from Wonder Cookstove (WS). However, research has shown that improved cookstoves can cut Particulate Matter (PM) and CO emissions by up to 90% when compared to conventional stoves. According to research by the Global Partnership for Clean Cookstoves, using an improved cookstove can reduce carbon dioxide emissions by an average of 1.3 tonnes annually [21].

Improved cookstoves may be able to cut global emissions of black Carbon (a particularly dangerous kind of $PM_{2,5}$) by up to 17%, according to a different WHO study [22]. In general, improved cookstoves are thought to be a major improvement over traditional or three-fired stone stoves in terms of lowering dangerous pollutants and greenhouse gas emissions, even though the precise volume of emissions flow from them can vary. Figure 13 shows the volume of emissions emitted from the WS when Abura Charcoal (AC) and assorted or mixed types of charcoal are both utilised during the HPPCS. The findings indicate that using both charcoals causes emissions from the WS to be roughly $19.58m^3$ and $19.85m^3$, respectively.

The mass CO_2 during the experiment's simmer phase is shown in Figure 14. It reveals that the CO_2 emissions from the Wonder stove when both AC and various charcoals are used exhibit substantially different during the simmer phase of the experiment, which lasts much longer than the HPPCS. When a certain quantity of water (2.5 litres) was heated to the point of boiling utilising AC, $6.67\ g$ of CO_2 were created, whereas $4.94\ g$ of CO_2 were equally created to perform the same task despite taking various amounts of time.

According to statistics, the difference-which amounts to around $1.73g$ of CO_2 or 25.84% of CO_2 produced from Abura charcoal-is less significant. These results at the simmer phase are considerably more desirable to compare than those reported by Booker et al. in 2011 [23], where EcoRecho and StoveTec were subjected to water boiling at the simmer and produced CO_2 values of $640g$ and $802g$, respectively. The variations in carbon content between the different types of trees used to make charcoal may also be the cause of these differences in results.

Figure 15 shows the various CO masses produced by the Wonder stove during the simmer phase of the WBT. Assorted or mixed charcoals, including AC, were utilised to carry out the 45-minute simmer. The findings showed that AC releases $0.25g\ CO$ on average while assorted or mixed charcoal produces $0.2g$ the same CO on average when 2.5 litres of water are heated to a boiling point. These findings demonstrate significantly lower CO values than those obtained by the researchers Booker et al., 2011 [23], who reported CO at the simmer phase of WBT for five improved cookstoves to be as follows: 98.6g for the EcoRecho stove, 59.1g for the Mirak stove, 68.7g for Prakit stove, 83.5g for StoveTec, and 71.9g Traditional three-fired stone stove, respectively. The carbon and moisture contents of the different trees from which charcoal was produced for the WBT could be the cause of these discrepancies in results.

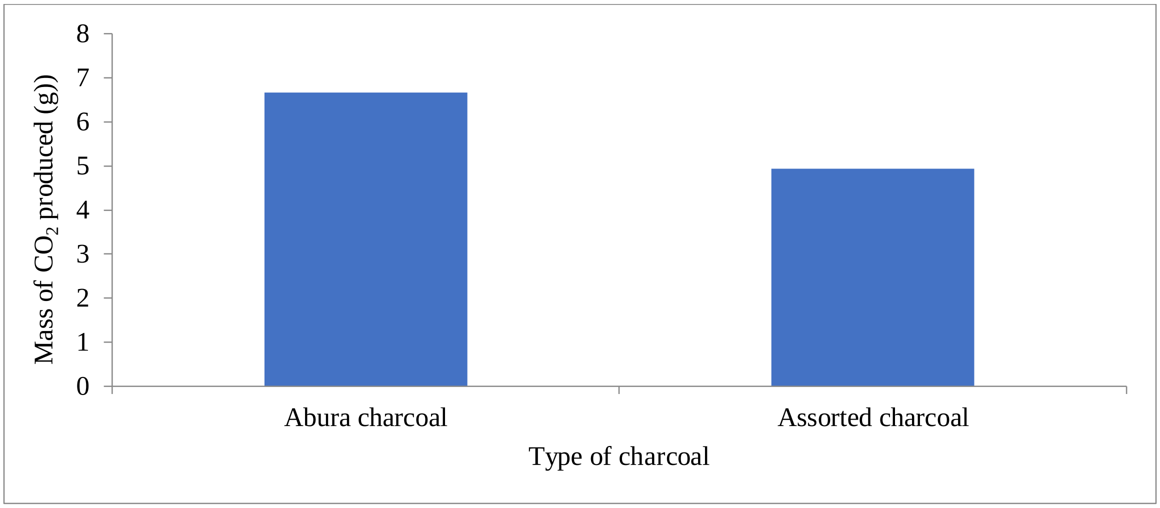

Fig. 14 Mass of CO_2 at a simmer when a WS is used

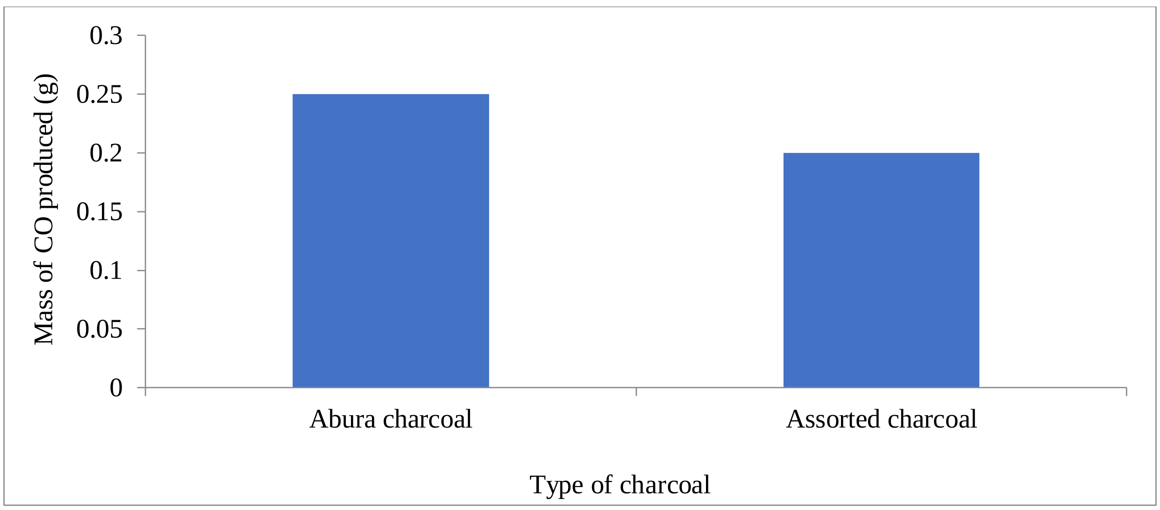

Fig. 15 Mass of CO at simmer phase of WBT of Wonder Stove (WS)

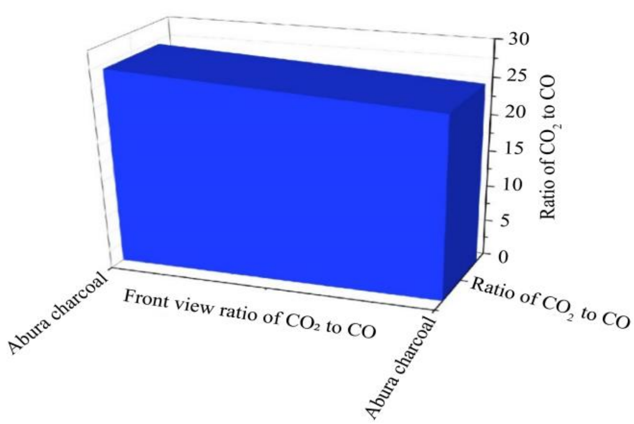

Fig. 16 Mass ratio of CO_2 to CO at simmer phase of WBT for WS

The CO_2 to CO ratio for AC and assorted or mixed types of charcoal during the simmering phase of the WBT is shown in Figure 16. According to these results, AC has a higher yield for CO_2 to CO than assorted or mixed charcoal, which has a lower yield. In other words, while the ratio for assorted charcoal is 24.94, it is 26.93 for Abura Charcoal (AC).

As CO_2 levels rise, the value CO falls; however, as CO levels rise, the ratio CO_2 CO falls, which might have a less favourable effect on health. Abura charcoal and the Wonder stove may, therefore, be advantageous for society. Figure 17 displays the mass $PM_{2.5}$ that was accounted for throughout the experiment's simmer phase for both Abura Charcoal (AC) and assorted or mixed types of charcoal. These findings show that the WS generates $1169.84\mu g$ $PM_{2.5}$ when AC is utilised and $1375.96\mu g$ $PM_{2.5}$ assorted or mixed charcoal is simmered for 45 minutes.

These findings suggest that even $PM_{2.5}$ levels vary when a single stove is used with different fuels and that $PM_{2.5}$ levels are solely determined by the type of fuel used. These findings suggest that the simmering $PM_{2.5}$ value of AC is relatively lower than that of other assorted types. Consequently, it performed better with WS than with assorted or mixed types.

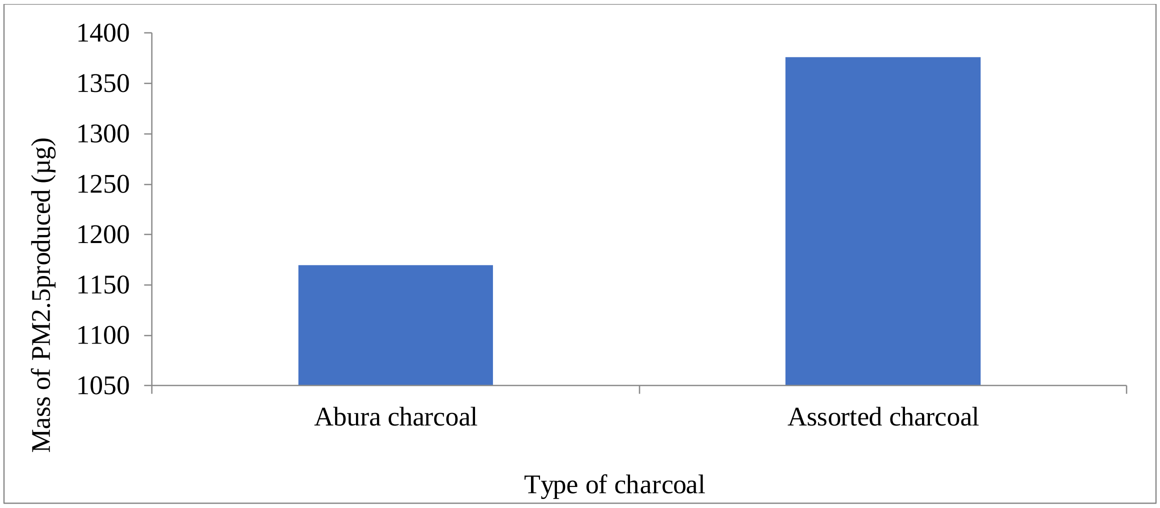

Fig. 17 Mass of $PM_{2.5}$ at simmer phase of WBT for WS

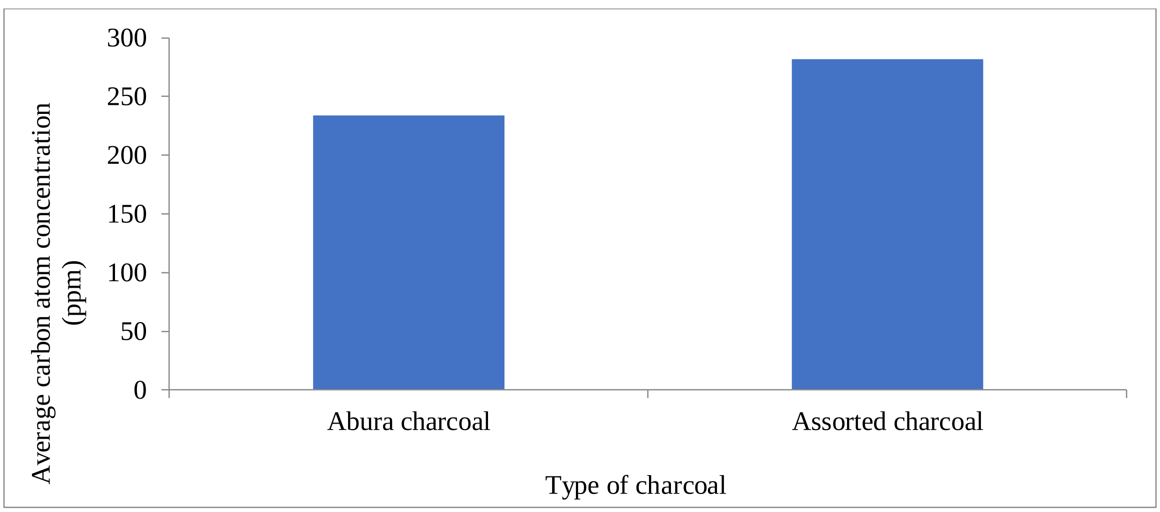

Fig. 18 Carbon atom concentration during HPPCS of the WBT when the Metal Stove (MS) is used

4.2. Metal Stove (MS) Emissions Metrics

When Abura Charcoal (AC) and assorted or mixed sets of charcoal are burned to heat 2.5 litres of water, Figure 18 shows the typical concentration of carbon atoms released from a Metal Stove (MS). However, using AC to boil the same amount of water results in a carbon concentration in the MS $234.09ppm$, whereas using assorted or mixed charcoal results in a carbon concentration $282.01ppm$ at HPPCS.

These data demonstrate a significant difference in carbon concentration $47.92\ ppm$or an 20.47% increase in value. Figure 19 depicts the average amount of charcoal burned from emissions from a Metal Stove (MS) when both AC and assorted or mixed charcoals were utilised at the experiment's HPPCS. It reveals that $1.25g$ AC was burned from emissions, and $1.76g$ assorted or mixed charcoals were burned from emissions. As a result, there is a difference of $0.51g$, or 40.80%, between the mass of AC burned from emission and the assorted or mixed ones, which is pretty substantial. AC is, therefore, more desirable because it produces less Carbon burnt from emissions than assorted or mixed ones.

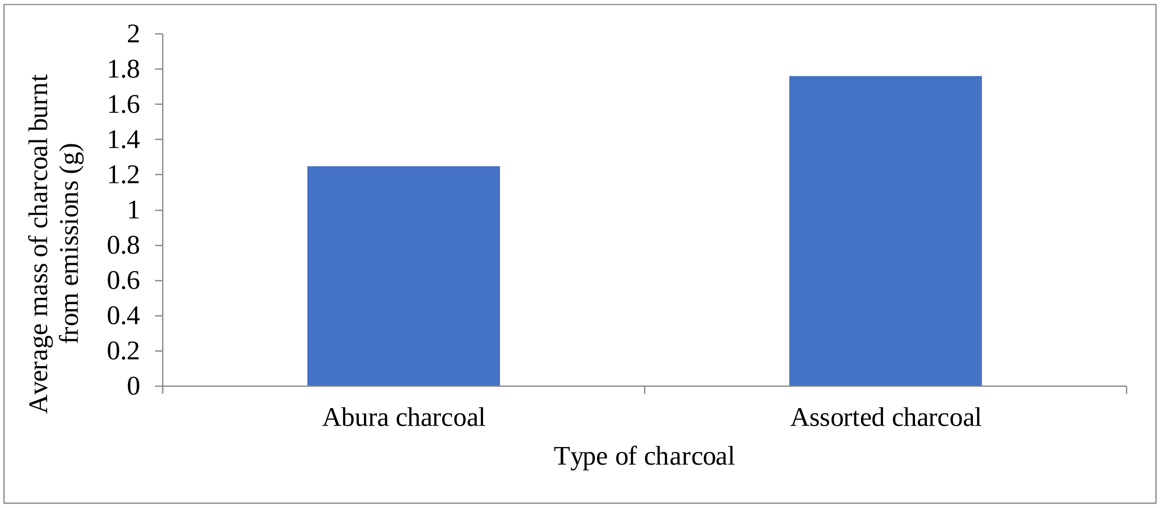

Fig. 19 Mass of charcoal burnt from emissions in MS at HPPCS of the WBT

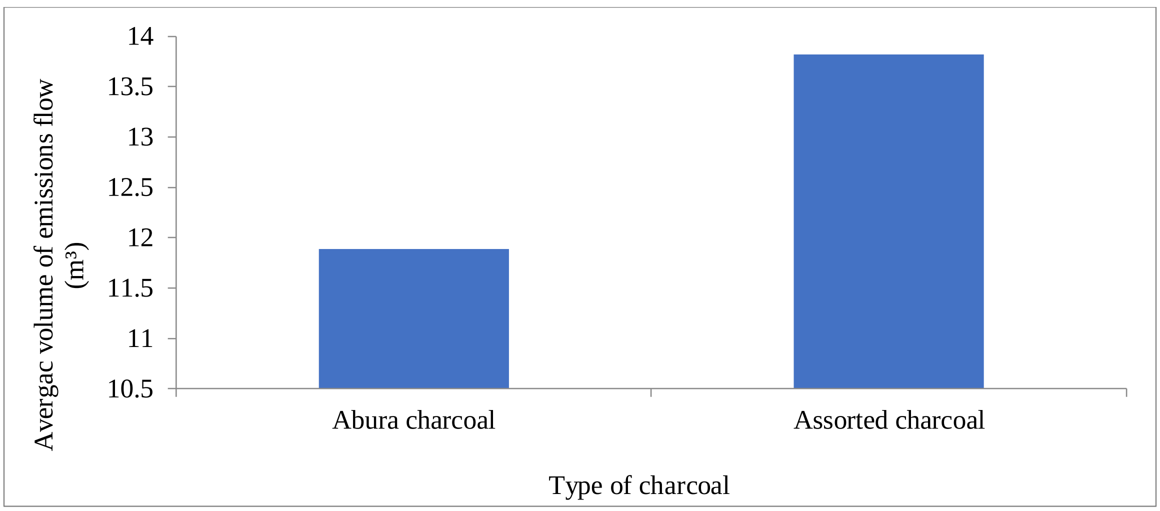

Fig. 20 Average volume of emissions produced in an MS at HPPCS of the WBT

When 2.5 litres of water are heated to a boil using AC and other sets of charcoal (assorted or mixed) at the HPPCS, the average amount of emissions flown or expelled from the metal stove is shown in Figure 20.

The graph indicates that, on average, a metal stove emits $11.89m^3$ when Abura charcoal is used and emits $13.82m^3$ when assorted or mixed charcoals are used. These findings demonstrate that using AC instead of assorted types of charcoal reduces the volume of emissions.

Figure 21 depicts the mass CO_2 produced in a metal stove when both AC and assorted or mixed charcoal are used to bring 2.5 litres of water to a boiling temperature during the WBT's HPPCS.

It has been demonstrated that when AC is used, $3.64\ g$ of CO_2 is produced compared to $5.07g$ of CO_2 produced when assorted or mixed charcoal is used, rendering AC the desirable choice.

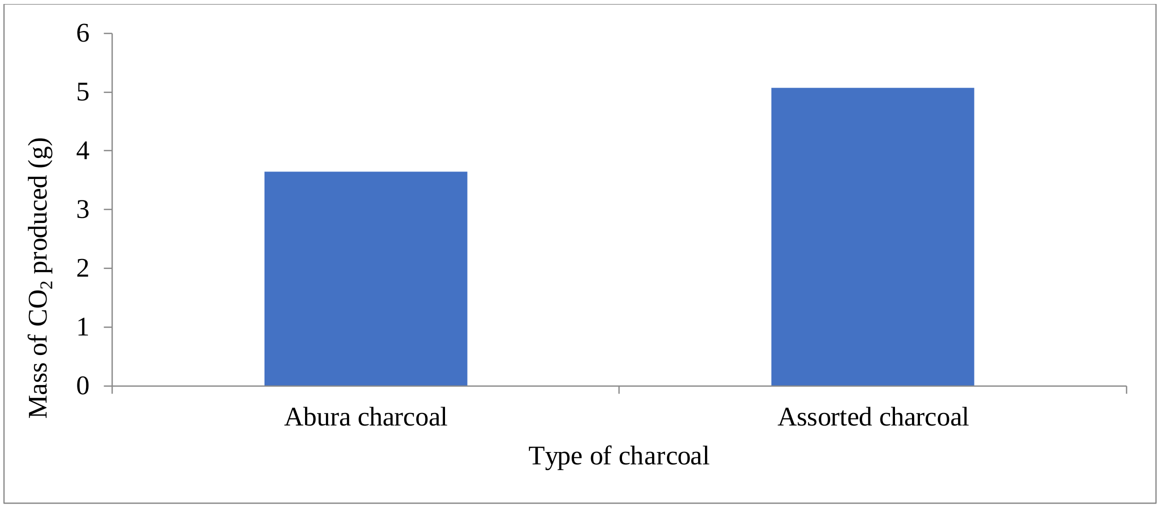

Fig. 21 Mass of CO_2 at HPPCS when a MS is used for the WBT

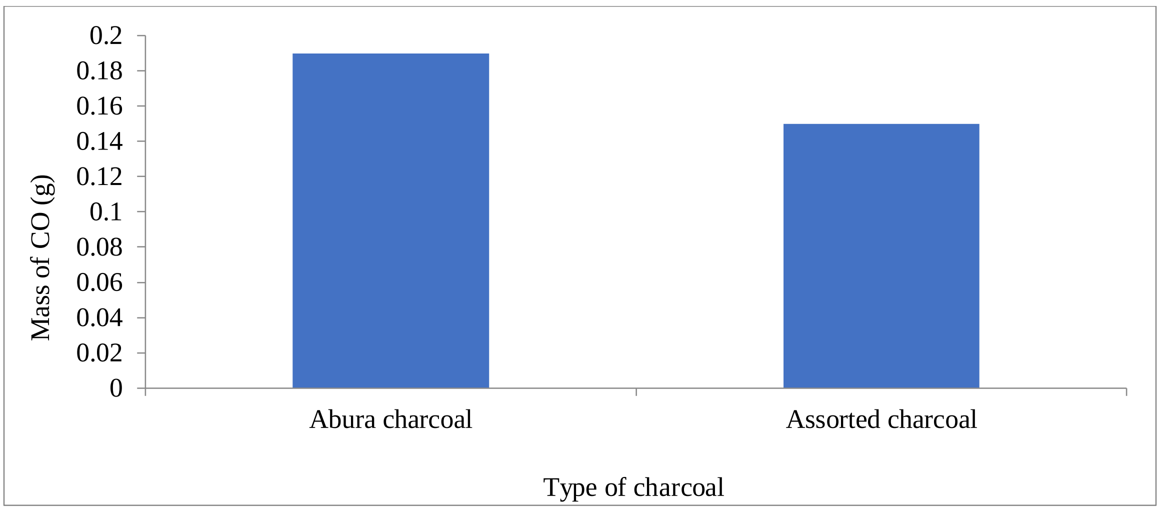

Fig. 22 Mass of CO at HPPCS for MS during the WBT

Figure 22 displays the mass of CO produced by the two sets of charcoals used in the WBT's HPPCS. The results show that when both sets of charcoals are used in MS, AC produces 21.05% more CO than the assorted or mixed charcoals, a difference of $0.04g$. The amount of CO produced by AC and assorted or mixed charcoals in this phase of the test, however, was $0.19g$ and $0.15g$, respectively. These findings are insignificant in light of what Booker et al., 2011 [23] found.

They established the CO values for StoveTec at $83.5g$ and for the Philips cooker at $6g$ (± 0.6) for WBT. Improved cookstoves are like MS, made to burn biomass fuels like charcoal more effectively than traditional cookstoves. They often emit less damaging pollutants CO and CO_2 , as a result. The design of the stove, the kind of fuel that is utilised, and how efficiently the stove is operated are some of the variables that can affect the ratio of CO_2 CO emissions from an improved cookstove. In general, improved cookstoves are made to produce more CO_2 than CO, as the latter is a more dangerous pollutant and may be an indication of incomplete combustion. The correct CO_2 CO emissions ratio from an improved cookstove will rely on its individual design and usage circumstances. In general, an enhanced cookstove's CO_2 to-emissions ratio is anticipated to be far lower than that of a traditional cookstove, which can emit extremely high amounts of both pollutants.

Figure 23 depicts the ratio of CO_2 to CO from various sets of charcoals consumed during the WBT's HPPCS. These results show that the CO_2 ratio in the metal stove is substantially greater when using assorted charcoal and much lower when using AC. This indicates that the Abura Charcoal (AC) has a higher CO concentration than the assorted or mixed charcoals. As a result, the CO_2 to CO ratios obtained by using AC and assorted or mixed charcoal are 19.29 and 34.78, respectively. Therefore, when assorted or mixed types of charcoal are used in the Metal Stove (MS) for a similar activity, the CO_2 to CO ratio is 15.49 higher than when AC is used in the same stove.

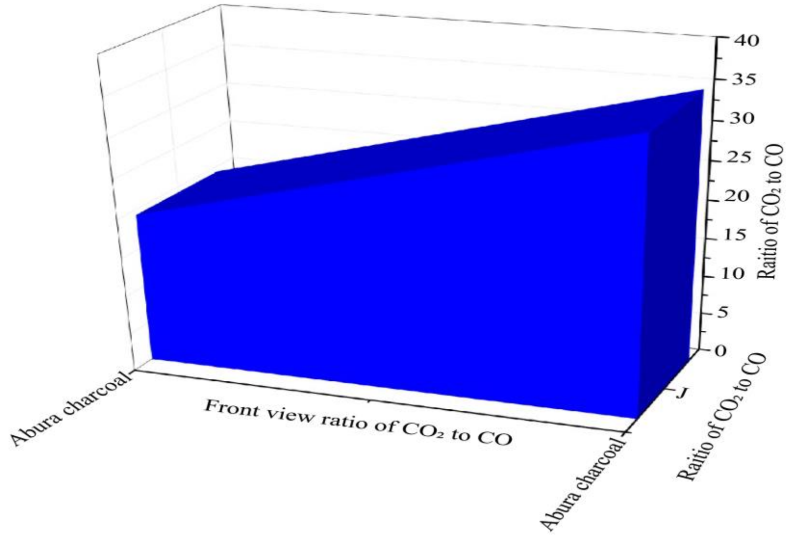

Fig. 23 Mass ratio of CO_2 to CO at HPPCS of the WBT for Metal Stove (MS)

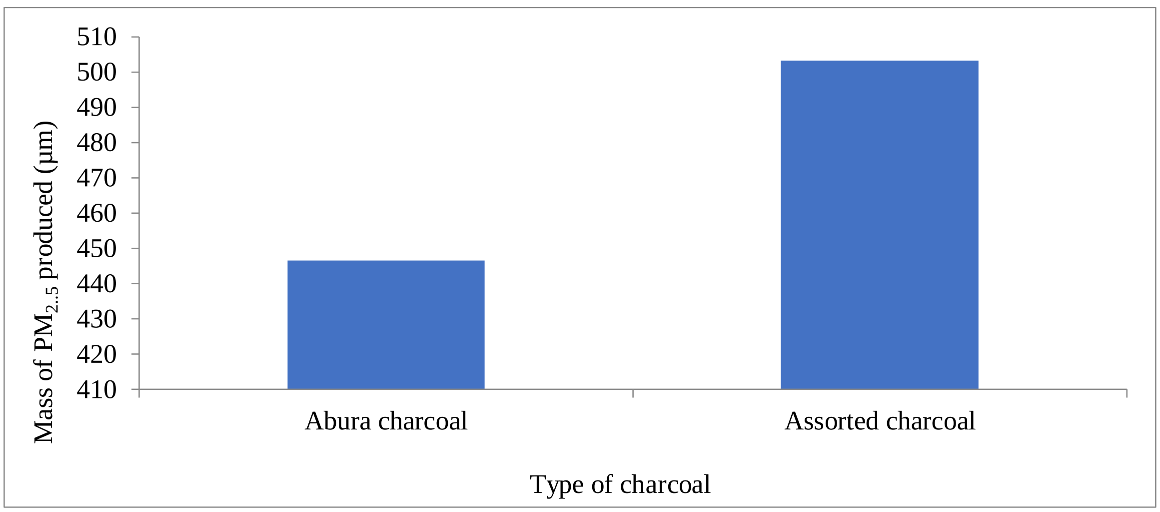

Fig. 24 Mass of $PM_{2.5}$ at cold start high-power phase of the WBT for Metal Stove

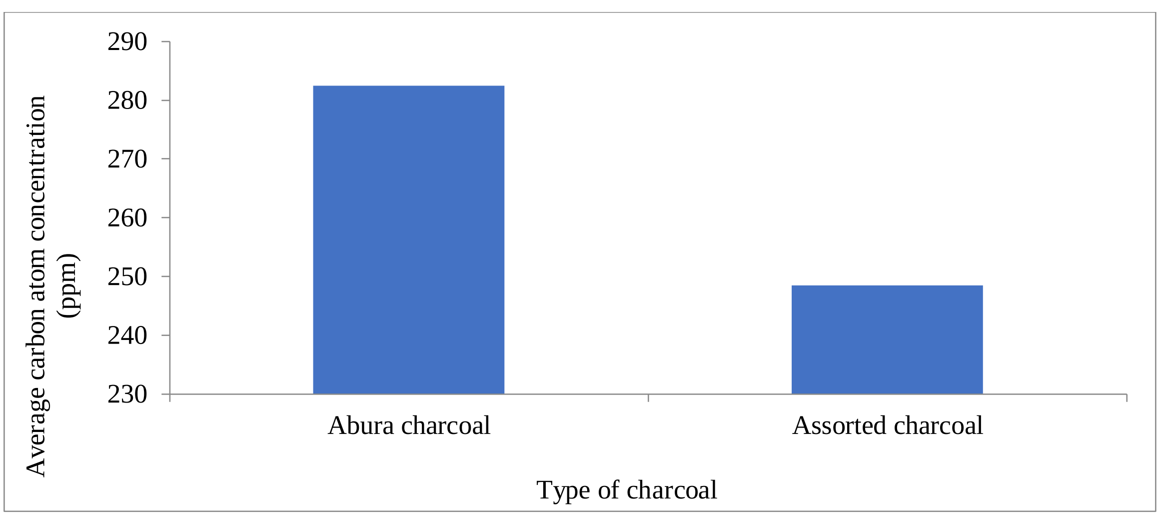

Fig. 25 Carbon atom concentration at simmer of the WBT when MS is used

The mass of $PM_{2.5}$ produced in an MS when both sets of charcoals were used is shown in Figure 24. The findings show that using AC in the MS produced emissions of about $446.56\mu g$ of $PM_{2.5}$, but using assorted or mixed charcoal produced emissions of $503.28\mu g$ of $PM_{2.5}$, with a variance of just $56.72\mu g$. Comparing the MS with AC to the assorted or mixed charcoal $PM_{2.5}$ values emitted, the difference shows that the MS with AC has a greater capacity to reduce the value of $PM_{2.5}$ and could be more environmentally friendly.

Compared to conventional cookstoves, an improved cookstove is made to burn fuel more effectively and emit fewer pollutants. Carbon monoxide (CO), a consequence of incomplete fuel combustion, is among the most significant greenhouse gases reduced by improved cookstoves. On the contrary, the fuel being burned contains carbon atoms.

The type of fuel utilised, the effectiveness of the stove's combustion, and the specifics of the stove's construction will determine the concentration of carbon atoms released from an improved cookstove. In general, more improved cookstoves are made to burn fuel more thoroughly, which reduces emissions of carbon monoxide and other harmful pollutants as well as carbon dioxide (CO_2).

This greenhouse gas accelerates climate change. However, some carbon monoxide and carbon dioxide emissions continue to be produced even with improved cookstoves. It is important to remember that an improved cookstove's carbon atom concentration is not always an accurate indicator of how much of an influence it has on the environment. The overall environmental impact of using a stove can be influenced by several other elements, including the source and sustainability of the fuel used, the stove's efficiency, and the user's cooking habits.

The average mass of carbon concentration during the experiment's simmer phase with the metal stove is shown in Figure 25. These findings show that using AC instead of assorted or mixed types of charcoal leads to higher carbon concentrations being produced by the metal stove. As a result, using AC in a metal stove produced a carbon concentration of $282.47\ ppm$ in the hood, but using other types of charcoal resulted in a concentration of $248.51\ ppm$ in the hood. This indicates a $33.96\ ppm$ difference.

When both sorts of charcoal are utilised to test the effectiveness of the Metal Stove (MS), the average mass of charcoal burned from emissions is shown in Figure 26. According to the findings, $2.61g$ of mass of charcoal is burned when AC is used in a metal stove, while $2.32g$ of mass of charcoal is burned when assorted types of charcoal are used to perform the same task under the same conditions.

The particulates and gases that are discharged into the air while testing a stove might be referred to as emissions from a stove in a stove hood. Smoke, steam, and other pollutants that may have a detrimental influence on indoor air quality and may pose health hazards are some of these emissions. To guarantee that pollutants from stove testing are adequately caught and vented outdoors, it is crucial to utilise a stove hood that is in good working order and to clean or replace the filters as needed.

This can lessen health hazards related to the testing of cooking emissions and enhance indoor air quality. It is crucial to remember that stove hood emissions can significantly affect indoor air quality since they can help pollutants accumulate in the laboratory. Due to this, it is advisable to use a stove hood with a high-quality fan or blower rating and to routinely clean and replace the hood's filter to make sure it is operating efficiently.

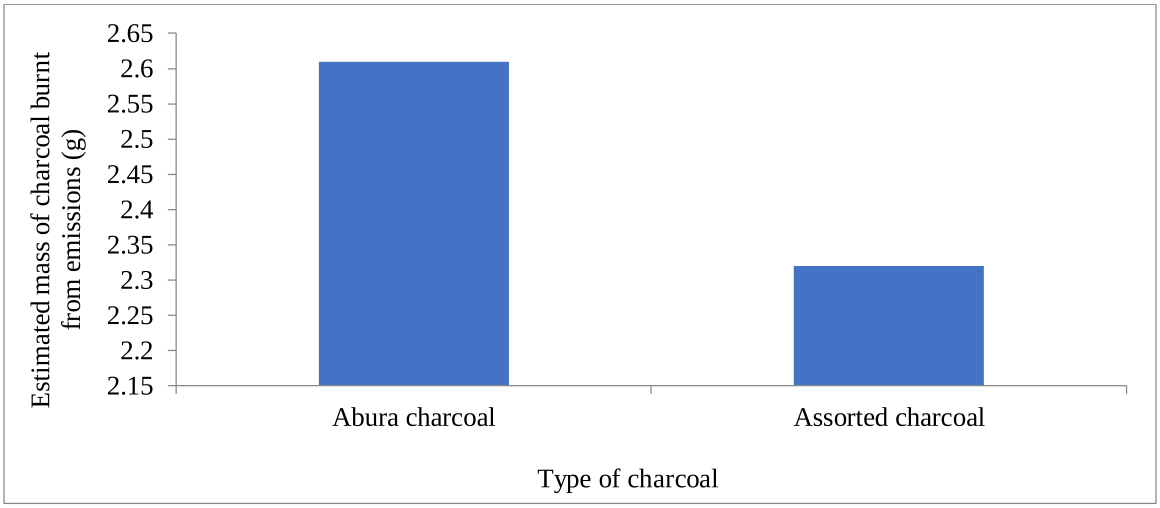

Fig. 26 Mass of charcoal burnt from emissions in MS at the simmering phase of the WBT

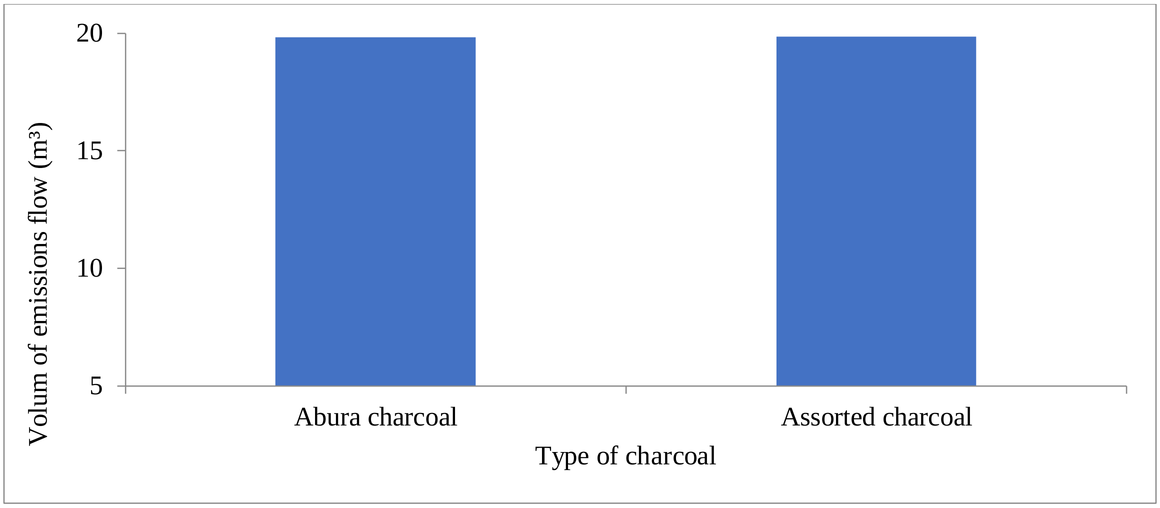

Fig. 27 Average volume of emissions produced by an MS at the simmer phase of the WBT

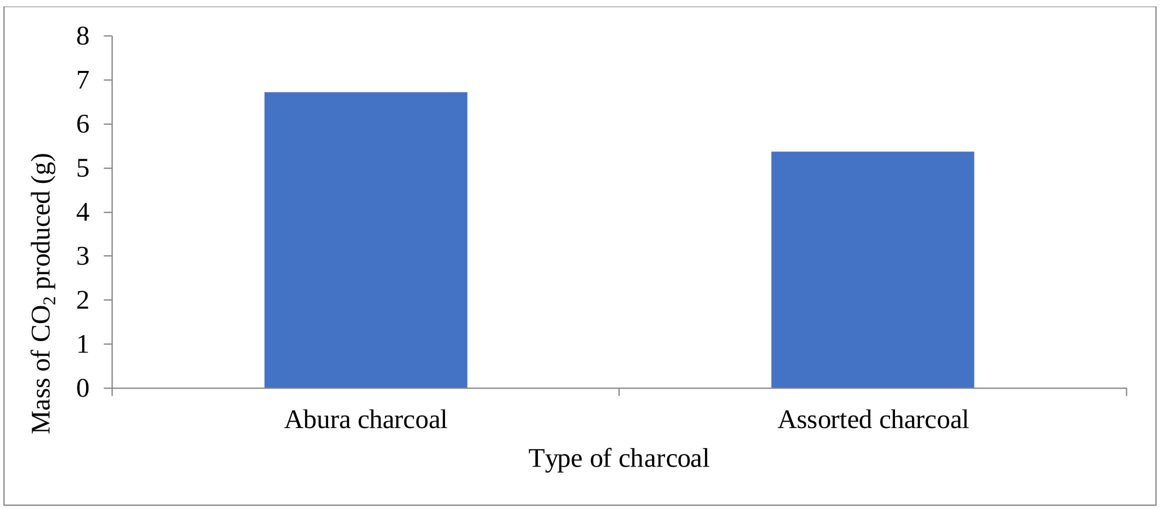

Fig. 28 Mass of CO_2 at simmer phase of the WBT for the MS

Figure 27 displays the average amount of emissions produced by a Metal Stove (MS) when 2.5 litres of water were simmered for 45 minutes using both types of charcoal. The amount of emissions released when using AC in the MS was 19.84 m^3compared to 19.87 m^3 when using other charcoals. However, the volume difference is barely significant ($approximately$ 0.03 m^3).

Figure 28 displays the masses of CO_2 generated during the experiment's simmer phase. It demonstrates that the MS emits 6.73g of CO_2 when using AC and 5.37g when using assorted charcoals. This shows that the metal stove works better at the simmer phase with assorted charcoals than it does with AC.

The CO emissions are normally quite low during the simmer phase of a water boiling test, especially if the stove or hob being used is correctly set and operating well. This is because the flame created by the stove or hob during the simmering phase is often smaller and less intense than it is during the high-power phase cold start. Thus, there are generally more complete combustion processes, which lead to lower CO and other pollutant emissions. However, insufficient combustion may occur, which can result in higher CO emissions if the stove is malfunctioning or if the pot being used is too large for the stove. To reduce CO emissions during the simmer phase, it is crucial to make sure that the stove or hob is operating effectively and that the pot used is the right size.

The masses of CO obtained at the simmer phase in the metal stove using both types of charcoals are shown in Figure 29. Using Abura Charcoal (AC) resulted in the production of 0.22g of CO, but using assorted charcoal resulted in only 0.23g of CO being calculated. However, this variation is relatively negligible ($about$ 0.01g).

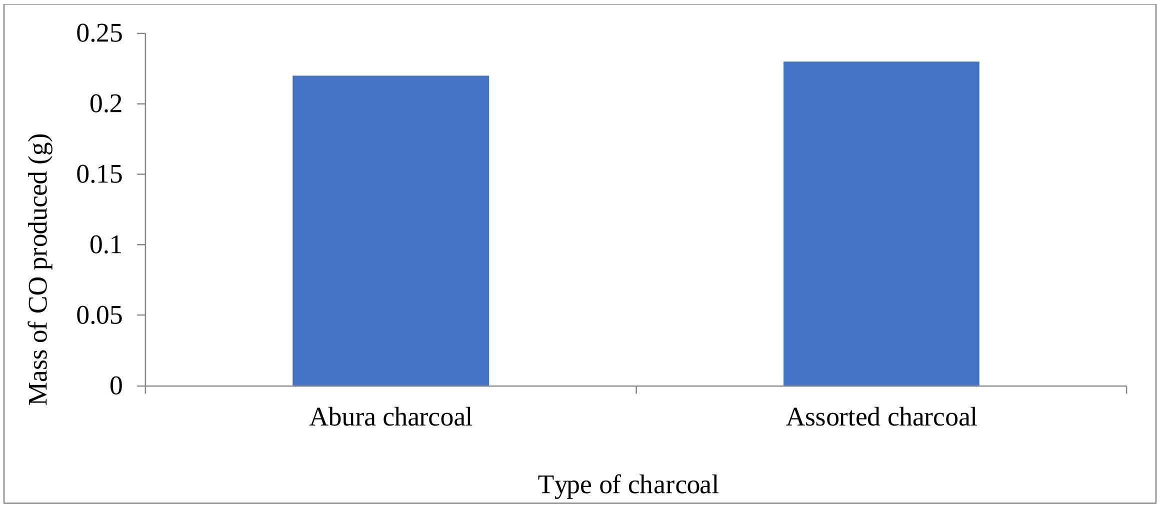

Fig. 29 Mass of CO at simmer phase of the WBT for MS

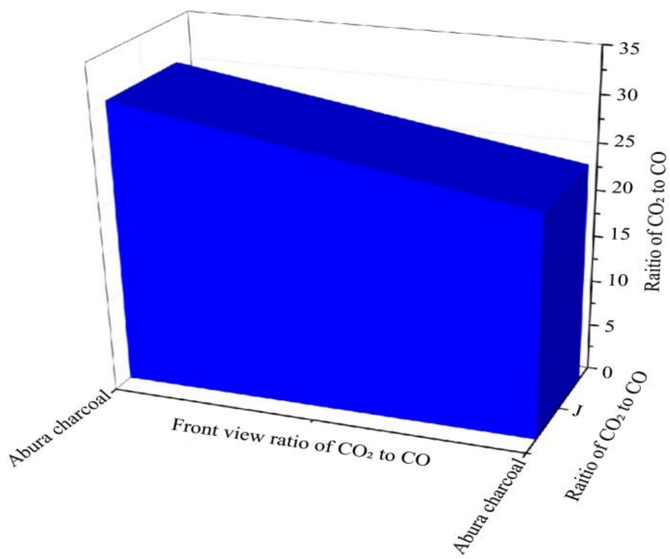

Fig. 30 Mass ratio of CO2 to CO at the simmering phase of the WBT for MS

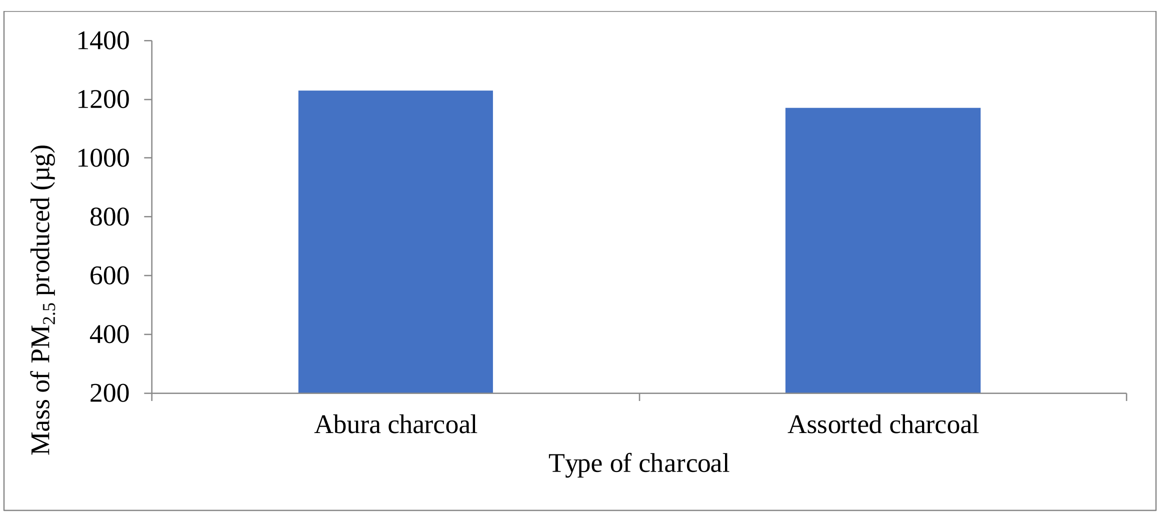

Fig. 31 Mass of $PM_{2.5}$ at simmer phase when MS is used for the WBT

Based on the exact stove construction and the fuel being used, the ratio of CO_2 to CO at the simmer phase can change while evaluating improved cookstoves. In general, better cookstoves are made to encourage more thorough fuel burning, which produces higher levels of CO_2 and lower levels of CO emissions as compared to traditional cookstoves. However, insufficient combustion can happen during the simmer phase when the flame is reduced to a low setting, leading to higher levels of CO emissions.

The architecture of the stove, the kind of fuel selected, and the working conditions will all have an impact on the CO_2 to CO ratio during this period. According to some research, the simmer phase CO_2 to CO the ratio of improved cookstoves ranges from roughly 10:1 to 30:1, with higher ratios denoting better combustion efficiency and lower CO emissions. It is crucial to remember that these ratios can change based on the particular stove and the testing circumstances.

Figure 30 displays the different mass ratios of CO_2 to CO in a metal stove when both types of charcoal were used during the simmer phase of the WBT. Using abura charcoal (AC) results in an average mass ratio of $30.35:1$ and using assorted or mixed charcoal results in a mass ratio of $23.71:1$, respectively. These findings are corroborated by the researcher [24], who reported comparable findings regarding the CO_2 ratio to CO.

$PM_{2.5}$ Refers to small particulate matter having an average diameter of less than or equal to 2.5 μm. It is one of the main pollutants released when solid fuels, such as charcoal, are burned, and it poses a serious health risk, especially to individuals who are exposed to it for an extended length of time. Because the stove releases the greatest $PM_{2.5}$ at the simmering phase of the WBT, this phase is crucial for evaluating an improved cookstove. This is due to the stove's decreased power output, which increases the likelihood of incomplete combustion and increases particulate matter production.

Because it gives an idea of the stove's overall performance, measuring emission levels of $PM_{2.5}$during the simmering phase is crucial. When an improved cookstove is simmering, it is more likely to generate significant levels of pollution throughout the rest of its operational range, which can have detrimental effects on the users' health. To find areas for improvement and create stoves that emit fewer pollutants by testing the performance of the stove during the simmering period, is paramount for this research.

This can lessen the negative health effects of cooking with solid fuels, especially in low-income countries like Sierra Leone, where better cookstoves can significantly enhance people's quality of life.

Figure 31 shows a trend observed $PM_{2.5}$ from a Metal Stove (MS) when it was exposed to two different charcoal products during the WBT's simmering phase.

Around $1230\,\mu g$ of $PM_{2.5}$are produced by the stove when AC is used, compared to $1170\,\mu g$ when the experiment's assorted or mixed charcoal is used at a simmer. Thus, showing that the cookstove cannot account for all of the $PM_{2.5}$emissions.

5. Conclusion

In general, post-combustion emissions measurements from improved cookstoves can be performed using two basic techniques. The hood technique was used for this study over the chambers technique because it is uncomplicated to use and allows for easy replication of the experiment. A particular species of hardwood was selected for the two different sets of charcoals that were produced to minimise any possible variances in the carbon and humidity contents.

Therefore, conducting the experiment repeatedly and averaging the outcomes have provided more precise data for each improved cookstove emission factor. The main objective of this work is to assess the post-combustion levels of the CO_2 CO and $PM_{2.5}$ through an experimental examination of two prevalent improved biomass cookstoves mostly used in Sierra Leone utilising a WBT.

Furthermore, the ratio of CO_2 to CO has been computed at both phases (HPPCS and simmer phase) of the WBT to ascertain which of the improved cookstoves is most likely effective in terms of combustion performance. The implications of these research results are significant for better cookstove choices, particularly for developing countries whose aspirations for clean cooking technologies continue to grow.

The investigation has produced several real measurements of the experiment's mass of carbon concentration, volume of trapped emissions in the hood, and mass of$PM_{2.5}$ during the HPPCS and simmer phases. Comparing the Wonder stove WS) using Abura Charcoal (AC) to a Metal Stove (MS) and other findings from past research on improved biomass cookstoves utilising various charcoal as fuels, the WS showed promise for utilisation.

Therefore, utilising a wonder stove with AC is a better option if one desires to reduce indoor CO_2, CO and $PM_{2.5}$ as summarised in Table 1 and Table 2. Hence, knowing the quantities of CO_2, CO and $PM_{2.5}$ from WS and MS would aid the government of Sierra Leone in forming policy choices, encourage sustainability, and aid in the fight against air pollution and climate change on a worldwide scale.

Table 1. An overview of the WS Emissions metrics

Stove type	Fuel type	Experiment phase	Average Carbon atom concentration	Average Volume of emissions flown in the hood	The average mass of charcoal burnt from emissions	Emission Factors			
			(ppm)	m^3/min	g/kg	$CO_2\ (g/kg)$	$CO(g/kg)$	$PM_{2.5}\ (\mu g/kg)$	$CO_2:CO$
Wonder Stove	Abura charcoal	HPPCS	192.75	10.79	0.9	2.58	0.12	307.49	21
		Simmer phase	283.56	19.58	2.57	6.67	0.25	1169.84	26.9
	Assorted charcoal	HPPCS	269.44	12.89	1.57	4.59	0.119	411.17	38.6
		Simmer phase	232.52	19.85	2.17	4.94	0.2	1375.96	24.9

Table 2. An overview of the MS emissions metrics

Stove type	Fuel type	Experiment phase	Average Carbon atom concentration	The average volume of emissions flown in the hood	The average mass of charcoal burnt from emissions	Emission factors			
			(ppm)	m^3/min	g/kg	$CO_2\ (g/kg)$	$CO(g/kg)$	$PM_{2.5}\ (\mu g/kg)$	$CO_2:CO$
Metal stove	Abura charcoal	HPPCS	234.09	11.89	1.25	3.64	0.19	446.56	19.29
		Simmer phase	282.47	19.84	2.61	6.73	0.22	1230	30.35
	Assorted charcoal	HPPCS	282.01	13.82	1.76	5.07	0.15	503.28	34.78
		Simmer phase	248.51	19.87	2.32	5.37	0.23	1170	23.71

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