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Research article

# Development and performance analysis of top lit updraft: natural draft gasifier stoves with various feed stocks

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ABSTRACT

The performance of an Ethiopian-designed and built-in gasifier stove was studied and evaluated. The water boiling test (WBT) findings are reported. This test was conducted in a controlled setting utilizing eucalyptus, bamboo, and sawdust-cow dung briquettes as test feedstocks, in accordance with WBT's 4.2.3 standard process and test manuals. Based on moisture content, the net calorific values of eucalyptus, bamboo, and sawdust-cow dung briquettes were calculated and determined to be 15.77 MJ/kg, 14.70 MJ/kg, and 15.35 MJ/kg, respectively. The efficiency of this stove was calculated utilizing those three feedstocks. As a result, the gasifier stove's efficiency having eucalyptus, sawdust-cow dung briquette, and bamboo as feedstock were 32.30 ± 0.3%, 31.5 ± 0.5%, and 26.25 ± 0.25%, respectively. This proportion did not include the ultimate charcoal production, but when this yield was employed as an energy input for additional charcoal burners, it increased to 53 ± 2%. The relationship between gasifier stove charcoal production and total efficiency is negatively related, with a linear equation of $Y = -0.7956X + 22.766$ and an R-squared value of 0.92. When compared to local stoves and foreign gasifier stoves, whose efficiency is in the range of 10 %–39% this efficiency rating was exceptional due to the fact that space between the internal and external cylinder help the secondary air to preheat before combustion and also the interior hallow cylinder help the primary air to move evenly in the vertical circular pattern for proper gasification, it will also help the gases that are produced during gasification process to move to the top part for combustion, indicating that this study can be fostered for prospective use.

## 1. Introduction

Biomass fuels are the world's fourth main energy source, accounting for 13% of the total energy supply (Waldheim and WALDHEIM, 2018), with a particularly high share in developing nations. In developing nations like Ethiopia, where biomass combustion accounts for 91% of its primary energy output (Mondal et al., 2018), biomass combustion supplies basic energy requirements for cooking and heating rural families, as well as processes in a range of traditional industries (Yurnaidi and Kim 2018) (D. Sakthivadivel, P. Ganesh Kumar, G. Praveen Kumar, P. Raman, Ranko Goic, 2020). In Sub-Saharan Africa, one of the options to satisfy the household energy demand is to sustainably use fuelwood for cooking (Hafner et al., 2020). By a ratio of two to three, improved design can increase the efficiency of biomass utilized for cooking (Bhattacharya 2003).

Improved cooking stoves, such as the gasifier stove, have been shown to reduce the amount of fuel used in the kitchen while also reducing pollutants (Adane, Alene, and Mereta 2021). Gasification stoves are also known as improved stoves since they use less biomass and emit less pollutants than standard open three-stone stoves. Most governmental and non-governmental groups in Ethiopia are concentrating their efforts on improving charcoal and wood injera stoves, rather than developing gasification stoves.

One of the most significant characteristics of this gasifier stove is that it collects incomplete combustion volatile gases that would otherwise escape during the carbonization process or charcoal production and burn them with primary air that enters through a hole in the middle of the innermost cylinder's wall from the bottom to the top, the hole being larger on the top for the combustion of volatile gases, and secondary preheated air that enters between the outer wall of the combustion

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chamber and the inner wall of the outer cylinder. This stove has two advantages: first, it will utilize incomplete gas as a source of energy since it will totally burn the gas using secondary air, and second, it will prevent gases from polluting the environment owing to incomplete combustion, as shown in Figure 1. It will also enable the production of charcoal and the avoidance of indoor air pollution (Gitau et al., 2019).

Traditional biomass sources such as wood fuel, agricultural residue, charcoal, and cow dung have been Ethiopia 's primary energy source in the past and present, and those feed stocks are mostly utilized for injera baking, thus using this technology for injera baking is important (Adem et al., 2019). The majority of this energy resource is used inefficiently, so as a consequence, the biomass resource is used in large quantities. As a result, natural forest loss has become a significant concern, with forest cover falling from 40% to less than 12% in less than a century (Babiso Badesso, Bajigo Madalcho, and Mesene Mena 2020). In addition to this depletion, collecting wood from the forest takes a long time for most individuals who engage in this activity, particularly women. As the percentage of forest cover decreases as a result of population growth, which is linked to consumption, fuel scarcity will force the use of crop residues and animal dung as fuel, which would otherwise be used as animal feed, and for the restoration of soil fertility, It will result in a 7% fall in agriculture GDP (Zenebe G. 2007). This might result in a significant drop in agricultural output at a time when the industry is projected to produce more, as indicated in the schematic Figure 2 below (United Nations Environment Programme (UNEP) 2019).

### 1.1. Stove development in Ethiopia

The primary goal of any energy conversion system's engineering study is to obtain the needed kinds of energy with the highest possible efficiency utilizing existing technology. Any energy conversion system that does not know how much energy can be taken from prospective sources and how much energy can be saved for the environment is not economically viable (Geremew et al., 2014) (Mamuye et al. 2018).

Open three stone wood stove is a traditional stove that is extensively used for cooking and baking across Ethiopia, particularly in rural homes. The stove's conversion efficiency ranges from 6 to 12 percent, see (Figure 3 a). It wastes more than 90% of biomass energy; over 95% of the population relies on biomass for their energy needs, and roughly half of that energy is consumed for cooking injera, largely on this traditional three stone fire stove (Tadesse 2020). Millions of tons of biomass fuels are wasted each year due to its inefficient features and dominance in the home sector. Aside from that, the smoke produced during its use is harmful to one's health. Mirt and Gonze can save up to 33% and 20% of the wood biomass consumed by the typical open three stone stove, respectively (Amare 2015) (Fekadu et al. 2019). When compared to Gonze, the Mirt stove can conserve 15% more biomass (Amare 2015), see (Figure 3 b and c).

These stoves are currently being widely pushed because to their ability to achieve a fuel economy of up to 31% when compared to an open fire system. It can also help to enhance the cooking environment by decreasing indoor air pollution and other issues like burns and overheating (Yayeh et al. 2021).

### 1.2. Benefits of improved stove

The advantages of a better cook stove are divided into two categories: those that benefit the household and those that benefit the environment. Internal benefits include lower smoke levels and interior air pollution, cost and time savings in obtaining fuel, and reduced biomass consumption, as well as the potential to use animal dung as fertilizer instead of fuel. External benefits include reduced demand on timber and energy resources, lower GHG emissions, and community skill development and employment creation during the manufacture of better cook stoves (Anhalt and Holanda 2009) (Raman et al. 2014).

### 1.3. Gasification

The process of transforming solid or liquid feed-stock into an useable gaseous fuel or chemical feed-stock that may be burned to produce energy or utilized to manufacture value-added chemicals is known as gasification (Basu 2010). Even while gasification and combustion are both thermochemical processes, they differ significantly. Gasification stores energy in chemical bonds in the resultant gas; combustion releases that energy by breaking those bonds. Gasification introduces hydrogen into the feedstock while eliminating carbon, producing gases with a higher hydrogen-to-carbon (H/C) ratio, whereas combustion oxidizes the hydrogen and carbon into $H_2O$ and $CO_2$, respectively (Basu 2010) (Waldheim, IEA and Waldheim Consulting, 2018).

### 1.4. Gasifier cook stove

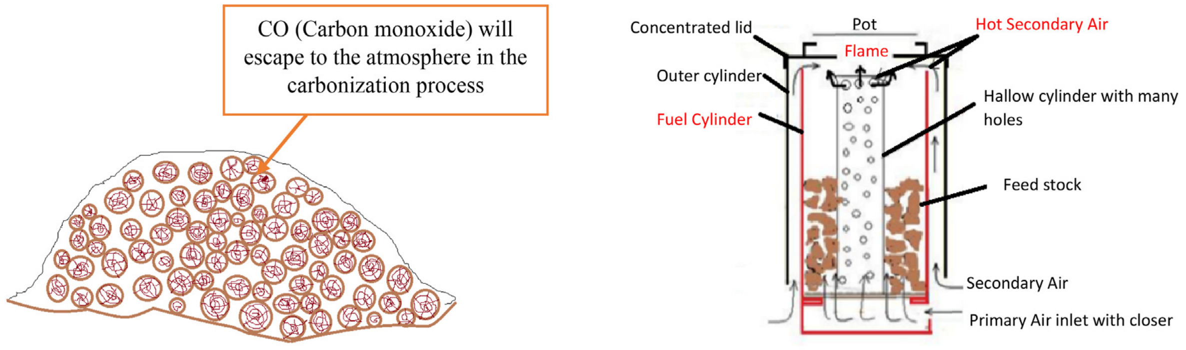
#### 1.4.1. Technical features

Gasifier-based cooking systems have numerous enticing features, including high performance, clean combustion, a uninterrupted and steady flame, ease of flame management, and perhaps long-term attention-free operation (Raman et al. 2014).

#### 1.4.2. Working principle

Gasification is the sub-stoichiometric combustion of biomass that produces a combination of flammable gases such as CO, $H_2$, and traces of $CH_4$ as well as incombustible gases such as $CO_2$ and $N_2$. A gasifier is made out of a container into which fuel and a little amount of air are supplied. The heat required for gasification is produced by partial combustion of the fuel (Basu 2010).

Pyrolysis of carbonaceous fuels and char gasification are both used in biomass gasification. During the pyrolysis process, volatile components



a) b)

**Figure 1.** (a) Traditional carbonization process (b) Gasifier stove.

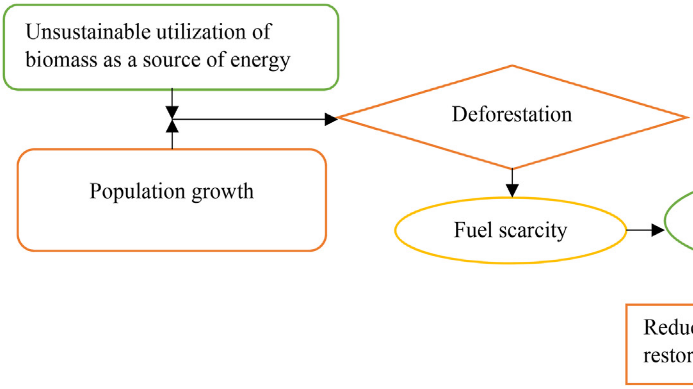


**Figure 2.** Schematic diagram of unsustainable biomass utilization.

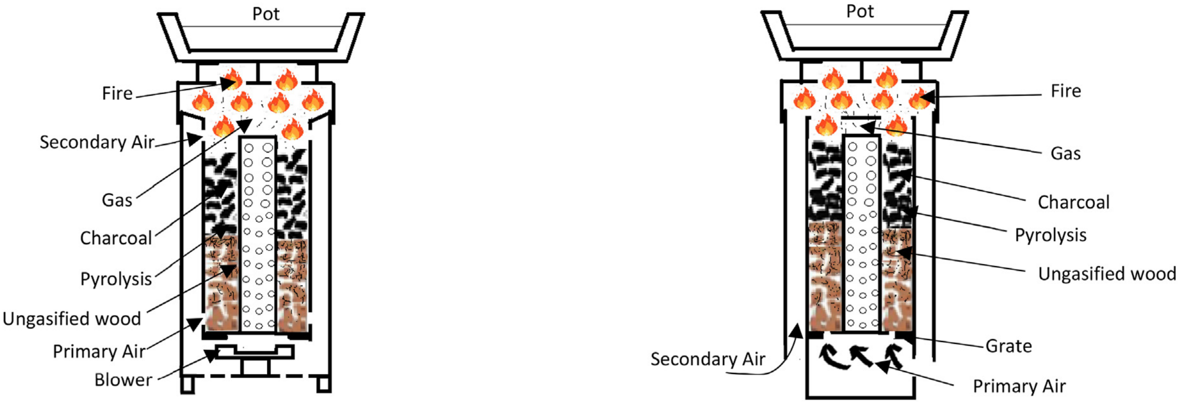
a) b) c)

**Figure 3.** Cooking stove (a) three stone open fire and injera baking stove (b) mirt (c) gonze in Ethiopia.

from the biomass are released at high temperatures, leaving char behind. The volatile components and some of the char react with oxygen to generate carbon dioxide, producing heat (Basu 2010). Gasifiers can be either natural or forced draft. In the forced draft gasifier, the air needed for the combustion of fuel is supplied by an external source like a fan or a blower while in the natural draft gasifier; the draft is created due to the pressure difference between the heated air near the flame and the cooler air in the surrounding as illustrated on Figure 4.

### 1.5. Current trends of gasifier stove

A micro gasifier stove, the ACS IES-15, with a similar design feature to this one, except the stove did not include an internal hollow cylinder with a punctured, wall and bottom disk, obtained a thermal efficiency of 36.7 ± 0.4 percent utilizing coconut shell as a feed stock (Sakthivadivel et al., 2019). Another study indicated that coconut shell has a thermal efficiency of 36.7 ± 1 percent, Prosopis Juliflora has a thermal efficiency of



a) b)

**Figure 4.** Two types of gasifiers (a) forced draft (b) natural draft.

36 ± 1 percent, and wood pellets have a thermal efficiency of 38.5 ± 1 percent (Sakthivadivel and Iniyan 2017). (Osei et al., 2020) achieved a thermal efficiency of 30.5–38.1 percent by applying WBT version 4.2.3 and using rice husk as fuel.

The efficiency of the stove can be increased by repurposing the heat lost from the combustion chamber's surface, and in this article, the heat on the combustion chamber's outer surface is used to heat up the secondary heat, which is critical to the volatile gas's combustion process.

The heat lost from the combustion chamber's surface can be repurposed to increase the stove's efficiency (Kaushik et al. 2016), and in this article, the heat on the combustion chamber's outer surface is used to heat up the secondary heat, which is essential to the volatile gas's combustion process effectiveness.

An updraft forced gasifier built and manufactured to produce gas at an equivalent ratio of 0.5 using a mixed feedstock of rice husk-sawdust had a thermal efficiency of 17.6 % while using a bluff body B, upper burner type (Susastriawan et al., 2021). When compared to traditional stoves, in a paper by (Okino et al., 2021), has obtained a thermal efficiency of 35.5 ± 2.5% using Senna spectabilis as a feed stock, followed by Eucalyptus grandis 25.7 ± 1.7%, and finally Pinus caribaea 19.0 ± 1.2%.

The thermal efficiency of a forced-up draft gasifier with a feed stock holding capacity of 1.5 kg of rice husk, a complete cooking time of 1 h, and dimensions of 60 cm high and a diameter of 16cm was evaluated to find out its thermal efficiency. A thermal efficiency of 34 % for RHGS (Rice Husk Gas Stove), with fuel consumption rate of 1.5 kg $h^{-1}$, combustion zone velocity of 1.46 cm/min, time to boil 3 L of water, 19 min, and 32.41% char was produced (Punin 2020). When analyzing the Rice Husk Gasifier stove with different five parameters, the correlation of charcoal output vs thermal efficiency is inversely connected in this paper, which is similar to this article finding on (see Fig 20) (Punin 2020).

An article with thermal performance evaluation of an improved biomass cookstove for domestic application obtained an average thermal efficiency of approximately 33% while boiling 7.5L of water (Barpatragohain et al. 2021). A natural draft gasifier with rock type of pyrolysis stove, has obtained over all thermal efficiency of 45.6% and a bio char produced from this stove was used for amendment of soil and it was burnt at very high temperature (Hailu 2020). A natural up draft gasifier with height of 34 com and 16cm diameter and 2m chimney height obtained an overall efficiency of 38.6 (Shaisundaram et al., 2021).

Based on the above findings, this study aims to build a natural up draft gasifier stove that can achieve an overall efficiency of more than 45 percent without the use of a fan or blower for the primary and secondary air. The size of the stove, which is the most important factor, will be determined by the quantity of biomass holding capacity and the distance between the feed stock and the stove bottom component, which will be determined by the amount of heat lost. An internal hallow cylinder that is perforated is included to maximize the effectiveness of the combustion process as well as the gasification process. The hole on the bottom of the cylinder is small, but it grows larger as it progresses to the top, which will perfectly facilitate the internal gasification as well as combustion process. Additionally, secondary air will enter the gasifier stove through the space between the external cylinder and the internal gasifier chamber. The heat that escapes from the surface of the gasifier chamber via convection and conduction heats the secondary air, resulting in a good combustion process on the gasifier chamber's outer top part. All of this thinking will provide a solid foundation for enhancing the stove's overall efficiency.

## 2. Materials and methods

### 2.1. Stove specification

The gasifier stoves are made of sheet metals using simple mechanical works and consist of fuel chamber to fill the biomass residue for burning, air inlets for partial combustion and pot stand for supporting the cooking utensils.

The gasifier stove is a natural one that did not require any form of energy to drive the air into the gasifier stove, unlike the other type of gasifier stoves that depend on electricity that is used to drive the air into the gasifier stove. This gasifier was made out of mild steel sheet metal and has a bulk fuel capacity of about 0.0005 $m^3$ (500gm) for a good gasification process. In this performance test, we used feed stocks in this range but this does not mean the internal fuel cylinder capacity is 0.0005 $m^3$. The fuel cylinder is twice the size of this value, which means the fuel to be gasified was filled to half the height of the fuel cylinder for a good gasification process. The stove was made up of two concentric tubes of different sizes, known as the outer cylinder and fuel cylinder (as shown in Figure 5. The fuel cylinder is sealed at the bottom, and inside it, there is a hollow cylinder with a perforated wall and bottom disk with dispersed hole to allow primary air and support fuel, and finally there is a top support that will be placed on top of the outer cylinder to hold the pot.

All of the stove's components are self-contained and is built without the use of temporary or permanent connectors. The gasifier stove has an overall height of 32 cm and a diameter of 19 cm. The presence of a central column for air in this stove distinguishes it from previously produced Top Lit- Updraft Natural Draft (TLUD-ND) gasifier stoves. The air column is drilled on the surface, as shown in the right-hand side of the left bottom Figure 5 (a), to allow more primary air radially into the fuel at different stages to compensate for air clotting that might occur while running with tiny sized fuel as we travel up the fuel column. This prevents the flame gasification from becoming air-starved owing to fuel particle interlocking. Furthermore, near the top of the central air column, closely spaced comparatively bigger holes were bored to transmit additional hot post-gasification secondary air. The inclusion of two hot secondary air entrance ports is intended to provide sufficient air while keeping the stove short and minimizing heat loss (see Figure 5).

### 2.2. Feed stocks

The initial step of the experiment was to gather different feedstocks for the water boiling tests in order to complete the tasks in a consistent manner. According to this, eucalyptus logs that had been utilized for building but were no longer needed, residual bamboo left over from local chair and table builders, and manually produced briquette from eucalyptus sawdust and cow dung were all cut into appropriate sizes, see (Figure 6, Figure 7 and Figure 8). Following the collection of the materials, a precise digital weighing scale was utilized to weigh the water and feedstock, see (Figure 9 b and c). The waste or by products were chosen to examine how well this gasifier performs with a low-cost feed stock while also assisting us in removing a waste or by product in a sustainable energy usage way. The feed stock supplies used in the study were readily available in the nearby area.

A mixture of saw dust with cow dung (MSCD) was in the proportion of 72.28% and 27.72% respectively.

### 2.3. Test protocol

There are three sorts of tests that may be used to assess a stove's performance. These tests are classified as follows, depending on the nature of the tests:

1) Water boiling Test (WBT)
2) Control Cooking Test (CCT) and
3) Kitchen Performance Test (KPT)

In the current experiment however, only WBT is conducted, since the main objective of this experiment is determining the performance of the stove using different feedstocks and comparing it with other stoves.

1) Water boiling test (WBT):

It is a laboratory-based test that is carried out by a qualified technician in a controlled setting to assess the stove's performance and many parameters

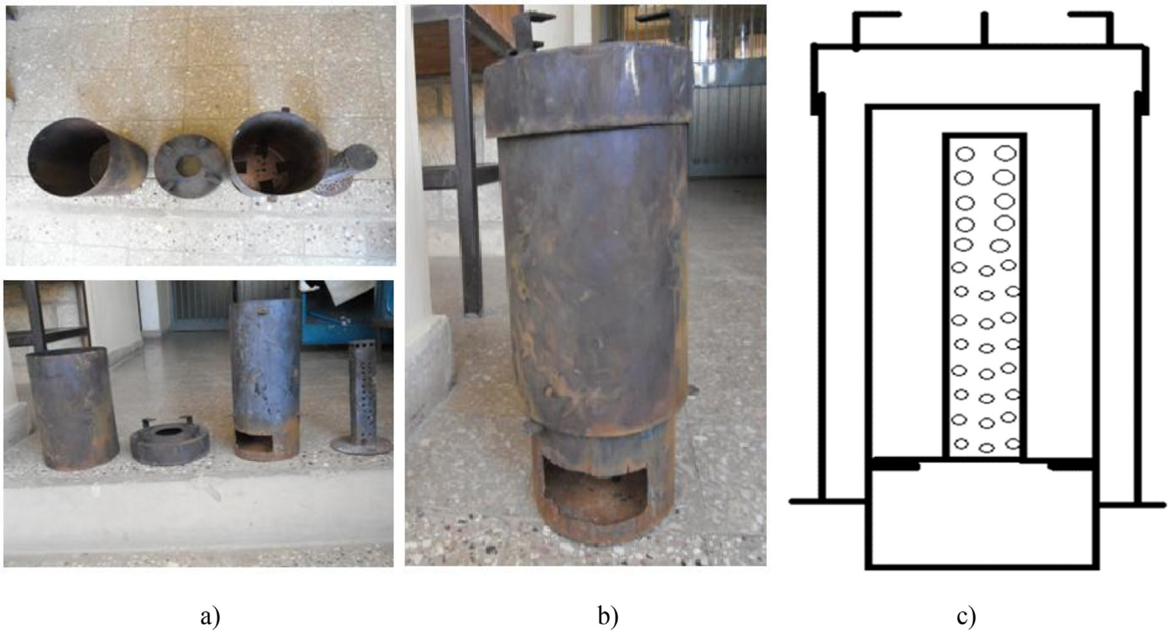


**Figure 5.** Fabricated gasifier (a) disassembled part, top and side view (b) assembled part (c) sectional view.

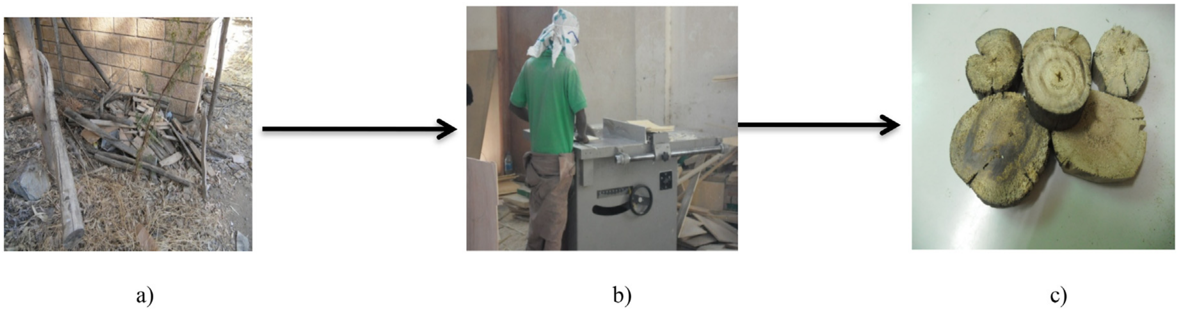


**Figure 6.** Eucalyptus feed stock (a) used eucapyptus log from construction (b) wood shop (c) sliced eucalyptus log.

that influence it. It is a valuable tool for fine-tuning the stove design to the needs of the user (PCIA & Global Alliance 2013). The only things needed for this experiment are a gasifier, feed stocks with its heating value, fire starting material, water, a pot, and a temperature monitoring equipment. We may determine the stove's thermal efficiency using the data from those materials and the relevant thermodynamics principles and formulas.

### 2.4. Testing equipment

The data gathering technology used to evaluate the gasifier stove was extremely sensitive, with digital weight balances being utilized to ensure accuracy, see (Figure 9 b and c). For the various data acquisition tasks, the following equipment was required:

- ➢ Digital stopwatch, used to record the time of each different activities (i.e., boiling) during the tests.
- ➢ Digital thermometer indicator (VICTOR 70 Digital Multi-meter) range: 0 °C–800 °C as shown in Figure 9 (a) below with 1/10 °C accuracy with model of K thermocouple wire for measuring the ambient temperature, boiling water temperature and the external body surface temperature of the gasifier stove.
- ➢ Electronic balance, with accuracy of 1gram, and capacity of 620 gm and 4000gm as show in Figure 9 b and c. These devices were used to

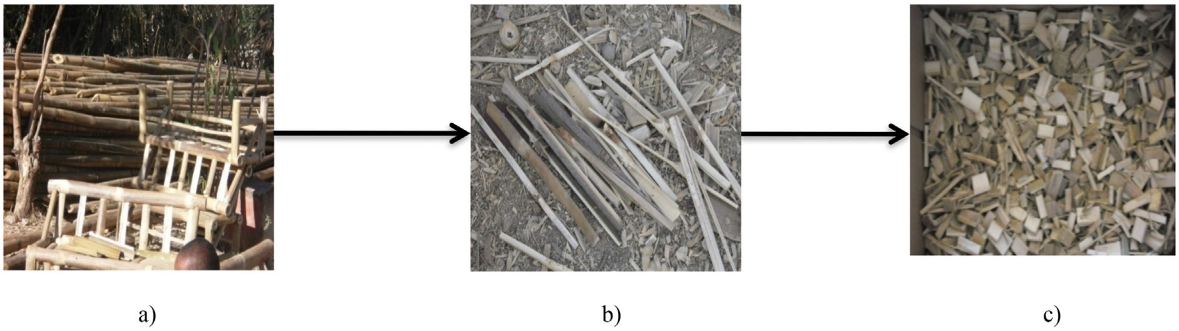
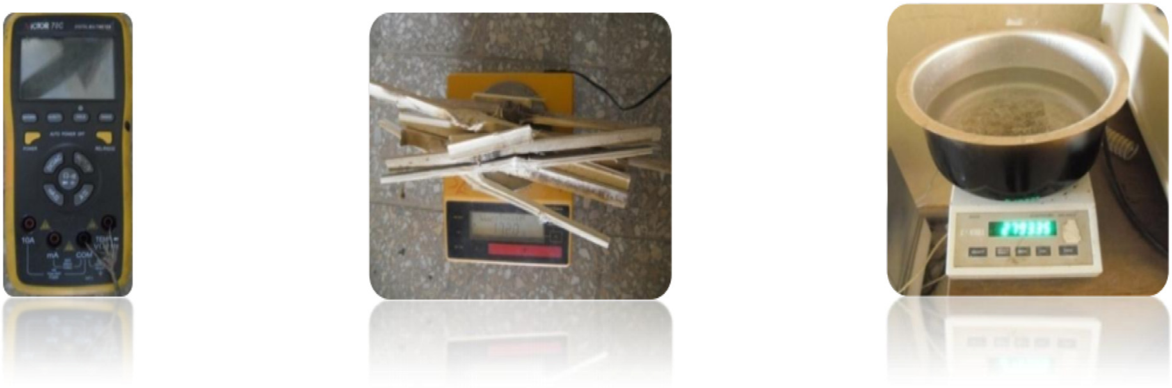


**Figure 7.** Left over bamboo, (a) bamboo chair (b) bamboo leftover (c) chopped bamboo.

a) b) c)

**Figure 8.** Preparation for MSCD (a) eucalyptus sawdust from wood shop (b) mixing cow dung with water (c) mixing saw dust with cow dung.



a) b) c)

**Figure 9.** Equipment's for the water boiling tests (a) victor 70 digital multi-Meter (b) 620 max digital weight balance (c) 4000gm max weight balance.

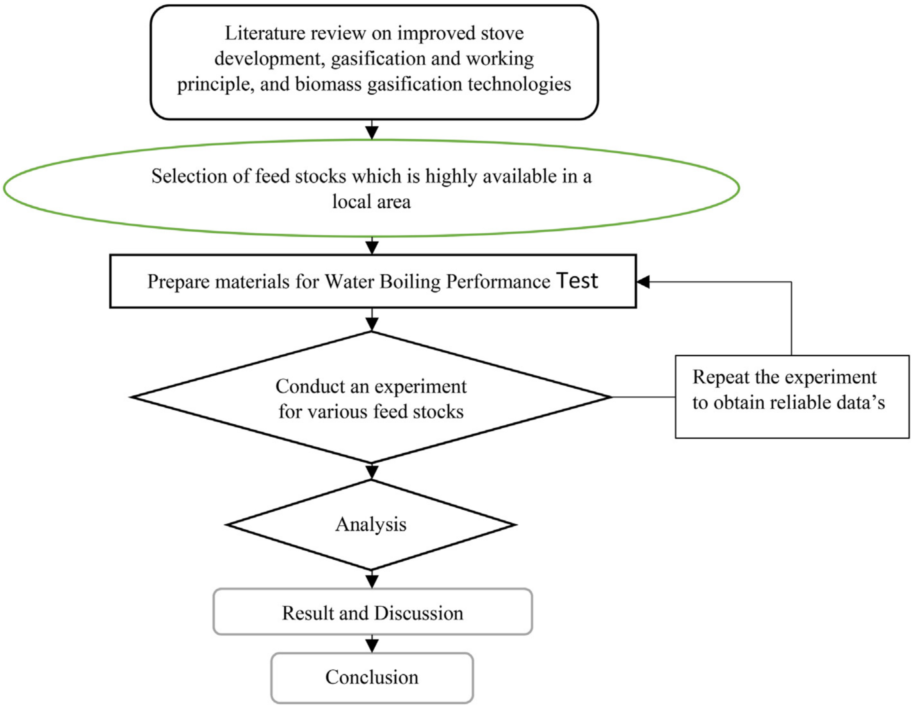


**Figure 10.** Work flow chart.

measure the weight of those different feed stocks and the weight of water in the pot respectively.

- Aluminum pots, plastic bottle to carry the water from the water tap to the pot.
- Thick heat resistance glove made from Cattle skin, kerosene and match, fire starter.
- Furnace to measure the moisture content; help to find the calorific value of feed stock.
- Closed cane, to extinguish the charcoal produced in the gasifier using air starvation techniques. And plastic bag to hold charcoal for weighing.

### 2.5. Data gathering procedures

The following schematic diagram depicts the overall working flow of this research, Fig 10. The tests are repeated a number of times in the fourth phase using various feed supplies. To accomplish so, the data collecting technique and equipment were both identical, allowing the experiments to be compared.

The research was fully experimental, as demonstrated by the work flow charts in Fig 10. Therefore, the techniques employed in this study were mostly focused on data gathering during the tests. The data obtained for performance calculations may be divided into three categories.

## 3. Lower heating value of the feed stocks

The moisture content (MC) on dry basis of biomass is the quantity of water in the material dry weight, expressed as the percentage of the materials dry weight (Reeb 1999) (PCIA & Global Alliance 2013). MC of the fuel sample is established using the oven-drying method, one of the methods covered in ASTM D4442. After weighing, the item is put in an oven set to 103 + 2 °C (214°F–221°F) and held there until no weight change is detected after 4 h of weighing. In 12–48 h, a 25 mm (1in) diameter timber piece will attain a consistent weight (Reeb 1999) (Simpson 1997).

The moisture content of each feed stock was measured using a conventional technique. The samples were placed in an oven set at 102 °C at 2:00 a.m. the next morning, after 24 h, the weight was measured again after it had completely dried, and the weight difference between these two measurements was the number of moisture content on those feed stocks, as shown in Table 1.

The lower heating value for thermal efficiency calculation can be determined using the aforementioned moisture content value of those feed stock and their higher heating value (HHV) from literature (Parikh et al. 2005).

**Table 1.** Moisture contents of the samples.

| Sample type | Weight differences (Moisture content) (gm) | Percentage of Moisture, $M^2_{cwb}$ (%) | Average moisture percentage $M_{cwb}$ (%) | **Moisture content on dry basis, $M^3_{cdb}$ (%)** | Average $M_{cdb}$ (%) |
|---|---|---|---|---|---|
| Eucalyptus | 1.3 | 8.44 | 7.84 | 9.22 | 8.51 |
| | 1.2 | 7.64 | | 8.28 | |
| | 0.9 | 7.44 | | 8.04 | |
| Bamboo | 0.3 | 7.32 | 8.74 | 7.89 | 9.59 |
| | 0.3 | 10.00 | | 11.11 | |
| | 0.4 | 8.89 | | 9.76 | |
| Mixture of Sawdust with Cow dung | 1.2 | 7.69 | 7.60 | 8.33 | 8.23 |
| | 1.4 | 7.87 | | 8.54 | |
| | 1.4 | 7.25 | | 7.82 | |

### 3.1. Weight of water, biomass and charcoal

The weight of water, biomass (as a feed stock), and ultimately the charcoal generated after full gasification are all required parameters for calculating Overall efficiency. The digital weight balances were used for this measuring assignment, as illustrated on Figure 9 (b and c).

### 3.2. Temperature data of the water

Temperature data was gathered every 5 min for each of the different testes. These temperature readings were taken in order to determine the water's highest and lowest temperatures. Apart from that, a temperature profile is drawn as illustrated in Fig 13.

### 3.3. Test setup for WBT

The first condition for a water boiling test is that it must be conducted in a controlled setting with constant sun intensity and wind speed over a period of time (PCIA & Global Alliance 2013). Aside from that, the temperature in the region must remain consistent.

The experiment was carried out in front of a material lab where no combustible materials were present. And, the location was a controlled setting with no variations in wind speed, ambient temperature, or sun intensity. After the materials have been measured (weight of water and feed stock, water, and air temperature), the wood can be fired using kerosene and match, fire starter, as indicated in Fig 11 (a) below.

By doing so, the test was proceeded after placing the pot on top of the gasifier burner at various times on different feed stocks. The tests were repeated fifteen times in this performance evaluation, Fig 11 (b) depicts the general test setup for the water boiling test. The temperature of water was measured at 5-minute intervals using a Victor 70C digital multimeter with a combined K-type thermocouple thermometer.

In this test, the thermocouple must be placed in the middle of the pot with its tip 50 mm above the bottom of the pot. As a result, we shall measure the temperature of the water rather than the temperature of the pot bottom (PCIA & Global Alliance 2013). When performing this test, take all necessary precautions, such as wearing thick heat-resistant gloves and avoiding combustible materials near the stove.

### 3.4. Technical calculations

The ratio of the energy used in the boiling process to the caloric content in the fuel used is described as stove performance by using water boiling test (WBT). The thermodynamic consideration underpins the idea of efficiency. The efficiency of advice for a given operation is the ratio of the energy output to the input energy, according with second rule of thermodynamics (PCIA & Global Alliance 2013) (Mohammadreza Rasoulkhani and Mohammad Hossein Abbaspour-Fard 2018) (Abasiryu et al. 2015). Heat is created in a biomass-fired cook stove by partial combustion of the biomass. Some of the heat created is transmitted to the vessel by radiation and convection from the fire bed and exhaust gasses which is used to boil water (D-Lab 2017). The remaining heat is lost to the environment through evaporation, distance from fuel to pot, convective loss from wind, unburned volatile gases, and radiation from pot, cool combustion air or fuel, radiation from stove, conduction through stove, wet wood stove, and pot contents (Zube 2010).

The energy utilized in the boiling process, or the energy that enters the pot, has two observable effects: increasing the water's temperature to its boiling point, and evaporating the water. The boiling efficiency could be calculated by calculating the total energy required in raising the water temperature from its beginning temperature to boiling point, and also in evaporating a known amount of water (PCIA & Global Alliance 2013). In the efficiency calculation, the lower calorific value of the fuel is utilized. The total energy provided can be calculated by

a)

b)

**Figure 11.** (a) Firing of the feed stock in the gasifier stove (b) Test set up for water boiling test.

measuring the total amount of fuel used during the test period (see Fig 14) and utilizing the net calorific value or LHV (lower heating value) (see Table 2).

The following calculation, similar to cooking efficiency, is used to determine the thermal efficiency of the gasifier stove. The total input power to the water, as shown in the calculation, is the sum of the energy used to increase the water temperature to its ultimate temperature and the energy used to evaporated water. This value is divided to the lower heating value of an equivalent dry fuel burned (Berrueta et al. 2008) (Abasiryu et al. 2015) (PCIA & Global Alliance 2013) (Kaushik et al. 2016).

$$\eta_{th} = \frac{[m_{wi}{*}C_{pw}{*}(T_e - T_i)] + [m_{wevp}{*}L]}{f_{cd}LHV_f} \tag{1}$$

$$\eta = \frac{[m_{wi}{*}C_{pw}{*}(T_e - T_i)] + [m_{wevp}{*}L]}{fac} \tag{2}$$

$$\eta = \frac{[m_{wi}{*}C_{pw}{*}(T_e - T_i)] + [m_{wevp}{*}L]}{f_{cd}.LHVf \; - \; E_{moist} \; - \; m_{char}{*}LHV_{char}}$$

The dry fuel ($f_{cd}$) and $E_{moist}$ can be calculated using Equation (3) and Equation (4) respectively

$$f_{cd} = fuel\ mass\ wet\ (1 - MC) \tag{3}$$

$$E_{moist} = fuel\ mass\ wet.MC\ (4.186(Te - Ti) + 2260) \tag{4}$$

where:

$\eta_{th}$ = Thermal Efficiency (PCIA & Global Alliance 2013) (Abasiryu et al. 2015),
$\eta$ = Overall Efficiency (Mohammadreza Rasoulkhani and Mohammad Hossein Abbaspour-Fard 2018).
$f_{ac}$ = energy value in the wood excluding energy in char (Shaisundaram et al., 2021).
$m_{w,\ i}$ = mass of water initially in cooking vessel, gm
$m_{char}$ = mass of charcoal (gm).
$C_{pw}$ = specific heat of water (4.186 kJ/kg $^{o}$C).
$m_{w,\ evap}$ = mass of water evaporated, gm
$f\ _{cd}\ (W_{dry})$ = mass of equivalent dry fuel consumed, gm.
$T_e$ = temperature of boiling water, $^{o}$C
$T_i$ = initial temperature of water in pot, $^{o}$C
MC = Moisture content of a fuel percentage (Wet fuel – dry fuel)/100.
L = latent heat of evaporation at 100 °C and 105 Pa, 2260 kJ/kg (PCIA & Global Alliance 2013),
$LHV_f$ = Lower heating value (net calorific value) of the fuel, MJ/kg) see Table 2.
$LHV_{char}$ = Lower heating value of charcoal, 28 MJ/kg (Berrueta et al. 2008) (Abasiryu et al. 2015).

Using the moisture content on the dry basis and higher heating value (HHV) of those feed stocks from literature, the lower heating value can be calculated for thermal efficiency as well as overall efficiency calculation (Parikh et al. 2005) (Gebreegziabher et al. 2013). Three samples were used for each of the three feed stocks in a moisture content test, as shown in Fig 12. As a result, the average moisture content value of those samples was used to calculate the LHV. According to this, the average moisture content, percentage of each feed stock was less than 9 %, as indicated in Table 1, which is more suitable for any gasification process.

In order to calculate the moisture content on dry basis the following formula is used (Simpson 1997) (PCIA & Global Alliance 2013).

$$M_{cdb} = \left(\frac{W_{wet} - W_{dry}}{W_{dry}}\right){*}100 \tag{5}$$

where:

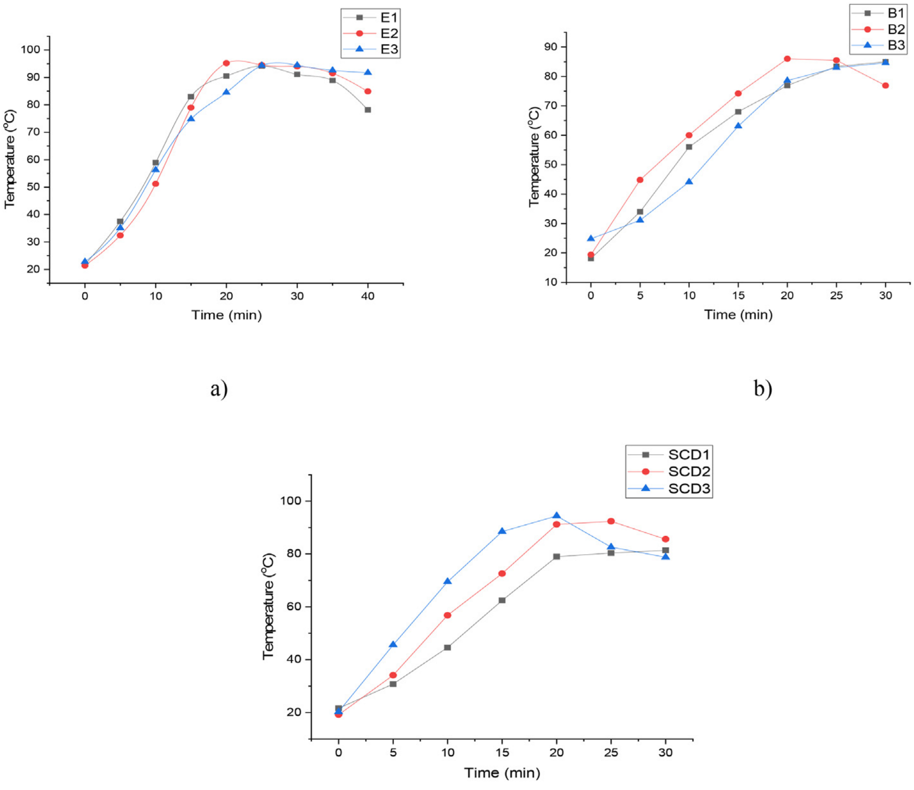
$M_{cdb}$ = Moisture content on dry Basis.
$W_{wet}$ = Wet weight (Initial Weight), gm.
$W_{dry}$ = Dry weight (Oven dry), gm.

**Table 2.** Higher and lower heating values of feed stocks.

| Feed Stocks | | Fuel Ratio | Higher Heating Value (HHV) MJ/kg | | Mcdb Moisture contents on dry basis (%) | Mcwb Moisture contents on wet basis (%) | Lower Heating Value (LHV)$^4$ MJ/kg |
|---|---|---|---|---|---|---|---|
| Eucalyptus | | 1 | 18.640 | | 8.51 | 7.84 | 15.772 |
| Bamboo | | 1 | 17.657 | | 9.59 | 8.75 | 14.698 |
| MSCD | Dung | 0.277 | 17.16 | 18.13 | 8.23 | 7.60 | 15.349 |
| | Eucalyptus Saw dust | 0.723 | 18.50 | | | | |

a) b)

**Figure 12.** (a) Furnace for drying the samples (b) Three samples (bamboo, eucalyptus and MSCD).



a) b)

c)

**Figure 13.** Temperature profile of water boiling test (a) using eucalyptus as a feed stock (b) using bamboo as a feed stock (c) using mixture of sawdust and cow dung.

And, the moisture content on the wet basis can calculated using the ratio of moisture with the initial weight. It can also be derived from moisture content on dry basis, and it can be calculated as follow (PCIA & Global Alliance 2013).

$$M_{cwb} = \left(\frac{W_{wet} - W_{dry}}{W_{wet}}\right)*100 = \left(\frac{M_{cdb}}{1 + M_{cdb}}\right)*100 \tag{6}$$

where.

$M_{cwb}$ = Moisture content on wet basis.
$M_{cdb}$ = Moisture content on dry basis out of 100%

The net heating values of wood

$$LHV_f = 18,648 - 210*Mcdb \tag{7}$$

$LHV_f$ = is the lower heating value of moist wood (kJ/kg) and $M_{cdb}$ = is the moisture content of wood on dried basis (wt. %) (Gebreegziabher et al. 2013) or (Gebreegziabher et al. 2013), using Eq. (5)

$$LHV_f = (1 - Mcwb)*\left[HHV - L_{T25}*(Mcdb + 9H)\right] \tag{8}$$

$LHV_f$ = Lower Heating Value of the fuel (MJ/kg).

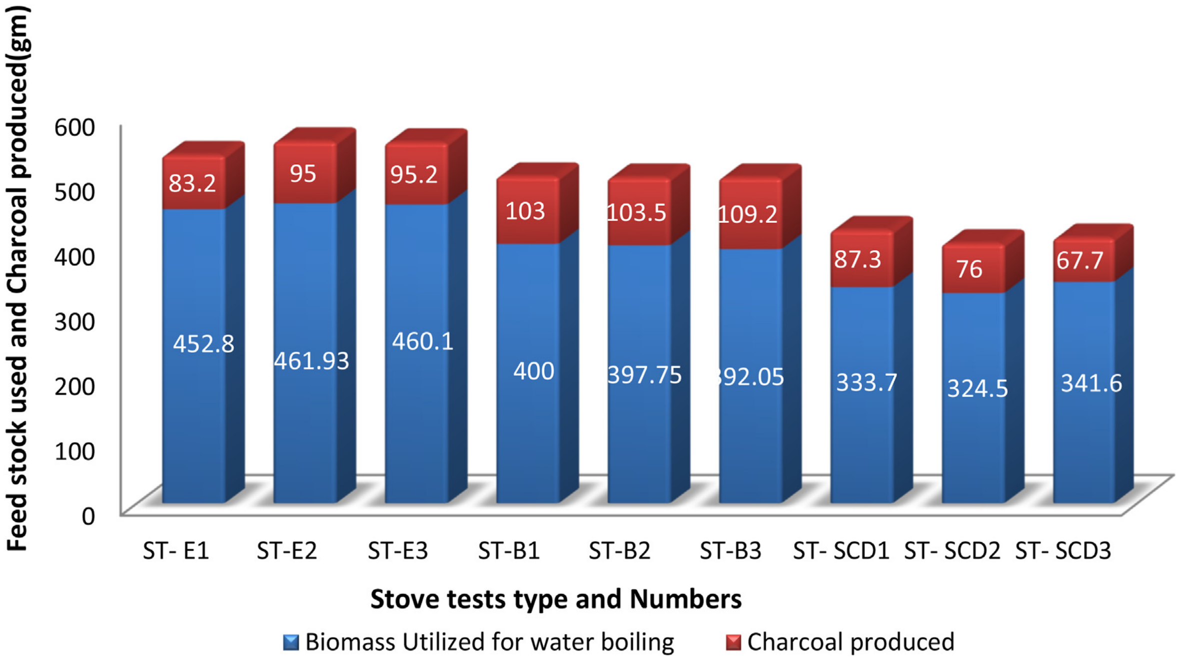


**Figure 14.** Feed stocks utilized for water boiling and charcoals production.

H = gravimetric fraction of hydrogen in the fuel ($^{1}$6 % typical value for wood) (PCIA & Global Alliance 2013).

L $_{T25}$ = Latent heat of water at constant pressure and 25 °C (= 2.44 MJ/kg) or.

LHV – Lower Heating Value is reduced (also called net heating value). This is the theoretical maximum amount of energy that can be recovered from the burning of a moisture-free fuel if the combustion products are cooled to room temperature, but the water generated by the reaction of the fuel-bound hydrogen stays in the gas phase. LHV differs from HHV by 1.32 MJ/kg in the case of wood fuels (PCIA & Global Alliance 2013).

$$\% \; Yield \; of \; Charcoal = \frac{W_{char}}{W_{feedstock}} \tag{9}$$

$$Sfc = \frac{f_{cd}}{P_{ci} - P_{cf}} \tag{10}$$

where;

W $_{char}$ = Total Weight of Charcoal.
W $_{feedstoc}$k = Total weight of feed stock.
$S_{fc}$ = Specific fuel consumption.
$P_{ci}$ = weight of Pot with water before test (grams).
$P_{cf}$ = weight of pot with water after test (grams).
$f_{cd}$ = equivalent dry wood consumed (grams).

## 4. Results and discussion

The first consideration in the construction of this gasifier stove is to optimize the high of the stove to ensure that the flame high from the feed stock to the pot would burn in such a way that heat loss to the external environment is minimal. The second one is, the secondary air, which runs from the bottom of the outer cylinder to the top of the inner cylinder to combust the volatile gas that comes due to the gasification process inside the inner cylinder, will be heated up before combustion by the heat emitted by the inner cylinder owing to the gasification process. And, the last one is the inner hollow cylinder that have a perforated wall (with maximum diameter as it goes from the bottom to the top) and floor are the design consideration that improves the stove's performance.

### 4.1. Lower heating value of the feedstocks

The MC of the three feed stocks is shown in Table 1 below, with a moisture content of 7–9% on average, for the wet basis and dry basis using Equation (6) and Equation (5) respectively.

We can simply compute the LHV of those feed stocks using Eq. (7) or using all of the moisture content values from Table 1 and value of HHV from literature (Parikh et al. 2005) (Kumar and Chandrashekar 2014) (Rusch et al., 2021) (Szymajda and Łaska 2019) (Szymajda et al. 2021), using Eq. (8) as shown in Table 2.

### 4.2. Temperature profile

The entire time taken for those three tests was determined by the flame characteristics of the gasification process; for example, a 40-minute flame stayed in the first test with eucalyptus, the other tests with bamboo and MSCD (Mixture of Sawdust and Cow Dung) waited only 30 min with flame.

The quantity of eucalyptus, bamboo, and a combination of saw dust and cow dung feed stock utilized ranged from 536 - 558 gm, 409–501.25 gm, and 400–425 gm (eucalyptus sawdust to cow dung ratio was 72.27%–27.73%), respectively. The maximum temperature for eucalyptus was 94.2 °C–94.4 °C, which lasted 15 min, 84 °C–86 °C for bamboo, and 88.5 °C–94.4 °C for saw dust and cow dung, which lasted just 5 min.

### 4.3. Utilized feedstock, charcoal produced and amount of water evaporated

When using ecaluptus as a feed stock, the gasification process is started by closing the primary air inlet gate, resulting in a complete pyrolysis reaction that is extinguished when the feed stock has been completely converted to charcoal. Whereas other feed stocks are started by half-opening the primary air inlet gate. In addition, unlike the other two feed stocks, eucalyptus feed stock did not result in intermittent fires. The quantity of wet feed stock used for water boiling is displayed on Fig 14; it was calculated by subtracting the charcoal generated from the total feed stock used, and it is presented at the bottom of the stacked column below the charcoal figure. One thing to note is that bamboo charcoal output was higher than the other feed stocks.

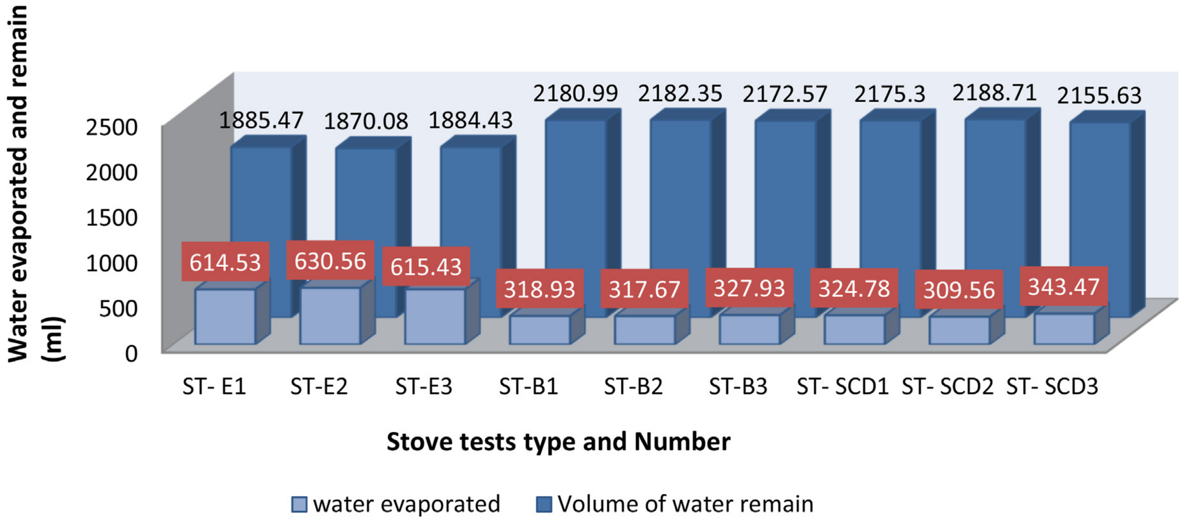


**Figure 15.** Water evaporated from and remains in the pot.

**Table 3.** Parameter for thermal calculation and thermal efficiency of the stove.

| S.N | Parameters | Units | Eucalyptus | | | Bamboo | | | Mixture of Sawdust & Cow Dung | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ST-E1 | ST-E2 | ST-E3 | ST-B1 | ST-B2 | ST-B3 | ST-SCD1 | ST-SCD2 | ST-SCD3 |
| 1 | Initial Temp of water | $^{0}$C | 21.8 | 21.7 | 22.8 | 19.3 | 19.4 | 24.8 | 21.6 | 19.2 | 20.3 |
| 2 | Final Temp of water | $^{0}$C | 94.2 | 94.4 | 94.4 | 85 | 86 | 84.6 | 92.4 | 91.2 | 94.4 |
| 3 | Biomass used for water boiling | gm | 452.8 | 461.9 | 460.1 | 400 | 407.8 | 392.1 | 333.7 | 324.5 | 341.6 |
| 4 | Initial volume of water | gm | 2500 | 2500.1 | 2499.9 | 2499.9 | 2500.5 | 2500.5 | 2500.5 | 2498.3 | 2499.1 |
| 5 | Moisture content | % | 7.84 | 7.84 | 7.84 | 8.74 | 8.74 | 8.74 | 7.60 | 7.60 | 7.60 |
| 6 | Equivalent dry fuel burned | gm | 417.3 | 425.7 | 424.0 | 365.0 | 372.1 | 357.8 | 308.3 | 299.8 | 315.6 |
| 7 | Water vaporized | gm | 614.5 | 630.6 | 615.4 | 318.9 | 317.7 | 327.9 | 324.8 | 309.6 | 343.5 |
| 8 | Specific heat of water | kJ/kg$^{0}$C | 4.186 | 4.186 | 4.186 | 4.186 | 4.186 | 4.186 | 4.186 | 4.186 | 4.186 |
| 9 | Latent heat of evaporation of water | kJ/kg | 2260 | 2260 | 2260 | 2260 | 2260 | 2260 | 2260 | 2260 | 2260 |
| 10 | Lower heating value | kJ/kg | 15772 | 15772 | 15772 | 14696 | 14696 | 14696 | 15349 | 15349 | 15349 |
| 11 | Thermal Efficiency* | % | 32.61 | 32.56 | 32.00 | 26.25 | 26. 52 | 26.00 | 31.17 | 31.56 | 32.02 |

* Thermal Efficiency is calculated using Equation (1)

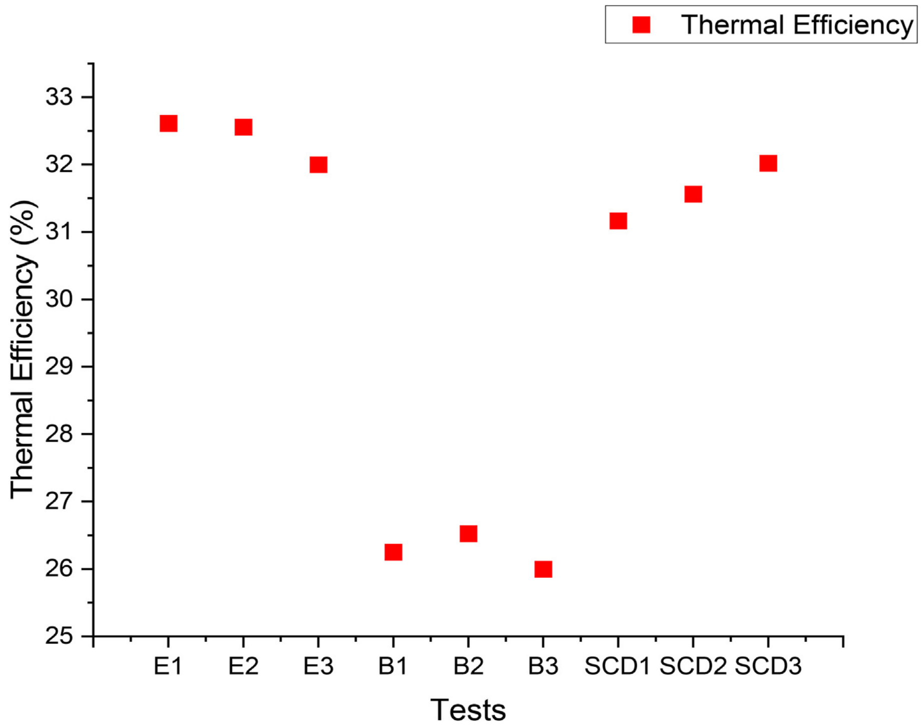


**Figure 16.** Thermal efficiency of the gasifier stove using different feed stocks.

**Table 4.** Percentage Yield of Charcoals and Specific fuel Consumption.

| S. N | Parameters | Units | ST-E1 | ST-E2 | ST-E3 | ST-B1 | ST-B2 | ST-B3 | ST-SCD1 | ST-SCD2 | ST-SCD3 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Initial weight of feed stocks | gm | 536.0 | 556.9 | 555.3 | 498.0 | 501.3 | 501.2 | 421.0 | 400.5 | 409.3 |
| 2 | Final weight of feed stocks | gm | 83.2 | 95.0 | 95.2 | 103.0 | 103.5 | 109.2 | 87.3 | 76.0 | 67.7 |
| 3 | Percentage yield of charcoal* | % | 15.52 | 17.6 | 17.14 | 20.68 | 18.65 | 21.79 | 20.74 | 18.98 | 16.54 |
| 4 | Specific fuel consumption** |  | 0.469 | 0.431 | 0.444 | 0.647 | 0.717 | 0.579 | 0.537 | 0.591 | 0.614 |

* Percentage yield of charcoal using Eq. (9).

** Using Equation (10)

During the test, the quantity of water evaporated using bamboo waste and MSCD briquette was almost same, but it was much less than the amount of water evaporated using eucalyptus feedstock, as indicated at the bottom front side of Fig 15 's column diagram. The largest amount of water evaporated during this experiment was 630.56 gm and the lowest amount was 309.56 gm out of a total of 2500 gm using eucalyptus slice log and bamboo residues as feed stocks.

### 4.4. Thermal efficiency

For the thermal efficiency using Eq. (1), after gasification, the ultimate by product (charcoal) in the gasifier was not considered as it is illustrated on Table 3, i.e., the energy in the charcoal, but this must be considered in order to determine the overall thermal efficiency. Eq. (2) will be used to compute the exact value of the gasifier over all conversion efficiency. The thermal efficiency of the stove is ranges from 26% to 33% as it shown in Fig 16.

### 4.5. Overall thermal efficiency

In contrast to thermal efficiency, the quantity of energy in the end product of the feed stocks (charcoal) is taken into account in the total overall thermal efficiency calculation. Only, overall thermal efficiency of the eucalyptus gasifier stock was included in our calculations.

Based on the lower heating value of eucalyptus charcoal, the overall thermal efficiency of the gasifier stove can be calculated using Eq. (2). Using the amount of charcoal produced by eucalyptus feed stocks from Table 4 and higher heating value of eucalyptus charcoal 28 MJ/kg (Berrueta et al. 2008), (Abasiryu et al. 2015) and finally by making all other value similar to the one that was used for thermal efficiency of the stove using eucalyptus feed stokes in Eq. (2), we obtained the values which is described on Fig 17.

### 4.6. Charcoal production versus thermal efficiency

The percentage yield of charcoal was determined using the weight of the charcoal produced during gasification divided by the weight of the original feed stock, see Eq. (9). And, the specific fuel consumption is calculated using Eq. (10), which is the ratio of dry fuel calculated having Eq. (3) and quantity of evaporated water as shown it is in Fig 15, all the results are explicitly shown in Table 4.

The charcoal generated by the gasifier stove is shown in Fig 18. To get a good amount of charcoal, we need to get the charcoal out of the gasifier stove as soon as the flames goes down and put it inside the closing cane. Otherwise, the charcoal will burn and react with the oxygen in the air, resulting in the formation of ash.

The percentage yield of bamboo tree charcoal was higher than that of eucalyptus and MSCD briquettes, as shown in Fig 19, but the thermal efficiency of the gasifier stove was lower with this feed stock, which can be compensated on the overall thermal efficiency while using this bamboo charcoal on other charcoal stoves.

When the relationship between the percentage yield of charcoal and thermal efficiency is linearized, it can be expressed with the linear equation Y = - 0.7956X+ 22.766 and the radius of curvature $R^2 = 0.92$, indicating that the linear equation and the real graph are extremely close, as shown in Fig 20. In other words, depending on thermal efficiency, this

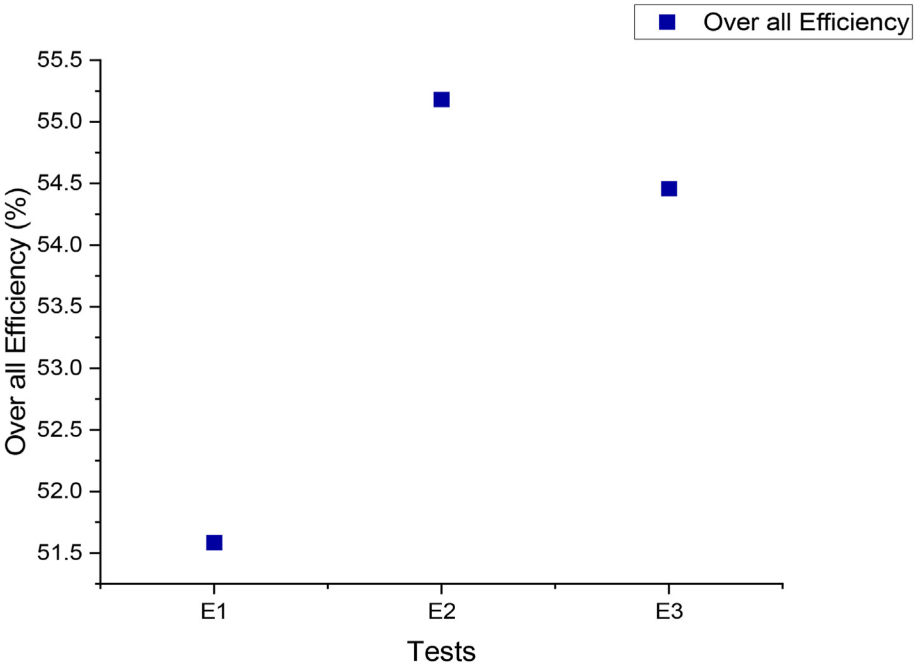


**Figure 17.** Overall thermal efficiency of the gasifier when eucalyptus is used.

**Figure 18.** Charcoal produced using the gasifier stove after gasification process.

linear equation may be used to calculate the percentage of charcoal yields.

The main benefit of this association is that feed stocks with low thermal efficiency and a high percentage of charcoal production can be applied in charcoal burners for further energy use. While the total overall efficiency is determined, this will compensate for the decreases in their thermal efficiency.

### *4.7. Comparisons with other stoves*

This gasifier stove was compared to two other gasifier stoves to see how they differed in terms of overall efficiency, as well as one other charcoal cook stove to compare thermal efficiency. When comparing the overall efficiency of those three stoves, the formula utilized is comparable. In comparison to the Novel Biomass stove by (Shaisundaram et al., 2021), Improved cook stove (ICS) by (Mohammadreza Rasoulkhani and Mohammad Hossein Abbaspour-Fard 2018) and metal charcoal stove by (Abasiryu et al. 2015), the over efficiency as well as the thermal efficiency of this Top-lit up draft, Natural Draft gasifier has a surprising result, as shown in Table 5. The reason for this was a proper removal of the charcoal at the end of the gasification process in addition of the optimal design of the stove. As the flame was switched off, the charcoal was collected from the gasifier, and the process of air starvation was correctly carried out, ensuring that the ash was not production.

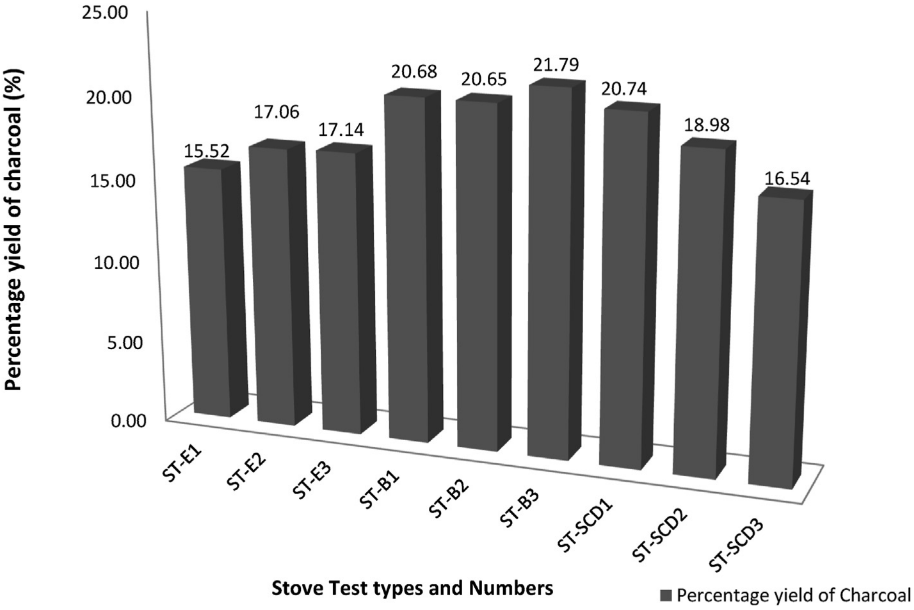


**Figure 19.** Percentage yield of charcoal.

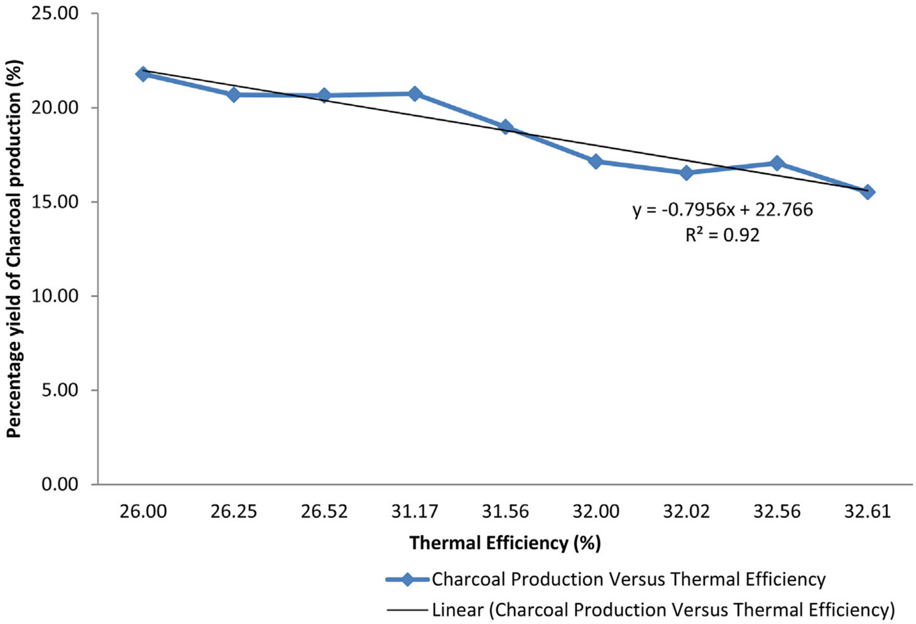


**Figure 20.** Percentage yield of charcoal versus thermal efficiency.

**Table 5.** Comparison of the research parameter with other research.

| S.N | Parameters | Units | Own Research | (Shaisundaram et al., 2021) | (Mohammadreza Rasoulkhani and Mohammad Hossein Abbaspour-Fard 2018) | (Abasiryu et al. 2015) |
|---|---|---|---|---|---|---|
| | | | Gasifier Stove Natural Draft | Novel Biomass Stove | ICS (Improved Cook Stove), Natural Draft | Metal charcoal stove |
| 1 | Initial Temp of water | $^0$C | 21.7 | 25 | 23 | 27 |
| 2 | Final Temp of water | $^0$C | 94.4 | 99 | 96.6 | 99 |
| 3 | Biomass used for water boiling | gm | 461.9 | 500 | 350 | 600 |
| 4 | Moisture Content | % | 7.84 | 15 | 5 | - |
| 5 | Equivalent dry fuel burned | gm | 425.7 | 425 | 332. 5 | - |
| 6 | Initial volume of water | ml | 2500.1 | 1300 | 3000 | 2000 |
| 7 | Water vaporized | ml | 630.6 | 1300 | - | 100 |
| 8 | Specific heat of water | kJ/kg$^0$C | 4.186 | 4.186 | 4.186 | 4.186 |
| 9 | Latent heat of evaporation of water | kJ/kg | 2260 | 2260 | 2260 | 2260 |
| 10 | Lower heating value | kJ/kg | 15772 | 20,000 | 17540 | 27600 |
| 11 | Amount of char remaining | gm | 95 | 200 | - | - |
| 12 | Lower heating value of charcoal | kJ/kg | 28,000 | 30,000 | - | - |
| 13 | Over all Efficiency | % | 55.18 | 38.6 | 34.6 | 20.02 |

*Over all Efficiency is calculated using Equation (2)

The charcoal generated throughout the procedure, particularly the eucalyptus charcoal, was comparable to charcoal available on the local market. This will allow us to use that high-calorie carbonized wood in other charcoal stoves, maximizing the efficiency of the process.

The dimensions of those gasifier stoves are comparable; for example, the Novel biomass and Improve cook stoves stand 30 cm tall and have a diameter of 20–25 cm, while the Gasifier Stove Natural Draft stands 36 cm tall and has a diameter of 19 cm. The only reason for the increase in overall and thermal efficiency is the design of this stove, which includes an additional secondary cylinder that directs secondary air from the bottom of the stove to the top, allowing time for the secondary air to heat up before reaching the top point of combustion, and a second reason is the interior hallow cylinder, which we don't see in the other two gasifier stoves.

The gasifier cylinder's interior hollow cylinder will allow primary air to be distributed to each point section. Also, once the gasification process has begun, the gas produced at each section of the gasifier cylinder has the opportunity to easily move up for combustion.

## 5. Conclusion

This gasifier stove had two advantages: it could be used as a good-performing cooking stove by capturing the energy released during the carbonization process, and it could also be used as a carbonizing machine, converting the feedstock into appropriated charcoal that could be used directly or converted into briquettes using a pressing machine. This also eliminates the unburden gas emitted during the carbonization process, helping to maintain a stable climate.

Eucalyptus feed stocks were shown to be a more suitable feedstock in the investigation. Thus, it burnt for around 40–45 min with a gentle, non-stop flame. This was not the only reason; the thermal efficiency of these feed stocks was greater 32.30 ± 0.30%, and the amount of smoke produced was virtually non-existent when compared to the other two feed stocks. The greatest temperature reached with this feed stock was 94.4 °C. The percentage production of charcoal of this gasifier stove is indirectly connected to the thermal efficiency, $Y = -0.7956X + 22.766$, which is a more convenient correlation ship for those who use a charcoal stove parallel with this stove, based on data received from nine stove tests. Considering the lower heating value of charcoal, the total overall thermal efficiency was 53 ± 2%.

In comparison to other contemporary gasifier technologies, the overall efficiency of this gasifier is amazing, and when compared to the development of cooking stoves in Ethiopia, the performance of this gasifier is among the best. Finally, heat losses on the stove bodies are significant, i.e., around 70% of the energy contained in the feed stock was wasted on the stove and pot, with the remaining energy recovered as charcoal. Only 29 ± 3% of the energy in the feed stock transfer for boiling of water excluding the energy content in the char. This is evident because a significant quantity of energy was lost as heat through various heat transfer mechanisms. As a consequence, significant heat was generated on the surface of the gasifier stove, indicating that the stove requires a strong body insulating material to improve its performance.

## Delcaration

### *Author contribution statement*

Arkbom Hailu: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed, materials, analysis tools or data; Wrote the paper.

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### *Data availability statement*

Data included in article/supplementary material/referenced in article.

### *Declaration of interest statement*

The authors declare no conflict of interest.

### *Additional information*

No additional information is available for this paper.

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