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# Design, development, and performance evaluation of husk biomass cook stove at high altitude condition

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ABSTRACT

In many of the developing countries including Sub-Saharan Africa, most of the improved cook stoves were designed by considering only wood fuel, and as such are not suitable for using husk type biomass available aplenty such as coffee husk, rice husk, saw dust, etc., which get generated sustainably. While some stove eversions have been reported for using briquettes and pelletized biomass employing husks, others such as gasifier stove versions have been reported which mostly are suitable for only batch feeding of husk type biomass. A continuous feed type husk biomass cook stove has been developed and thoroughly evaluated in this study for clean burning at high altitude condition in Ethiopia. The water boiling test (WBT) and emission tests were conducted for a detailed stove performance evaluation. The experimental testing was carried out using two pots with different sizes both for coffee husk and rice husk biomass employing water boiling test version 4.2.3 protocols. The WBT experimental results indicate that for a 3.5 l pot, the average thermal efficiency and time to boil water are 29% and 7.7 min for coffee husk where as 28% and 8.4 min for rice husk, respectively, during the hot start phase. The maximum CO emissions of the stove measured are 262 ppm and 235 ppm using coffee husk and rice husk biomass, respectively, during the simmer phase. The international workshop agreement (IWA) norms applied to classify the performance of the stove, and the result indicated that the average indoor CO emissions were 0.186 g/min and 0.274 g/min using rice husk and coffee husk biomass, respectively. The average specific fuel consumption for this stove was 98 g/lit, which is better than the improved biomass cook stove, in which specific fuel consumption was 115 g/lit. The total selling price of the husk biomass cook stove developed amounts to 6.72 USD.

## 1. Introduction

According to a World Health Organization (WHO) report, around 3 billion people cook over open flames using biomass such as wood, animal dung, agricultural residue, and coal. More than 4 million people die prematurely from household air pollution caused by solid biomass fuel cooking [1]. It is vital to offer clean energy and hygienic cooking in this situation. Because of the world's high energy demand, the price of fossil fuels (oil and natural gas) has been steadily rising, and the energy crisis has been steadily worsening [2]. On the other hand, there is an increase in demand globally for environmentally friendly and cheap energy. Biomass is one of the choices among these kinds of energy resources since it is abundantly available, inexpensive, renewable, and environmentally friendly [3]. Developing countries must meet their energy demands. Residues derived from agricultural waste and woody elements will commonly be used as energy fuel [4]. Ethiopia is the primary center of origin and genetic diversity for Arabica coffee [5]. In Ethiopia, coffee processing industries generate enormous amounts of coffee husk and pulp annually. Nevertheless, these materials have been poorly utilized and managed or burned in open fields [6]. According to the Ethiopian Coffee and Tea Authority, the Jimma and Sidama regions contribute more than 60% of Ethiopia's coffee, with the rest coming from Wollega, Yirgacheffe, and Harar [7]. Rice is the world's second most widely planted agricultural crop as a primary food [8]. It is considered one source of renewable energy generated from the residue of rice. The area of rice production in Ethiopia's uplands is about 30 million hectares. A total of 5.6 million hectares are more suitable, 25 million hectares are suitable, and the irrigated area is 3.7 million hectares [9] in the south-western highlands of Ethiopia. According to the Jimma zone

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**Nomenclature**

| | |
|---|---|
| ASTM | American society for testing and materials |
| A/F | Air to fuel ratio |
| CO | Carbon monoxide |
| Cp | Specific heat of water = 4.186 KJ/Kg °C |
| CV | Calorific value |
| Δc | Net change in char during test phase |
| $F_C$ | Fixed cost |
| FC | Fixed carbon |
| $f_d$ | Equivalent dry biomass fuel consumed |
| fm | Moist biomass fuel consumed |
| FP | Firepower) |
| GSE | Geological Survey of Ethiopia |
| g/lit | Grams per liter |
| IAP | Indoor Air Pollution |
| IWA | International workshop agreement |
| Kg/hr | Kilogram per hour |
| kW | Kilowatt |
| L | Liter |
| Ppm | Parts per million |
| $r_b$ | Burning rate |
| Pf | Weight of pot with water after test |
| $P_i$ | Weight of pot with water before test |
| P | Weight of empty Pot |
| ppm | Parts per million |
| SFC | Specific biomass fuel consumption |
| Tb | Local boiling point of water (°C) |
| $T_i$ | Water temperature before test (°C) |
| $T_f$ | Water temperature after test (°C) |
| ti | Initial test time (min) |
| tf | Final test time (min) |
| Δt | Change of the time |
| USD | United States Dollar |
| VC | Variable cost |
| VM | Volatile matter |
| WBT | Water Boiling Test |
| WHO | World Health Organization |
| $W_i$ | Initial weight of the biomass sample |
| $W_f$ | Weight of biomass after oven-dry |
| $W_c$ | Weight of the empty container |
| $W_v$ | Amount of water vaporized |
| $\eta_{th}$ | Thermal efficiency |
| LHV | Lower heating value |
| MC | Moisture content |
| min | Minute |

**Fig. 1.** Biomass burning in the fields of Southwestern Ethiopia.

agricultural development office, the Gera, Gomma, Shabe Sombo, Limmu-Kossa, and Limmu-Seka districts of the Jimma zone are the major rice-growing areas, covering 2018 hectares with 49,736 'quintals' of rice production. The Chewaka district of the Buno-Bedelle zone is also well known for rice production [10]. Coffee husks are the most common solid waste from the handling and processing of coffee, with approximately 1 kg of husk produced for every 2 kg of coffee beans [11]. About 20,000 t of coffee husks are left on the field in Ethiopia as waste material. Fig. 1 shows the indication of burning of biomass in the fields of Southwestern Ethiopia [12].

### *1.1. Review of previous studies related to the topic*

According to **Mehetre et al.** [13], the enhanced biomass cookstoves saved 35–50% on fuel compared to conventional stoves, lowering household expenses. As a result, each family may save 300 kg of fuel each year and cook in a healthier environment. **Raktimjyoti et al.** [14] evaluated the improved biomass stove by considering the water boiling test, and the results indicate that the thermal efficiency for boiling 5 L of water was 25%. **Soni et al.** [15] state that one of the candidates for solid fuel is coffee husk pellets. They are a byproduct produced from coffee production waste. They studied hole system design for coffee husk stoves and evaluated the stove by considering the Water boiling test and emission test. The experiment results indicate that the maximum thermal efficiency and CO emissions were 16.47% and 298 ppm, respectively. **Ayantu et al.** [16] have worked on an experimental analysis of a cook stove for the efficient utilization of biomass energy in Ethiopia. The average thermal efficiency and time to boil 5 L of water for the stove were 27% and 36 min, respectively. **Julius et al.** [17] developed the energy-efficient rice husk-fired cook stove for space heating, water boiling, and cooking purposes. The results indicate that the temperature inside the combustion chamber of the stove was 556.6 °C, and the time is taken to combust 1 kg of rice husk was 30 min.

**Alexis et al.** [18] designed a household-size continuous flow rice husk gasifier stove to provide rural families with an alternative device for cooking. The stove, basically, has a 12-cm diameter by 30-cm high fuel reactor where rice husks are burned and subsequently converted into combustible gasses. A plate-type gas burner with 40 pieces 4-mm diameter holes sets the gas into flame, which is eventually used for cooking. The air needed for gasification was supplied by a 12-volt, 0.12-A DC fan. The stove operates following the principle of a moving-bed down-draft reactor, in which rice husks are fed at its top end, and the char is discharged from the bottom end. The results indicated that one liter of water at 27 °C can be boiled on the stove within 5.0 to 7.6 min, and two liters of water can be boiled within 10.4 – 15.2 min. The amount of rice husks used to fuel the stove varies from 1.07 to 1.12 kg per hour, with computed specific gasification rates of 90 – 102 kg/hr-m$^2$. The average thermal efficiency of the stove was 18 – 25% by using a water boiling test.

**Pitamber et al.** [19] modified and evaluated the updraft domestic gasifier stove (Belonio type) first for rice husk and then for different feedstocks. For the analysis, 50% rice husk, 50% biomass pellet, and 50% wood chips were used as feedstock. The stove was evaluated by parameters like fuel consumption rate, water boiling test, gasification efficiency, flame temperature, and temperature along the axis of the gasifier with a regular time interval. The result indicates that the water boiling test thermal efficiency was 27.93% for wood chip mix, 27.89% for pellet mix, and 26.97% for rice husk. In the case of pellet mix and wood chips, the fuel consumption rate was 1.71 kg/hr, whereas, for rice husk, it was 1.2 kg/hr.

**Simone et al.** [20] designed and developed a rice husk-fueled cook stove for household cooking in a typical sub-Saharan setting. They conducted the experiment by using a water boiling test and a controlled cooking test. The result indicated that the thermal efficiency from WBT was 18%. In contrast, the CCT (specific consumption of 4.2 MJ per kg of cooked food) indicates how the improved cook stove represents a viable alternative to three-stone fires and other rudimentary cooking systems, allowing the recovery of energy from waste biomass.

**Hafid et al.** [21] conducted the experimental performance study of the biomass cook stove with terrified rice husk as fuel using the water boiling test method. The pre-treatment of biomass via torrefaction was undertaken to increase the calorific value of the fuel so that it could increase the thermal efficiency of the gasification cook stove. The study was also conducted to obtain the optimum conditions for air flow rate, the height of the bed, and torrefied rice husk. The experiment was done by inserting rice husk torrefied as fuel with a variation of the height of the bed of 42.6 cm, 31.5 cm, and 21.3 cm, the secondary air flow rate openings (fully open, partial, and close), and the type of fuel used was the rice husk terrified at a temperature of 250 °C for 60 min (fuel A) and 300 °C for 30 min (fuel B). The result showed that the optimum operating conditions were found at 21.3 cm of bed height, with a full closed secondary air opening and type A fuel. While, type A fuel with a bed height of 31.5 cm and a secondary air opening fully closed had the highest efficiency value of 18.75%.

**Riaz Ahmad et al.** [22] conducted a comparative evaluation of the improved commercial coal-fired stoves in China. Seven different model stoves were selected and their performance was evaluated when burning raw coal and coal briquettes during the high and low power stages, respectively. It was discovered that Model 2-TL had the highest average thermal efficiency, 87.2 ± 0.5%, when burning coal briquettes at high and low power.

### *1.2. The research gap and importance of the husk biomass stove design*

The literature review indicates that only few detailed performance studies have been reported on continuous feed type direct husk biomass stoves and none in high altitude condition. Generally compared with different article reviews, the husk biomass stove developed in this study was improved by changing the biomass fuel inlet hole design, air inlet positions and diameters, and angle of the biomass hopper design, which was different from other husk biomass stoves. In Ethiopia, there are different types of stoves like the traditional three-stone, Elsa, Lakech, Anilla, Mirt, Gounzie, Tikikil, and others. However, there is still a limit to these stoves such as stove efficiency, portability, continuous feed of biomass, low cost, and outdoor and indoor air pollution. Also, most of the improved stoves in the country were designed by considering only wood fuel, and are unsuitable for using agricultural residue biomass like coffee husk rice husk, etc. The purpose of this research study is to design, fabricate, and evaluate the performance of the cook stove coffee husk and rice husk biomass. Portability, continuous feed and local manufacturability are the associated features of this clean burning efficient cook stove.

## 2. Methods and materials

### *2.1. Research study areas*

The study area was located at 7.13 and 8.56 N and 35.49 and 38.38 E. average annual temperature (19.5 °C), local water boiling point (96 °C), 1780 m altitude above sea level, and the annual rainfall (1200 mm –2500 mm) [24]. According to [25], the altitude range conditions were classified as low altitude (1100–1400 masl), medium altitude (1400–1700 masl), and high altitude (1700–2200 masl).

### *2.2. Design consideration*

The design consideration of the husk biomass cook stove was based on its: lower fuel consumption, low cost, portability, **e**ase of operation, and **s**uitability for using locally available materials.

### *2.3. Descriptions of the stove*

The husk biomass cook stove was designed by considering household family-level stoves. The overall height and weight of the stove are 0.45 m and 7.75 kg, respectively. The cook stove was fabricated from a sheet metal thickness of 1.5 mm and round bars of 8 mm and 6 mm. Fig. 3 indicates the 2D drawing parts of the designed husk biomass stove with its components. Generally, the stove was made up of eight main components. The potholder, main drum, heat shield, main cone, legs, ash container, shatter, and inner cone (combustion chamber). The biomass fuel is placed on the main-cone hopper and inserted via the inner cone holes into the combustion chamber, as shown in Fig. 2.

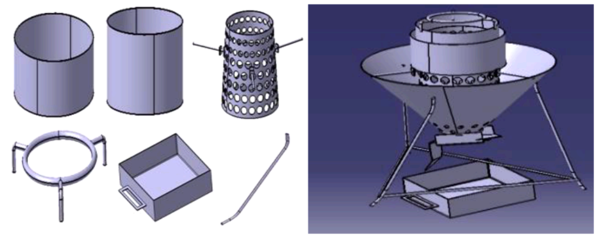

**Fig. 2.** The 3D model components of the stove.

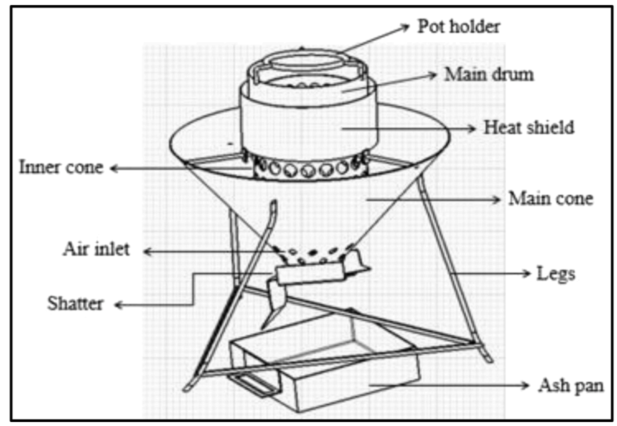


**Fig. 3.** The 2D detail components of the stove.

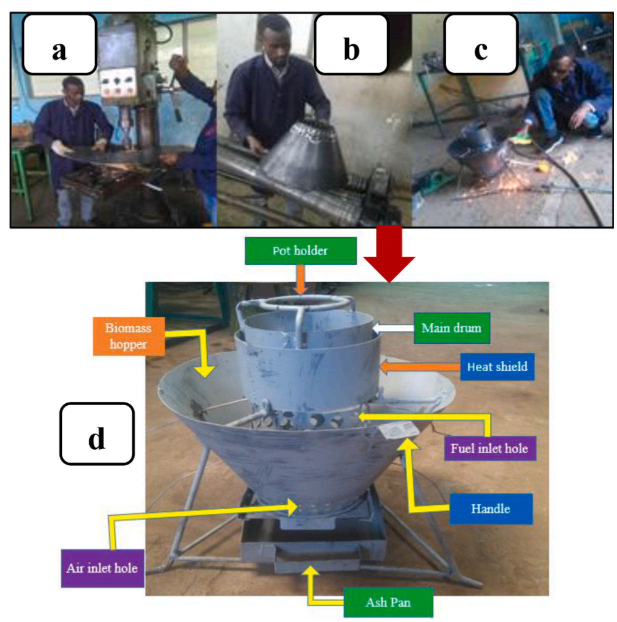


**Fig. 4.** The manufacturing process a) drilling, b) bending, c) welding, and d) full prototype of the husk biomass cook stove.

**Fig. 5.** Instruments used during data collection.

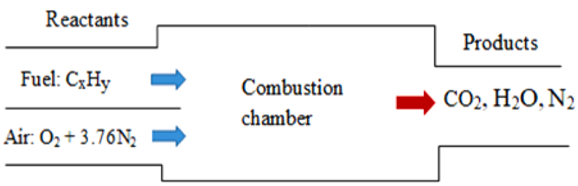


**Fig. 6.** Schematic diagram of the biomass combustion process for this study.

**Fig. 7.** Emission testing while the data was being collected.


**Fig. 8.** The WBT experiment set up for using rice husk and coffee husk biomass.

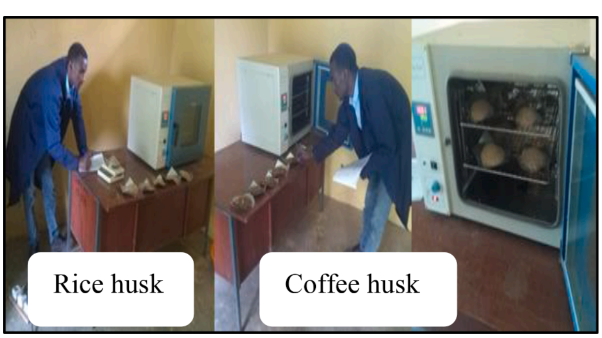


**Fig. 9.** MC of rice husk and coffee husk biomass using oven-dry.

*2.4. Prototype manufacturing process*

The husk biomass cook stove prototype was fabricated, as shown in Fig. 4. Simple processes such as sheet metal cutting, drilling, bending, and welding have been used to manufacture the prototype. Fig. 5, Fig. 6, Fig. 7, Fig. 8, Fig. 9, Fig. 10, Fig. 17, Fig. 18, Fig. 19, Fig. 21, Table 1, Table 2, Table 4, Table 5, Table 6, Table 7.


**Fig. 10.** Coffee and rice husk biomass samples for predicting the porosity and void ratio.

*2.5. Methods for evaluation of the stove*

The stove's performance was evaluated considering the water-boiling test (WBT) and emission test experiments. The collected data was analyzed by the standard water boiling test version 4.2.3 spreadsheet to determine the stove's performance.

*2.6. Instruments used during the experiment*

K-type Thermocouple, MY64-Multimeter, UT302D-Infrared thermometer, Mercury thermometer, Testo 310 Flue gas analyzer, Digital thermo hygrometer, DHG-9055A-Oven dry, Stopwatch, biomass sacks, Ash buckets, Pots or Dist and gloves for heat resistance.

*2.7. Study variables*

*2.7.1. Constant variables that were used*

ü Gross calorific values of biomass
ü Net calorific values of biomass
ü The effective calorific value of biomass
ü The net calorific value of char/ash
ü Dry mass of empty pot
ü The weight of an empty container for char

*2.7.2. Measured variables*

The main parameters that were measured and calculated are:

Ø Temperature
Ø The moisture content of the biomass
Ø Fuel consumed (moist).
Ø Burning rate
Ø The boiling point of water
Ø Weight of biomass (fuel)
Ø Turndown ratio
Ø Firepower
Ø Thermal efficiency

*2.8. Characterization of biomass*

*2.8.1. Proximate analysis of biomass*

The proximate analysis of coffee husk and rice husk biomass samples was tested at the Geological Survey of Ethiopia laboratory. The proximate analysis report is summarized in Table 3.

*2.8.2. The ultimate analysis of biomass*

The ultimate analysis of the used biomass was considered according

**Table 1**
A brief review of different kinds of literature related to husk biomass cook stove.

| Authors | Title | Methods and fuels used | Task performed and their findings |
|---|---|---|---|
| Hafid Alwan, Anton Irawan, Santika, Erlin Nurindah (2020) | Performance test of biomass cook stove with torrefied rice husk as fuel using water boiling test method | ü Water boiling test<br>ü Rice husk biomass | ü The maximum thermal efficiency of the stove was 18.75%. |
| Soni Sisbudi Harsono, Prayogo,Tasliman, Maizirwan Mel and Fabrobi Ridha (2018) | Effect of holes system designing for low energy stove using coffee husk bio pellet as a solid fuel | ü WBT and Emission test<br>ü Coffee husk biomass | ü The thermal efficiency between heat for evaporating water and heat produced by bio-briquette was compared.<br>ü WBT results at different stove holes were analyzed.<br>ü The thermal efficiency for (10, 20, and 40) holes was 16.39%, 15.96%, and 15.38%, respectively. |
| Adcp, Fan-beam Plueddemann, A J Terray, E A Merewether,R (2013) | Design and performance of a household-size continuous-flow rice husk gas stove | ü Water boiling test<br>ü Rice husk biomass | ü The average thermal efficiency of the stove was 18 to 25% using the water boiling test. |
| Paulo Medina, Jose Nunez, Victor M. Ruiz-Garcia and Alberto Beltran (2021) | Experimental and numerical comparison of CO2 mass flow rate emissions, combustion, and thermal performance for a biomass plancha-type cook stove | ü CFD simulation analysis<br>ü WBT and Emission test<br>ü Biomass fuels were used | ü The thermal efficiency of WBT and CFD simulation was compared.<br>ü Heat transfer and combustion processes were studied.<br>ü The numerical and experimental results ranged from 2 to 9% and 1–2% for CO2 mass flow rate and combustion efficiency, respectively. |
| Raktimjyoti Barpatragohain, Niyarjyoti Bharali, and Partha Pratim Dutta (2021) | Thermal performance evaluation of an improved biomass cook stove for domestic applications | ü Water boiling test and Emission test<br>ü Biomass fuels | ü Heat loss parameters were studied.<br>ü The thermal efficiency while boiling 5 liters of water was 25%.<br>ü During the start, CO was 20 ppm and then reduced to 5 ppm as combustion progressed. |
| Bhusal, Pitamber Ale, Bhakta Bahadur | Performance Evaluation of Domestic Rice | ü Water boiling test<br>ü Rice husk | ü The water boiling test thermal |

**Table 1** (*continued*)

| Authors | Title | Methods and fuels used | Task performed and their findings |
|---|---|---|---|
| Singh, Ramesh Man (2015) | Husk Gasifier Stove (Belonio Type) and Study on Modification of Design for using Different Biomass | ü Wood chips | efficiency was 27.93% for wood chip mix, 27.89% for pellet mix, and 26.97% for rice husk.<br>ü The fuel consumption rate was 1.71 kg/hr for the cases of pellet mix and wood chip mix, whereas, for rice husk, it was 1.2 kg/hr. |
| V.S. Shaisundaram, M.Chandrasekaran, V.Prabakar, L. Karikalan, S. Ramasubramanian (2021) | Design and experimental analysis of efficient biomass stove | ü Water boiling test only<br>ü Wood fuels were used | ü An efficient biomass stove was fabricated and tested for domestic use.<br>ü A 4 kW capacity biomass stove was designed using Catia software. |
| Ayantu Daniel, Yilma T. and Nasim Hasan (2017) | Experimental analysis of cook stove for efficient utilization of biomass energy in Ethiopia | ü CFD analytical simulation and WBT<br>ü Wood fuel was used | ü The effect of the stove geometry on its heat transfer efficiency was studied.<br>ü WBT and analytical results were done and compared.<br>ü The average thermal efficiency of the stove was 27%.<br>ü The time to boil 5 l of water was 36 min. |
| Debela Geneti, Dr. Ing. Getachew Shunki T. and Prof. Dr.A. Venkata Ramayya (2016) [23] | Product development through CFD simulation and experimental testing of a 200 Liter biomass-fired institutional cook stove | ü Water boiling test and CFD simulation<br>ü Wood fuel was used | ü The experimental result was done by using WBT Version 4.2.2.<br>ü Validation of CFD simulation was also done by comparing it with experimental results.<br>ü The stove SFC was 41.25 g/lit.<br>ü The cooking time for 200 liters of water was 129.5 min. |
| Parmigiani, Simone Pietro Vitali, Francesco Lezzi, Adriano Maria Vaccari, Mentore (2014) | Design and performance assessment of a rice husk-fueled stove for household cooking in a typical sub-Saharan setting | ü Water boiling test and Controlled cooking test<br>ü Rice husk biomass | ü From the water boiling test results, the average thermal efficiency was 18%.<br>ü From controlled cooking test results, the specific energy consumption was 4.2 MJ per |

(*continued on next page*)

**Table 1** (*continued*)

| Authors | Title | Methods and fuels used | Task performed and their findings |
|---|---|---|---|
| | | | kg of cooked food. |

**Table 2**
Dimension specification parts of the stove.

| Components | Dimensions |
|---|---|
| Main cone diameter (large to small) | (450 mm/180 mm) |
| Heat shield diameter | 200 mm |
| Heat shield height | 95 mm |
| Inner cone diameter (large to small) | (220 mm/150 mm) |
| Main drum diameter | 175 mm |
| Main drum height | 115 mm |
| Potholder diameter | 120 mm |
| Potholder height | 25 mm |
| Each Leg's height | 310 mm |
| Ash container (length × width × height) | (202 mm × 202 mm × 50 mm) |
| Shatter (length × width × height) | (90 × 90 × 20 mm |
| Air inlet hole diameter | 10 mm |
| Number of the air inlet hole | 54 |
| Biomass inlet hole diameter | 20 mm |
| Number of the biomass inlet hole | 113 |
| Overall height of the stove | 450 mm |
| The overall weight of the stove | 7.75 kg |

**Table 3**
Proximate analysis report of biomass at the Geological Survey of Ethiopia laboratory.

| Sample type | MC (%) | VM (%) | FC (%) | Ash (%) | S (%) | CV (Cal/gm) |
|---|---|---|---|---|---|---|
| Coffee husk | 13.65 | 71.75 | 19.71 | 4.35 | 0.10 | 4756.03 |
| Rice husk | 11.34 | 63.30 | 13.81 | 18.89 | 0.37 | 3987.17 |

**Table 4**
Ultimate analysis of Coffee husk and Rice husk biomass [2, 27].

| Sample type | Ultimate analysis (weight%, dry basis) | | | |
|---|---|---|---|---|
| | C | H | N | $O_2$ |
| Coffee husk | 43.39 | 6.37 | 1.41 | 45.08 |
| Rice husk | 35.36 | 6.1 | 0.21 | 44.68 |

**Table 5**
Oxygen required for element analysis and its products for coffee husk.

| Elements | Mass (per kg) | Oxygen required | Products |
|---|---|---|---|
| Carbon | 0.4339 | 1.1571 | 1.591 |
| Hydrogen | 0.0637 | 0.5096 | 0.5733 |
| Oxygen | 0.4508 | −0.4508 | _ |

**Table 6**
Oxygen required for element analysis and its products for rice husk.

| Elements | Mass (per kg) | Oxygen required | Products |
|---|---|---|---|
| Carbon | 0.3536 | 0.9429 | 1.2965 |
| Hydrogen | 0.061 | 0.488 | 0.549 |
| Oxygen | 0.4468 | −0.4468 | _ |

to its elemental analysis [26].

### 2.9. *Stoichiometric calculations*

The starting concepts for all biomass burning depend on the chemistry of biomass combustion and stoichiometric conditions for combustion. A balanced equation for the combustion of biomass was described as follows [28]:

Fuel (biomass) + air (oxidizer) → *Product* of combustion + Energy (Heat)

CxHy + z (O2 + 3.76N2) → aCO2 + bH2O + cN2

**Table 7**
Summary costs of the cook stove.

| Type of products | Total production cost (USD) | Fixed and operating cost (USD) | Total sell price (USD) |
|---|---|---|---|
| Husk biomass cook stove | 6.18 | 0.56 | **6.74** |

#### 2.9.1. *Theoretical air and air-fuel ratio*

The minimum amount of air needed for the complete combustion of biomass fuel is theoretical air or stoichiometric air [29]. In this case, the products do not contain any oxygen. If it supplies less than theoretical air, the product could include carbon monoxide, so it is better to supply more than theoretical air to prevent this occurrence.

**The air–fuel ratio** is the standard measure of the amount of air used in a combustion process.

Using the amount of air required for burning 1 kg of fuel, the air-to-fuel ratio was calculated as [30]:

$$A / F = \frac{m_{air}}{m_{fuel}} = \frac{n_{air \times M_{w,\ air}}}{n_{fuel \times M_{w,fuel}}} \tag{2.1}$$

Where $m_{air}$ is the mass of air, m $_{fuel}$ is the mass of fuel, n $_{air}$ is the number of moles of air ($O_2$), $M_{w,\ the\ air}$ is the molar mass of air ($O_2$).

#### 2.9.2. *Stoichiometric analysis for coffee husk biomass*

Consider 1 kg of fuel, which contains 0.4339 kg of carbon and 0.0637 kg of hydrogen as combustible elements. Then the theoretical air-fuel ratio for the stoichiometric amount of air required per kg of fuel was calculated as:

Oxygen required for C and $H = 0.4339 \times 32 / 12 + 0.0637 \times 16 / 2 = 1.1571 + 0.5096 = 1.667$ kg

External oxygen required = 1.667 – 0.4508 kg oxygen internally present = **1.216 kg**

Air required = 1.216 kg/0.232 = 5.241 kg

Theoretical air-fuel ratio = 5.241 kg/1 kg = **5.241**

Mass of fuel (biomass) = 1 Kmol [12] × Kg/Kmol = **12 kg**

Mass of air 2 ($O_2$) = 2 Kmol air [16 × 2] kg/Kmol air = **64 kg**

Therefore, $A/F = \frac{64\ \ kg}{12\ \ kg} = \mathbf{5.33}\ \frac{kg\ air}{kg\ fuel}$

#### 2.9.3. *Stoichiometric analysis for rice husk biomass*

Consider 1 kg of fuel, which contains 0.3536 kg of carbon and 0.061 kg of hydrogen as combustible elements. Then the theoretical air-fuel ratio for the stoichiometric amount of air required per kg of fuel was calculated as:

Oxygen required C and $H = 0.3536 \times 32/12 + 0.061 \times 16 / 2 = 0.9429 + 0.488 =$ **1.4309 kg**

External oxygen required = 1.4309 – 0.4468 kg oxygen internally present = **0.984 kg**

Air required = 0.984 kg/0.232 = 4.241 kg

Theoretical air-fuel ratio = 4.241 / 1 = **4.241**

$A/F = \frac{m_{air}}{m_{fuel}} = \frac{n_{airM_{w,\ air}}}{n_{fuelM_{w,\ fuel}}}$

Mass of fuel (Biomass) = 1 Kmol [12] × Kg/Kmol = **12 kg**

Mass of air (2 ($O_2$) = 2 Kmol air [16 × 2] kg/Kmol air = **64 kg**

Therefore, $A/F = \frac{64\ \ kg}{12\ \ kg} = \mathbf{5.33}\ \frac{kg\ air}{kg\ fuel}$

### 2.10. Performance test of biomass cook stove

The performance of biomass stoves depends on many parameters, like the characteristics of the biomass fuel used, the sizes and types of pots used, the type of cooking process, ambient conditions, ventilation levels, etc. There are many best practices for stove laboratory testing protocol methods, such as Chinese national standards, BIS from India, HTP, CSI-Indo, ISO19867–1, WBT, and IWA, according to [31]. This study was mainly focused on using WBT and IWA to determine the performance of the stove.

#### 2.10.1. Water boiling test (WBT) version 4.2.3

The three phases were conducted in the water boiling test. This combination of tests has been intended to measure the stove's performance at both high and low power outputs, which are important indicators of the stove's ability to use fuel.

The WBT Version 4.2.3 consists of three phases that immediately follow each other:

ü cold-start high-power phase
ü hot-start high-power phase
ü simmer phase

*2.10.1.1. According to [32], the parameters that were measured or calculated were as follows.* **Time to boil (Δt)**

It is the time to boil water in the primary pot and simply a time difference and expressed as:

$$\Delta t = t_{f--}t_i \tag{2.2}$$

**Overall stove thermal efficiency**

It is a ratio of the work done by heating and evaporating water to the energy released by the burning equivalent amount of dry biomass and is expressed as:

$$\eta = \frac{[\mathrm{cp} * (\mathrm{Pi} - P) * (\mathrm{Tf} - \mathrm{Ti})] + 2260 * (\mathrm{Wv})}{\mathrm{fd} * \mathrm{LHV}} \tag{2.3}$$

$$\mathrm{fd} = \mathrm{fm} * [1 - (1.12*\mathrm{MC})] - 1.5 * \Delta\mathrm{C} \tag{2.4}$$

**Burning rate ($r_b$)**

It measures biomass consumption rate while bringing water to a boil. The burning rate was calculated from the biomass fuel's recorded initial and final weight and the time to complete WBT and expressed as:

$$\mathrm{r_b} = \frac{\mathrm{fd}}{\mathrm{t_f} - \mathrm{t_i}} \tag{2.5}$$

$$\mathrm{fd} = \mathrm{fm} * [1 - (1.12*\mathrm{MC})] - 1.5 * \Delta$$

$$fm = f_i - f_f \tag{2.6}$$

**Specific fuel consumption (SFC)**

It was measured as the amount of equivalent dry biomass required producing one liter or one kilo of boiling water and is expressed as:

$$\mathrm{SFC} = \frac{\mathrm{f_d}}{(\mathrm{Pf} - P) * \left(\frac{\mathrm{Tf} - \mathrm{Ti}}{\mathrm{Tb} - \mathrm{Ti}}\right)} \tag{2.7}$$

**Turndown ratio (TDR)**

The turndown ratio is the average high power to average low power. It represents the degree to which the user can control the firepower of the stove:

$\mathrm{TDR} = \frac{\mathrm{FP_c}}{\mathrm{FP_s}}$ or it can be calculated by

$$TDR = \frac{\frac{\mathrm{Fuel_{CS}}}{\mathrm{Time_{CS}}} + \frac{\mathrm{Fuel_{HS}}}{\mathrm{Time_{HS}}}}{2} + \frac{\mathrm{Fuel_{Simmer}}}{\mathrm{Time_{Simmer}}} \tag{2.8}$$

**Firepower (FP)**

It is a ratio of the equivalent dry fuel energy consumed by the stove per time, and the firepower unit is Watt and expressed as:

$$FP = fd * \frac{\mathrm{LHV}}{60 * \Delta\mathrm{t}} \tag{2.9}$$

#### 2.10.2. Emission testing

Air pollutants emitted from solid-fuel biomass use have many health and environmental impacts [33]. The emission test of the husk biomass cook stove was taken by using a flue gas analyzer.

*2.10.2.1. Testo 310 flue gas analyzer.* The 310 sets a new standard in reliable combustion turning with its simple design, rugged housing, and advanced sensor technology. For this study, a testo 310 flue gas analyzer was measured for the biomass combustion testing by using a cook stove.

*2.10.2.2. Parameters that were calculated from the emission test.*

ü CO Emissions

ü $CO_2$ Emissions

### 2.11. IWA performance metrics

IWA is an international workshop agreement used for evaluating and classifying the stove's performance accordingly. The studied parameters include thermal efficiency, high and low power CO emissions, fuel consumption, and indoor CO emissions [34].

### 2.12. Data collection method

- The data was taken by testing the performance evaluation of a husk biomass cook stove.
- The test was conducted by using the coffee and rice husk biomass for two types of pots.
- A water-boiling test (WBT) and an emission test method were conducted while data was taken during the experiment.
- The overall collected data were analyzed using software such as Engineering equation solver (EES), R-Software, Water boiling test (WBT) version 4.2.3 and simple descriptive statistics according to its suitability.

#### 2.12.1. Conducting experiment

Cooking on stoves requires continuously adding biomass fuel, like feeding a baby. It requires immense patience. The tests were conducted on coffee husk biomass fuel with an average 0.4 cm x 0.8 cm particle dimension and rice husk biomass with a 0.2 cm x 0.5 cm particle dimension.

The experiment was done by three treatments (cold start, hot start, and simmer) and variables (3.5 L pot, 5.5 L pot, coffee husk, and rice husk biomass) with five replications for each WBT to fulfill the new protocol of WBT version 4.2.3. An emissions test was also conducted simultaneously with the WBT.

#### 2.12.2. Biomass sample for experiment

Based on ASTM [35], the calibrated temperature for moisture content using oven-dry was 105 °C and the time stay of biomass in an oven-dry was 24 h.

*2.12.2.1. Weight and moisture content of biomass fuel sample.* **Wet basis**

$$\%MC = \frac{\mathrm{W_i} - \mathrm{W_f}}{\mathrm{W_i} - \mathrm{W_c}} \times 100 \tag{2.10}$$

*2.12.2.2. Bulk density of biomass.* The average bulk density was calculated as [36]:

$$Bulkdensity = \frac{\text{weight of biomass sample}}{\text{the volume of used container}} \quad (2.11)$$

*2.12.2.3. Porosity and void ratio of the used biomass.* Porosity and void ratio are important parameters for evaluating the properties of biomass. It can be affected by particle size distributions and particle shapes. The particle density of coffee husk and rice husk is 220.7 and 182, respectively [37].

According to [36], the porosity and void ratio of the biomass were calculated by the following formula:

$$Porosity = \frac{\text{particle density} \ - \text{bulk density}}{\text{particle density}} \quad (2.12)$$

$$Voidratio = \frac{\text{porosity}}{1 - \text{porosity}} \quad (2.13)$$

i For coffee husk biomass

$$Porosity = \frac{220.7 - 142.36}{220.7} = 0.355 = 35.5\%$$

$$Voidratio = \frac{0.355}{1 - 0.355} = 0.551 = 55.1\%$$

ii For rice husk biomass

$$Porosity = \frac{182 - 125}{182} = 0.313 = 31.3\%$$

$$Voidratio = \frac{0.313}{1 - 0.313} = 0.455 = 45.5\%$$

### 2.13. Experimental procedure

- Ø The biomass was prepared according to appropriate moisture content, and its weight was measured using a digital balance.
- Ø The cross-section size of biomass was recorded.
- Ø The measured biomass was inserted into the combustion chamber of the stove.
- Ø The pot (Dist) was put on the cook stove.
- Ø Clean water (2.5 l and 3.5 l of water were added to the 3.5 l and 5.5 l pot, respectively) was prepared and added to the cook stove.
- Ø Ambient temperature, environmental humidity, and initial water temperature were all taken.
- Ø The small amount of kerosene was used for starting a fire.
- Ø The data were taken continuously up to the local boiling point of water at a regular time interval.
- Ø Finally, the biomass and char left were measured.

### 2.14. Data analysis methods

The analysis used in this study includes the comparison between the coffee husk and rice husk biomass by using two types of standard pots (3.5 l and 5.5 l pots). A water boiling test and an emission test were also conducted to evaluate the stove's performance. The measured data was analyzed using the WBT spreadsheet version 4.2.3.

### 2.15. Cost of the husk biomass cook stove

The total cost of the stove prototype was determined by considering the cost of the used machine, labor costs, and raw material costs.

**Table 8**
WBT results using rice husk biomass for a 3.5 L Pot.

| Parameters test | Unit | Cold start Average | Hot start Average | Simmer Average |
|---|---|---|---|---|
| Burning rate | g/min | 32 | 34 | 7 |
| Thermal efficiency | % | 26.613 | 28 | 25.54 |
| Specific fuel consumption | g/lit | 121 | 121 | 134 |
| Firepower | Watt | 6981.055 | 7470 | 1508 |
| Time to boil Pot water | min | 9.2 | 8.4 | 45 |
| Turn-down ratio | _ | _ | _ | 5 |

**Table 9**
WBT results using Rice husk biomass for 5.5 L Pot.

| Parameters test | Unit | Cold start Average | Hot start Average | Simmer Average |
|---|---|---|---|---|
| Burning rate | g/min | 29 | 31 | 8 |
| Thermal efficiency | % | 25.61 | 26 | 24.01 |
| Specific fuel consumption | g/lit | 102 | 104 | 123 |
| Firepower | Watt | 6305.352 | 6763 | 1810 |
| Time to boil Pot water | min | 13.2 | 12.2 | 45 |
| Turn-down ratio | _ | _ | _ | 3 |

**Table 10**
WBT results using coffee husk biomass for 3.5 L Pot.

| Parameters tested | Unit | Cold start Average | Hot start Average | Simmer Average |
|---|---|---|---|---|
| Burning rate | g/min | 33 | 37 | 7 |
| Thermal efficiency | % | 28.53 | 29 | 27.74 |
| Specific fuel consumption | g/lit | 127 | 125 | 152 |
| Firepower | Watts | 8868.848 | 9899 | 1933 |
| Time to boil Pot water | Min | 8.9 | 7.7 | 45 |
| Turn-down ratio | _ | _ | _ | 5 |

## 3. Results and discussion

### 3.1. Water boiling test (WBT) experiment results

Based on the data obtained during the experimental test, the following results were described in the table below:

From the WBT experimental results obtained during the hot start phase by using rice husk biomass and a 3.5 l pot are presented in Table 8, the average burning rate, thermal efficiency, firepower, and time to boil water were 34 g/min, 28%, 7470 W, and 8.4 min, respectively. Comparatively, the obtained thermal efficiency result of the husk biomass cook stove was higher than that of the improved biomass stove done by [14], in which thermal efficiency was 24.5%, and the traditional three-stone stove resulted in thermal efficiency of 15.4%, according to [38].

From the WBT experimental results obtained during the hot start phase by using rice husk biomass and a 5.5 l pot presented in Table 9, the average burning rate, thermal efficiency, firepower, and time to boil water were 31 g/min, 26%, 6763 W, and 12.2 min, respectively. Comparatively, the obtained thermal efficiency result of the husk biomass stove was higher than the improved biomass stove [38, 39].

**Table 11**
WBT results using coffee husk biomass for a 5.5 L Pot.

| Parameters test | Unit | Cold start Average | Hot start Average | Simmer Average |
|---|---|---|---|---|
| Burning rate | g/min | 28 | 32 | 11 |
| Thermal efficiency | % | 26.66 | 27 | 25.14 |
| Specific fuel consumption | g/lit | 98 | 98 | 123 |
| Firepower | Watt | 7546.674 | 8657 | 2916 |
| Time to boil Pot water | Min | 12.6 | 10.8 | 45 |
| Turn-down ratio | _ | _ | _ | 3 |

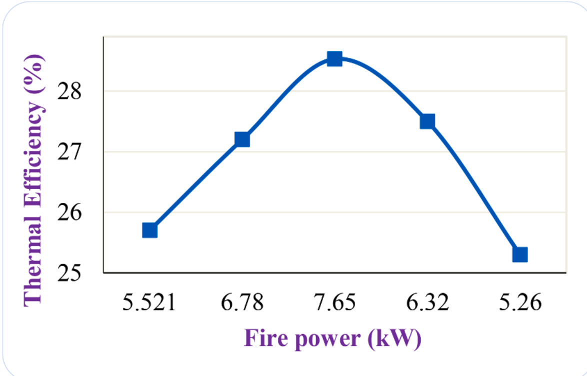


**Fig. 11.** Thermal efficiency versus firepower during the cold start for coffee husk.

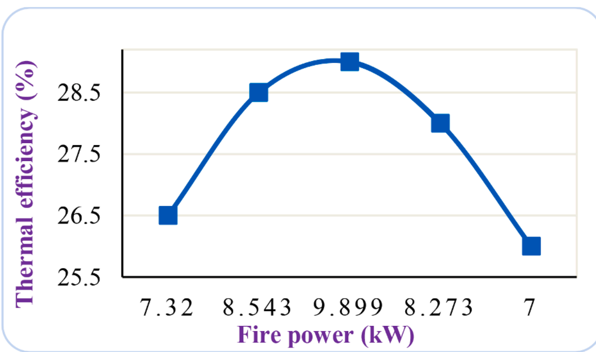


**Fig. 12.** Thermal efficiency versus firepower during the hot start for coffee husk.

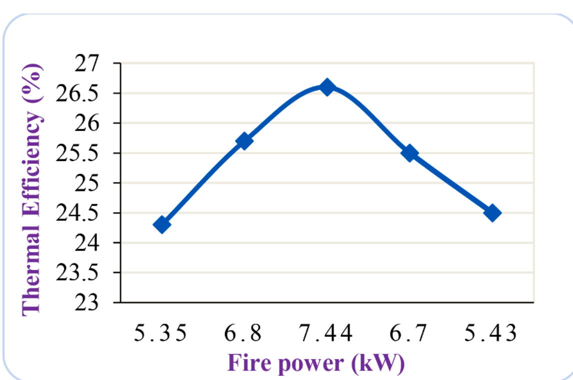


**Fig. 13.** Thermal efficiency versus firepower during the cold start for rice husk.

From the WBT experimental results obtained during the hot start phase by using coffee husk biomass and a 3.5 l pot presented in Table 10, the average burning rate, thermal efficiency, firepower, and time to boil water were 37 g/min, 29%, 9899 W, and 7.7 min, respectively. Comparatively, the obtained thermal efficiency result of the husk biomass cook stove was higher than that of the coffee husk bio-pellet stove as done by [15], in which thermal efficiency was 16.47%, and the traditional three-stone stove resulted in thermal efficiency of 10–15% according to [40].

From the WBT experimental results obtained during the hot start phase by using coffee husk biomass and a 5.5 l pot presented in Table 11, the average burning rate, thermal efficiency, firepower, and time to boil water were 32 g/min, 27%, 8657 W, and 10.8 min, respectively. Comparatively, the obtained thermal efficiency result of the husk biomass cook stove was higher than that of the coffee husk bio-pellet stove as done by [15, 40].

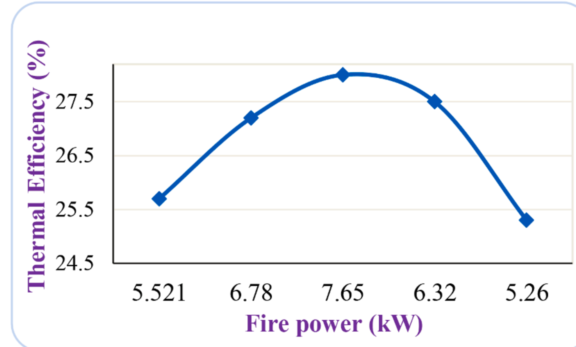


**Fig. 14.** Thermal efficiency versus firepower during the hot start phase for rice husk.

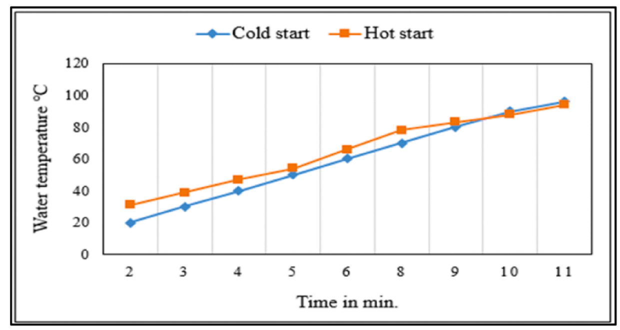


**Fig. 15.** Boiling water temperature versus time duration using rice husk biomass.

*3.1.1. Results of thermal efficiency versus firepower using coffee husk biomass*

From Fig. 11, the maximum thermal efficiency and firepower were 28.53% and 7.76 kW, respectively. The result indicates that as the thermal efficiency increases, the firepower also increases.

From Fig. 12, the maximum thermal efficiency and firepower were 29% and 9.899 kW, respectively. The result indicates that the maximum results of the stove using WBT was during the hot start phase using coffee husk biomass.

*3.1.2. Results of thermal efficiency versus firepower using rice husk biomass*

From Fig. 13, the maximum thermal efficiency and firepower were 26.61% and 7.44 kW, respectively. It indicates that as the thermal efficiency increases, the firepower also increases.

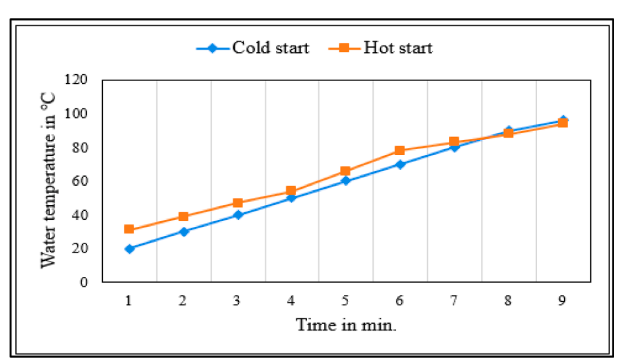


**Fig. 16.** Boiling water temperature and time duration using coffee husk biomass.


**Fig. 17.** The WBT flame photo's using coffee husk and rice husk biomass.


**Fig. 18.** Water temperature and ash or char produced during the test.

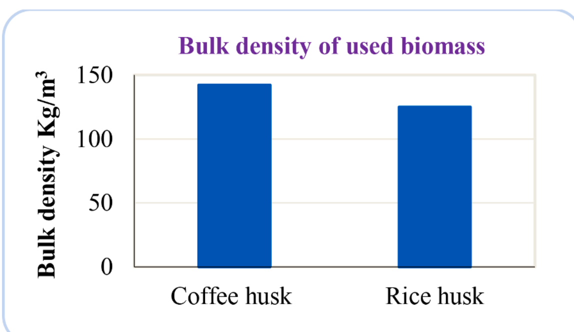


**Fig. 19.** Bulk density of coffee husk and rice husk biomass.

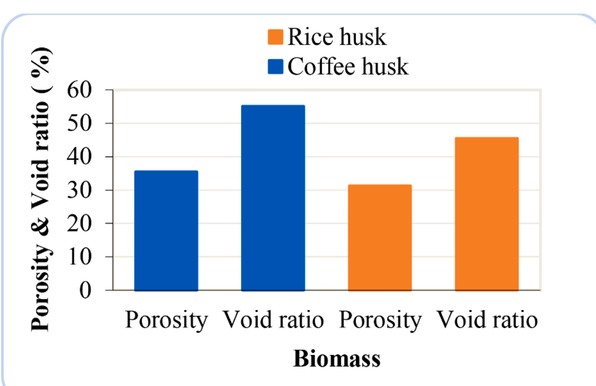


**Fig. 20.** Average porosity and void ratio of used biomass sample.

From Fig. 14, the maximum thermal efficiency and firepower were 28% and 7.65 kW, respectively. The result indicates that the thermal efficiency increases with firepower during the hot start phase using rice husk biomass.

#### 3.1.3. Water boiling point versus time duration during water boiling test (WBT)

Fig. 15 indicates that the maximum boiling point of water during WBT was 96 °C and 94 °C for the cold start and hot starts phases, respectively, using rice husk biomass.

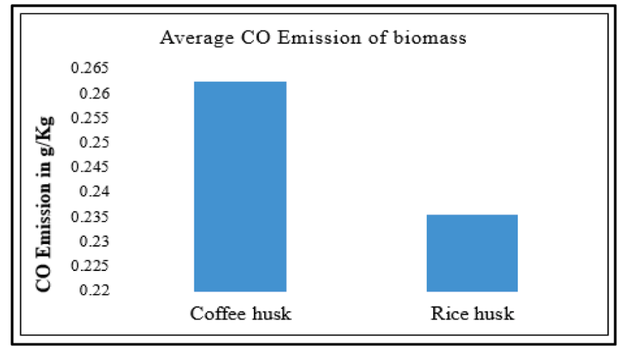


**Fig. 21.** Comparative average emission results of CO using biomass.

**Table 12**
IWA average performance results by using biomass.

| IWA performance metrics | Units | Average test results Coffee husk biomass | Rice husk biomass |
|---|---|---|---|
| High power thermal efficiency | % | 29% | 27.22 |
| Low power-specific consumption | MJ/Min/L | 0.016 | 0.012 |
| High power CO | g/MJd | 5 | 4.2 |
| Low power CO | g/min/L | 0.046 | 0.039 |
| Indoor Emissions of CO | g/min | 0.274 | 0.186 |

Fig. 16 indicates that the maximum boiling point of water during WBT was 95 °C and 93 °C for the cold start and hot start phase, respectively, using coffee husk biomass.

### 3.2. Average calculated biomass bulk density

The average bulk density results of the used coffee husk and rice husk biomass were described as follows:

The above figure indicates that the average bulk density of coffee husk and rice husk was 142.36 kg/m$^3$ and 125 kg/m$^3$respectively.

### 3.3. Average calculated porosity and void ratio of biomass

From Fig. 20, the average porosity of coffee husk and rice husk was 35.5% and 31.3%, respectively. Also, the average void ratio of coffee husk and rice husk was 55.1% and 45.5%, respectively.

Based on the above results, the biomasses have different emissions. The cook stove using coffee husk biomass has 0.262 g/kg (262 ppm) emissions, and the cook stove using rice husk has 0.235 g/kg (235 ppm) emissions. The results indicate that the obtained CO emissions from the cook stove using rice husk and coffee husk biomass were lower than that of the coffee husk bio-pellet stove, in which its CO emission factor was 273 ppm [15].

### 3.4. IWA performance metrics results of the stove

IWA is an international workshop agreement that provides a framework for rating cook stoves against performance tiers for performance indicators, including fuel use (efficiency), emissions like CO, indoor emissions, and safety.

From Table 12, based on IWA performance metrics, the average results of high power thermal efficiency, low power specific consumption, and indoor emission CO are classified under tiers 2, tier 4, and tier 4, respectively. In addition, high power carbon monoxide and low power CO are also grouped under tier 4, which indicates under best-recommended ranges. Therefore, the obtained results indicate that the cook stove using coffee and rice husk biomass is safe to use according to

**Table 13**
The results comparison of husk biomass cook stove with related publications.

| Stove types | Fuel used | Average thermal efficiency (%) | Sources |
|---|---|---|---|
| Coffee husk bio-pellet low energy stove | Coffee husk | 16.39 | [15] |
| Rice husk gasifier Stove | Rice husk | 25.67 | [41] |
| Experimental analysis of cook stove | Wood | 27 | [42] |
| Rice husk fueled stove for Household cooking | Rice husk | 18 | [20] |
| Continuous rice husk stove | | 29 | [43] |
| Husk biomass cook stove | Coffee husk | 29 | This study |
| Husk biomass cook stove | Rice husk | 28 | This study |

the IWA performance metrics principles or criteria.

### 3.5. The results comparison of husk biomass stove

The biomass cook stoves' thermal efficiency was studied and compared because thermal efficiency includes the overall performance of the stoves. From Table 13, the average thermal efficiency of this study was different from the compared papers due to the following factors: the used fuel types and characteristics (ultimate and proximate analysis), bulk density, porosity, void ratio of biomass, altitude, and others.

## 4. Conclusions

An efficient clean burning husk biomass cook stove was successfully designed, fabricated, and tested. This research was done by considering the design of the cook stove, which was suitable for using the locally available materials, especially agricultural residue wastes like coffee husk and rice husk biomass. The average specific fuel consumption for this stove was 98 g/lit, which is better than the improved biomass cook stove, in which specific fuel consumption was 115 g/lit. The designed and fabricated cook stove can alleviate the problems related to cooking costs, deforestation, asset utilization, time needed for collecting firewood, and air pollution due to the burning of biomass in an open field.

From WBT during a hot start phase of 3.5 L of water, the thermal efficiency and the time for coffee husk were 29% and 7.7 min, while with rice husk the performance was 28% and 8.4 min, respectively. Comparatively, the thermal efficiency of the cook stove was higher by using coffee husks rather than rice husks as biomass. From emission tests the average CO emission using coffee husk and rice husk was 262 ppm and 235 ppm, respectively.

Finally, the production cost of the stove was determined by considering raw material costs, fixed and operating costs with the total cost of husk biomass cook stove as 6.74 USD. Based on the experimental results on performance, emission, and economic studies varied out in this study, the designed and fabricated husk biomass cook stove can be recommended for communities where coffee husk and rice husk biomass are available.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

The data that has been used is confidential.

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## References


[1] R. Mal, R. Prasad, V.K. Vijay, A.R. Verma, The design, development and performance evaluation of thermoelectric generator (TEG) integrated forced draft biomass cookstove, Procedia Comput. Sci. 52 (1) (2015) 723–729, https://doi.org/10.1016/j.procs.2015.05.085.

[2] B. Bilal, S.W. Fanta, N. Satheesh, Kinetic based simulation of fixed bed gasifier and performance study on syngas production from different biomass feed-stocks, Ethiop. J. Sci. Technol. 11 (3) (2018) 195–222.

[3] B. Bilal, S.W. Fanta, N. Satheesh, Kinetic based simulation of fixed bed gasifier and performance study on syngas production from different biomass feed-stocks, Ethiop. J. Sci. Technol. 11 (3) (2019) 195, https://doi.org/10.4314/ejst.v11i3.2.

[4] D. Sakthivadivel, P. Ganesh Kumar, V.S. Vigneswaran, M. Meikandan, S. Iniyan, Performance study of an advanced micro-gasifier stove with coconut shell, Eur. J. Sustain. Dev. Res. 3 (4) (2019) 1–8, https://doi.org/10.29333/ejosdr/5905.

[5] F. Anthony, et al., Genetic diversity of wild coffee (Coffea arabica L.) using molecular markers, Euphytica 118 (1) (2001) 53–65.

[6] W. Merete, A. Haddis, E. Alemayehu, A. Ambelu, The potential of coffee husk and pulp as an alternative source of environmentally friendly energy, East African J. Sci. 8 (1) (2014) 29–36.

[7] M. Pauline, N. Mama, F. Justin, Development of a method for the mineralization of coffee husk (Coffea canephora P.) to obtain raw material for soap factories, African J. Biotechnol. 9 (49) (2010) 8362–8364, https://doi.org/10.4314/ajb.v9i49.

[8] I.J. Fernandes, et al., Characterization of rice husk ash produced using different biomass combustion techniques for energy, Fuel 165 (2016) 351–359.

[9] T. Belayneh, J. Tekle, Review on adoption, trend, potential, and constraints of rice production to livelihood in Ethiopia, Int. J. Res. 5 (6) (2017) 644–658.

[10] K. Dalecha, Pre-extension demonstration of Jimma modified engine operated rice thresher, In, South Western Oromia 8 (5) (2021) 13907–13913.

[11] W. Sime, R. Kasirajan, S. Latebo, A. Mohammed, E. Seraw, Coffee husk highly available in Ethiopia as an alternative waste source for biofuel production, Int. J. Sci. Eng. Res. 8 (7) (2017) [Online]. Available, http://www.ijser.org.

[12] Dawit Solomon, L. Johannes, Belay Berhanu, and Hailu Araya, "Socio-economic scenarios of low hanging fruits for developing climate-smart biochar systems in Ethiopia," 2017, [Online]. Available: https://ecommons.cornell.edu/handle/1813/55321.

[13] T.D. Tessema, B.A. Mekonnen, Assessment of improved biomass cook stoves in Ethiopia: utilization practices and adoption factors; the case of Merawi, Kolela district, Acad. Entrep. J. 27 (2021) 1–19.

[14] R. Barpatragohain, N. Bharali, P.P. Dutta, Thermal Performance Evaluation of an Improved Biomass Cookstove for of an Improved Biomass Cookstove, Springer, Singapore, 2021 no. July.

[15] S.S. Harsono, B. Prayogo, M.Mel Tasliman, F. Ridha, Effect of holes system designing for low energy stove using coffee husk bio-pellet as solid fuel, J. Adv. Res. Fluid Mech. Therm. Sci. 51 (2) (2018) 215–226.

[16] A. Daniel, "Addis Ababa University Institute of Technology School of Mechanical and Industrial Engineering Thermal Engineering Department " Geometrical optimization of biomass cook stove for efficient utilization of energy " (In case of Tikikil Stove) a thesis rese," 2016.

[17] J.K. Tangka, J.N. Mbinkar, V.C. Tidze, E.T. Sako, Development of a rice husk fired biomass stove for cooking, water and space heating, Eur. Biomass Conf. Exhib. Proc. 2018 (26thEUBCE) (2018) 263–270.

[18] F. Adcp, A.J. Plueddemann, E.A. Terray, and R. Merewether, "Design and performance of a," 2013.

[19] P. Bhusal, B.B. Ale, and R.M. Singh, "Performance evaluation of domestic rice husk gasifier stove (Belonio type) and study on modification of design for using different biomass," no. January 2015, pp. 55–62, 2015.

[20] S.Pietro Parmigiani, F. Vitali, A.M. Lezzi, M. Vaccari, Design and performance assessment of a rice husk fueled stove for household cooking in a typical sub-Saharan setting, Energy Sustain. Dev. 23 (2014) 15–24.

[21] F. Using, W. Boiling, and T. Method, "Wcej 1," vol. 4, no. 1, pp. 1–10, 2020.

[22] R. Ahmad, et al., Comparative evaluation of thermal and emission performances for improved commercial coal-fired stoves in China, RSC Adv 12 (32) (2022) 20886–20896, https://doi.org/10.1039/d2ra03364j.

[23] D.G. Desisa, G. Tibba, A.A. Science, and V.R. Ancha, "Product development through CFD simulation and experimental testing of a 200 liter biomass fired institutional cook stove liter biomass fired institutional cook stove," no. March 2017, 2016.

[24] F.B. Chalchissa, G.M. Diga, A.R. Tolossa, Modeling the responses of coffee (Coffea arabica L.) distribution to current and future climate change in Jimma Zone, Ethiopia, Sains Tanah 19 (1) (2022) 19–32, https://doi.org/10.20961/stjssa.v19i1.54885.

[25] T. Liebig, F. Ribeyre, P. Läderach, H.M. Poehling, P. van Asten, J. Avelino, Interactive effects of altitude, microclimate and shading system on coffee leaf rust,

J. Plant Interact. 14 (1) (2019) 407–415, https://doi.org/10.1080/17429145.2019.1643934.
[26] S. Amertet, Y. Mitiku, G. Belete, S. Amertet, Y. Mitiku, G. Belete, Analysis of a coffee husk fired cogeneration plant in South Western Ethiopia coffee processing industries, Low Carbon Econ 12 (1) (2021) 42–62, https://doi.org/10.4236/lce.2021.121003.
[27] S.M. Frolov, "Organic waste gasification : a selective review," pp. 556–650, 2021.
[28] Y. Wang, L. Yan, CFD studies on biomass thermochemical conversion, Int. J. Mol. Sci. 9 (6) (2008) 1108–1130.
[29] A. Foanene, Combustion of the fuels, A Ann. „Constantin Brancusi", Univ. Targu Jiu, Eng. Ser. (1) (2018) 29–35.
[30] L.S. Paraschiv, A. Serban, S. Paraschiv, Calculation of combustion air required for burning solid fuels (coal /biomass / solid waste) and analysis of flue gas composition, Energy Rep. 6 (2019) 36–45, https://doi.org/10.1016/j.egyr.2019.10.016. September2020.
[31] J. Jetter, "Overview of ISO 19867-1 laboratory testing outline," no. December 2018.
[32] A.B. Demie, G.H. wondimagegn, S. Abubeker, Fabrication and performance evaluation of small scale wood gas stove for house hold purpose using water boiling test method, Int. J. Sci. Res. Publ. 9 (11) (2019) p9587, https://doi.org/10.29322/ijsrp.9.11.2019.p9587.
[33] R. Duan, et al., Association between short-term exposure to fine particulate pollution and outpatient visits for ulcerative colitis in Beijing, China: a time–series study, Ecotoxicol. Environ. Saf. 214 (2021), 112116, https://doi.org/10.1016/j.ecoenv.2021.112116.
[34] G.Y. Obeng, E. Mensah, G. Ashiagbor, O. Boahen, D.J. Sweeney, Watching the smoke rise up: thermal efficiency, pollutant emissions and global warming impact of three biomass cookstoves in Ghana, Energies 10 (5) (2017) 641.
[35] J.A. de Mattos Carneiro-Junior, G.F. de Oliveira, C.T. Alves, M.A.I. Duro, E. A. Torres, Termogravimetric characterization of biomass impregnated with biodegradable ionic liquids, Floresta Ambient 26 (Specialissue2) (2019), https://doi.org/10.1590/2179-8087.043418.
[36] Y. Zhang, A.E. Ghaly, B. Li, Availability and physical properties of residues from major agricultural crops for energy conversion through thermochemical processes, Am. J. Agric. Biol. Sci. 7 (3) (2012) 312–321, https://doi.org/10.3844/ajabssp.2012.312.321.
[37] D. Batra, T.R. Rao, Analysis of an annular finned pyrolyser-II, Energy Convers. Manag. 41 (6) (2000) 573–583.
[38] C. Someswararao, G.Prasanna Kumar, C.V.V. Satyanarayana, Performance evaluation of improved cook stoves, Nat. Environ. Pollut. Technol. 11 (4) (2012) 621–624, https://doi.org/10.22271/tpi.2020.v9.i8b.5012.
[39] Z.J. Chen, A.J. Przekwas, A coupled pressure-based computational method for incompressible/compressible flows, J. Comput. Phys. 229 (24) (2010) 9150–9165.
[40] M.F. Chagunda, C. Kamunda, J. Mlatho, C. Mikeka, and L. Palamuleni, "Performance assessment of an improved cook stove (Esperanza) in a typical domestic setting: implications for energy saving," pp. 1–9, 2017, doi: 10.1186/s13705-017-0124-1.
[41] O. Ismail, M. Urbanus, H. Murage, and O. Francis, "Conversion of rice husks into an energy source through gasification technology," vol. 5, no. 9, pp. 1264–1268, 2016, doi: 10.21275/ART20161814.
[42] A. Daniel, T. Yilma, and N. Hasan, "Experimental analysis of cook stove for efficient utilization of biomass energy in Ethiopia," no. December 2017.
[43] E.M. Kwofie, M. Ngadi, S. Sotocinal, Energy efficiency and emission assessment of a continuous rice husk stove for rice parboiling, Energy 122 (2017) 340–349, https://doi.org/10.1016/j.energy.2016.12.104.