# Development and Experimental Performance Evaluation of Multi-Purpose Stove Fueled by Bio-briquette made of Coffee Husk as a Prime Feedstock

Chala Workineh Negeri

A Thesis Submitted to

The Department of Mechanical Engineering

School of Mechanical, Chemical and Materials Engineering

Presented in partial fulfillment of the requirement of the degree of Master's in Thermal Engineering

Office of Graduate Studies

Adama Science and Technology University

July, 2023

Adama, Ethiopia

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Advisor: Gezahagn Habtamu (PhD)

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# DECLARATION

I hereby declare that this Master Thesis entitled "*Development and Experimental Performance Evaluation of Multi-Purpose Stove Fueled by Bio-briquette Made of Coffee Husk as a Prime Feedstock*" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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# RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "*Development and Experimental Performance Evaluation of Multi-Purpose Stove Fueled by Bio-briquette Made of Coffee Husk as a Prime Feedstock*" prepared under my/our guidance by Chala Workineh Negeri submitted in partial fulfillment of the requirements for the degree of Master of Science Thermal Engineering. Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

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# APPROVAL PAGE

I, the advisors of the thesis entitled "*Development and Experimental Performance Evaluation of Multi-Purpose Stove Fueled by Bio-briquette Made of Coffee Husk as a Prime Feedstock*" and developed by Chala Workineh Negeri hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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We, the undersigned, members of the Board of Examiners of the thesis by Chala Workineh Negeri have read and evaluated the thesis entitled "*Development and Experimental Performance Evaluation of Multi-Purpose Stove Fueled by Bio-briquette Made of Coffee Husk as a Prime Feedstock*" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Thermal Engineering.

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# ABSTRACT

*In Ethiopia, traditional single stoves using charcoal, sawdust, agricultural residues, and firewood as fuel sources have low energy efficiency and are becoming costly, while coffee husk waste has potential as a clean energy source for cooking and baking when converted to bio-briquettes. This study aimed to develop a multipurpose biomass stove using ignitable bio-briquettes made from coffee husk and cornstarch binder. The dimensions of the fabricated stove were 85cm in height, 64cm in width, and had a length of 64cm, incorporating a mitad, detachable cooking place, and baking chamber. The performance of the stove was evaluated through various tests, including water boiling, control cooking, and baking tests, using sawdust and bio-briquettes as fuel. The bio-briquettes produced had a moisture content of 7.18%, volatile matter of 28.6%, fixed carbon content of 50.34%, and ash content of 13.87%, with a higher heating value of 6108.99 cal/g. The performance of a multipurpose stove using charcoal for water boiling tests and bio-briquettes for baking bread and boiling water was also evaluated. The stove achieved thermal efficiencies of 25% and 41% for cold start and hot start, respectively. The baking chamber showed thermal efficiencies of 40% and 42% for cold start and hot start, respectively, during water boiling tests. The specific fuel consumption for the control cooking test was 87g of briquettes per kg of food cooked, and the time to bake was 14 minutes. The study also evaluated the performance of the multipurpose stove mitad for baking injera, and the Multipurpose stove mitad reached the desired temperature of 180°C within an average duration of 7.5 minutes, which is significantly faster than traditional three-stone stoves. The mitad demonstrated the lowest fuel consumption per injera baked at 383.88g/kg, showing superior efficiency over other stoves. Its overall performance in baking 10 injera was 24.86% efficient, with 15.21% exergy efficiency via direct calculation. In summary, the multipurpose stove and bio-briquettes provide cost-effective, eco-friendly cooking and baking, with the mitad enabling efficient, even injera baking.*

**Keywords:** *Multi-purpose biomass stove, injera mitad, coffee husk briquette, bread baking, cooking*

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# LIST OF ACRONYMS

| Symbol | Description |
|---|---|
| A/A | Addis Ababa |
| CATIA | Computer Aided Three-Dimensional Interactive Application |
| CCT | Control Cooking Test |
| CFD | Computational Fluid Dynamics |
| ECO | Ecological |
| ETB | Ethiopian birr |
| GIZ | German Agency for International Cooperation |
| IDSRS | Improved Double Skirt Rocket Stove |
| IRS | Institutional Rocket Stove |
| KCJ | Kenyan Ceramic Jocko |
| PM | Particulate matter |
| PPM | Parts per million |
| SCG | Spent Coffee Ground |
| TSOFS | Traditional Three-Stone Open Fire Stove |
| WBT | Water Boiling Test |
| MS mitad | Multipurpose stove mitad |

# NOMENCLATURE

**Symbols**

$\eta$ Energy efficiency (%)

$\psi$ Exergy efficiency (%)

E-energy

Ex -Exergy

T temperature

t- time

hvap- heat of vaporization

$Cp_m$ specific heat capacity of mitad

MC moisture content

AC ash content

FC fixed carbon content

VM volatile matter

A area

kcal- kilocalories

min-minute

K- thermal conductivity

$U_t$-top loss coefficient

$m_{p_f}$- mass of pot with water after the test (finally)

QL -overall heat loss

Qin -overall heat input

$h_{1c}$-convection heat coefficient from mitad to lid cover

$h_{2c}$- convection heat coefficient lid cover to sky

$h_{1r}$-radiation heat coefficient from the mitad to lid cover and

$h_{2r}$ - radiation heat coefficient from lid cover to sky

$m_{fc}$-Fuel Consumed

$m_{fi}$-Initial Fuel Mass

$m_{ff}$-Final Fuel Mass

$m_{w_v}$- mass of water vaporized

$m_{p_i}$ -mass of pot with water before the test (initially)

**Subscripts**

| | |
|---|---|
| 1 Initial state | Conv- convection |
| 2  Final state | Rad -radiation |
| a  Ambient | Cond conduction |
| Al  Aluminum | eff- effective |
| in  Input | i input |
| ip Initial state of pot | l lost |
| iw Initial state of water | m- mitad |
| fp Final state of pot | lc lead cover |
| fw Final state of water | b-batter |
| o Output | bc baking chamber |
| wd Wood | ut- utilized |
| c cold start | fl- fuel |
| h hot start | |

# CHAPTER 1

# 1. INTRODUCTION

## 1.1 Background of the Study

Deforestation is indeed a global issue, and the use of trees as fuel contributes to this problem. In Ethiopia, despite the scarcity of fuel, the majority of the population still relies on traditional single stove for cooking and baking using charcoal, saw dust, agricultural residues and firewood as fuel sources. The single stoves has low energy efficient due to their design limitations, there are used for single baking or cooking and can be fired by specific type of fuel which are nowadays getting costly. In the contrary Ethiopia has large accumulation of coffee husk that can be converted to bio-briquette for cooking and baking purposes in a stove. Approximately 3.3 million tons of surplus coffee, cotton, wheat, and barley residues are produced yearly, and efforts are underway to convert these wastes into useful solid biomass fuel. One approach is to convert coffee husk waste into charcoal briquettes, which can be used for cooking. According to previous studies, Ethiopia disposes of about 192,000 tons of coffee husk waste annually, but the husk has the potential to deliver a clean energy source for daily use when converted to briquettes(Assefa et al., 2022; Weldemedhin et al., 2014; Wondwosen et al., 2017).

In Ethiopia currently various biomass cookstoves utilizes like Lakech, Gonzie, Mirchaye, Mirt, and Ezy stoves. However, most of these stoves are manufactured by local manufacturers without scientific design and calculations, resulting in lower efficiency than expected. For instance, Mirt stoves are designed to reduce environmental degradation by using firewood to bake Injera, while Lakech stoves use charcoals. These stoves are single purpose (Richard et al., 2022). These methods are inefficient and result in significant heat loss to the environment. Moreover, they pose health risks, particularly for women and children.

To address these challenges, various stoves have been developed in Ethiopia using traditional and modern approaches (Atsede and Samson, 2019; Fetene et al., 2019; Senait, 2019). While progress has been made in cooking and brewing, baking remains a difficulty for mothers. Baking requires heat from both the bottom and the top, and existing stoves typically do not provide a multipurpose solution for cooking, brewing, and baking. Additionally, they often rely on a single type of fuel.

To tackle the issues of fuel consumption, stove efficiency, and baking problems, a study proposes a solution: converting damp waste such as coffee husk into a solid fuel and developing a stove that enables mothers to cook and bake simultaneously. By utilizing coffee husk as a bio-briquette fuel source, the study aims to reduce deforestation and provide a sustainable alternative. The development of a multipurpose stove would offer convenience and efficiency for cooking, brewing, and baking, addressing the specific needs of mothers in Ethiopia.

In Ethiopia bread, injera and different kinds of stew and breweries are daily needed. These cooking and baking activities are done using separate biomass stoves that occupies relative larger area. All these baking and cooking activities can be done by designing and developing multipurpose biomass stove.

The focus of this study is to produce ignitable bio-briquette from coffee husk for use in biomass stove cooking, design and experimentally test a multipurpose and multi fuel fired biomass stove that can be used for baking injera and cooking.

## 1.2 The New Stove Designed and Fabricated

The new multipurpose biomass stove (Figure 1.1) is composed of four main parts: the upper and lower fuel beds (grates), the baking room, the ash pan room, and the pot sit. For clean, and emission reduction chimney is incorporated. The baking room has spaces left on each side for hot air to pass through, preventing the hot air from escaping with the energy it has absorbed. This implies that it includes a skirt as well. Additionally, the fuel beds (grates) is detachable, which makes it easier to load fuel. Additionally, because bread must be heated in both directions during baking, this stove enables us bake bread by transferring a fuel bed over or underneath it. In general, this stove makes it simpler to cook and bake at the same time, or, if we don't bake, to cook and brew (coffee or tea) at the same time.

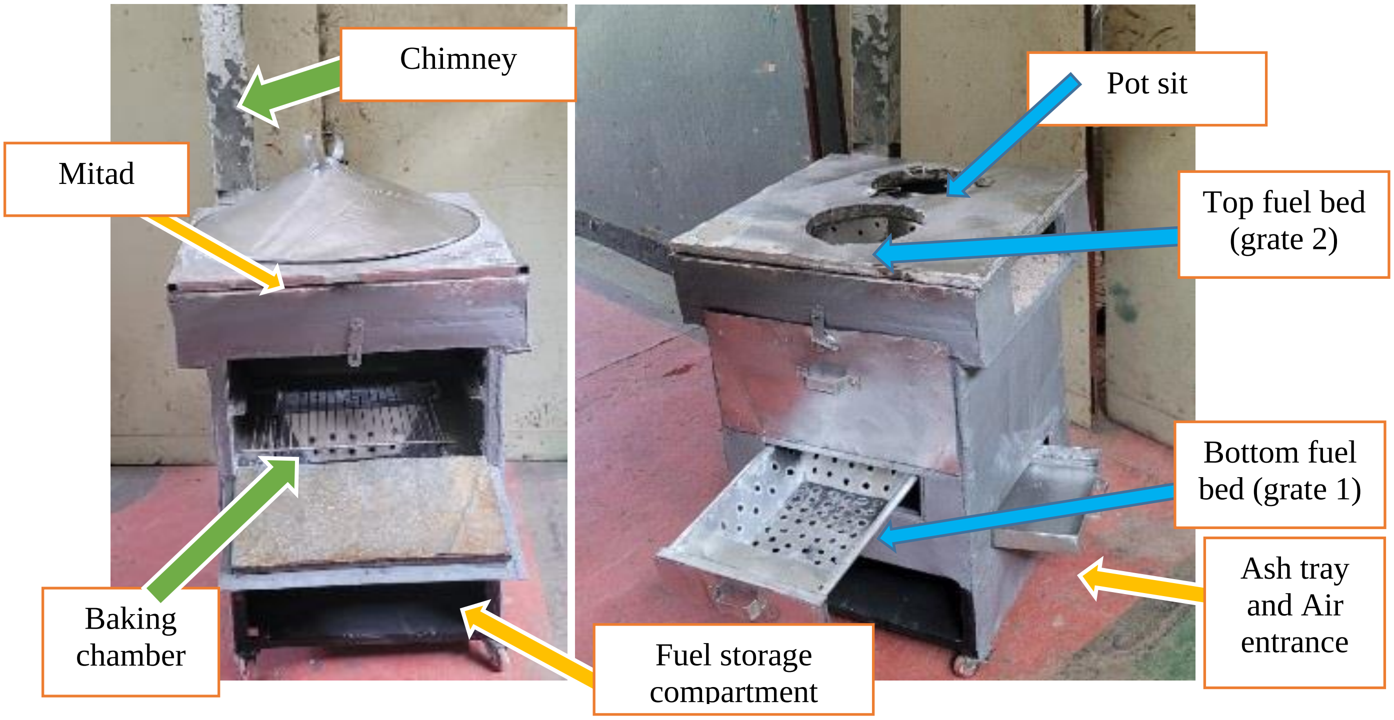


Figure 1:1. Newly designed and fabricated multipurpose biomass stove

## 1.3 Statement of the Problem

The majority of Ethiopian population still relies on traditional single biomass stove for every day cooking and baking using charcoal, saw dust, agricultural residues and firewood as fuel sources. The single purpose biomass stoves has a lot of challenges like they have low energy efficient due to their design limitations, contribute to reduction in forest density, have high emission that pose health risks particularly for women and children, they are used for single baking or cooking and can be fired by specific type of fuel which are nowadays getting costly. In the contrary Ethiopia has large accumulation of agricultural residuals that can be used for baking and cooking particularly huge amount of leftover coffee husk that can be converted to bio-briquette for cooking and baking purposes. But coffee husk is loose or has low bulk density thus difficult to store and transport unless it is converted to briquette. The major technical challenge that determines the use of bio-briquette made from coffee husk in biomass stoves is ignition delay or it is difficult to ignite A shift in design of single purpose domestic biomass stoves to poly-stoves that can bake and cook as an alternative technology which can be fired by different traditional fuels such as charcoal, firewood, saw dust and bio-briquette made from coffee husk  is essential for conserving energy, saving cooking space, and control indoor pollution.  In this work, a multipurpose biomass stove developed and its injera baking, and water boiling performance is experimentally tested using the commonly used fuels and bio-briquette made from coffee husk. By utilizing coffee husk as a bio-briquette fuel source that can be ignited easily, the study aims to reduce deforestation and provide a sustainable alternative. The development of a multipurpose stove would offer convenience and efficiency for cooking, brewing, and baking, addressing the specific needs of mothers in Ethiopia.

## 1.4 Objectives

### 1.4.1 General Objective

The general objective of this study is to fabricate ignitable bio-briquette from coffee husk and design, construct and experimentally evaluate multipurpose cooking stove that can be fired by coffee husk bio- briquette as a prime feedstock and other biomass.

### 1.4.2 Specific Objectives

The specific objective of this study are

- To prepare bio-briquettes using coffee husk and corn starch binder, and
- To characterize the briquettes through proximate analysis.
- Design Multipurpose stove using software CATIA V5.
- Develop a prototype multi-purpose cooking stove that can be used for both cooking and baking purposes.
- Experimentally test the developed multipurpose cooking stove performance using coffee husk bio-briquette, saw dust and charcoal as per the standard cook stove performance test protocols such as cold start, and  hot start WBT and control cooking tests.

## 1.5 Significance of the Study

This study holds immense significance as it addresses two crucial challenges: alleviating fuel scarcity and promoting environmental cleanliness through the utilization of local waste as a sustainable fuel source. Traditional cooking methods have long been acknowledged as detrimental to the health of mothers and children, underscoring the urgent need for improved solutions. By developing an efficient stove, not only can cooking time be reduced, but the opportunity to simultaneously cook and bake is also made possible. This innovation is particularly vital for both rural and urban populations, catering to their distinct needs and enhancing their overall cooking experience.

## 1.6 Scope and Limitations of the Study

The study aimed to encompass the design, construction, and experimental performance evaluation of a multipurpose stove that utilized coffee husk charcoal briquettes as its primary feedstock. The research involved the utilization of dampened coffee husk waste as an energy source, which was then converted into charcoal briquettes through the process of pyrolysis. The evaluation of the stove's performance was conducted through various experiments, including water boiling tests and controlled cooking tests. Furthermore, the bio-briquettes produced underwent laboratory testing to assess factors such as moisture content, carbon content, ash content, and more.

The major limitation of this study are significant as they can impact the accuracy and completeness of the findings. The time constraints may have prevented the researchers from conducting a more thorough investigation into the combustion process, potentially missing out on important details that could have shed more light on the phenomenon being studied. Additionally, the shortage of necessary materials such as stainless steel and sophisticated flue gas analyzers may have limited the researchers' ability to collect and analyze data, potentially leading to incomplete or inaccurate results.

## 1.7 Organization of the Study

This thesis paper consists of seven chapters, each serving a specific purpose and contributing to the overall coherence of the study. The first chapter presents  an introduction, outlining the objectives, significance, and scope of the study. It provides an overview of what will be covered in the subsequent chapters. Under chapter two, a comprehensive literature review is presented, focusing on biomass cookstoves and the utilization of coffee husk as a fuel source. This review synthesizes existing research and knowledge to provide a solid foundation for the study. The third chapter presents the materials and methodology employed in the preparation of the thesis paper are discussed. This includes the fabrication process of the multipurpose stove and bio-briquettes, as well as the experimental methods utilized. The fourth chapter discusses the design and theoretical analysis of the multipurpose stove and coffee husk bio-briquettes. It explores the underlying principles and concepts that guided the development of these components. Fifth chapter composes the fabrication of the prototypes, fuel preparation , experimental setups and procedures. Chapter six presents the results obtained from the experimentation are presented. This includes laboratory findings and a comprehensive discussion of the results, allowing for a deeper understanding and interpretation of the data. Finally, the last chapter concludes the thesis paper by summarizing the main findings and presenting recommendations based on the work conducted. It serves as a final stage of the study, providing closure and highlighting areas for further exploration or improvement.

# CHAPTER 2

# 2. LITERATURE REVIEW

## 2.1 Introduction

This chapter encompasses several literature reviews pertinent to the study of biomass cookstoves and coffee husk bio-briquette fuel. Biomass cookstoves are devices that utilize combustion to generate heat from biomass and direct it towards cooking pots. In rural areas, people rely on these cookstoves for both cooking and heating purposes by burning biomass fuels as their primary source (Kshirsagar and Kalamkar, 2014). Furthermore, the design features of cookstoves that impact their performance and efficiency are also examined in this section. Additional components like grates, chimneys, and others are explored for their potential to enhance the efficiency of cookstoves. Moreover, the utilization of coffee husk waste as a viable and environmentally friendly solution to address fuel scarcity is also discussed in this review.

## 2.2 Biomass Cook Stoves

A biomass cook stove is a physical apparatus that utilizes the combustion of air and fuel to produce heat, which is then directed towards a cooking surface. In many cultures, these devices serve multiple purposes. Modern cook stoves exhibit improved efficiency, reduced emissions, and enhanced user safety compared to traditional open fires. Across different regions worldwide, a diverse array of cook stove designs exists, ranging from traditional to improved versions, influenced by various factors such as dietary preferences, socio-cultural aspects, and the types of available fuel sources.

### 2.2.1 Classifications Biomass Cook stoves

The amount of applied engineering expertise, material of construction, kind of draft employed, combustion, intended use (for household or communal purposes), functionality, presence of chimney, portability, and type of feedstock used are commonly used to classify and identify cook stoves (Suhartono et al., 2018; Sutar et al., 2015). Figure 2.1 shows a biomass cookstoves classification.

- Based on technology used
  - Traditional, improved and advanced cook stoves
- Based on material of construction
  - Mud, ceramic, metal, cement and hybrid cook stoves
- Based on kind of draft employed
  - Natural and forced draft cook stoves
- Based on combustion type
  - Direct or gasifier type cook stoves

- Based on intended use
  - For household or institutional purposes
- Based on Functionality
  - Mono-function or multi-function cook stoves
- Based on Presence of Chimney
  - With or without chimney
- Based on Portability
  - Fixed or Movable (portable)
- Based on Type of Feedstock Used
  - Fuel wood, charcoal , agricultural residues, and multi-fuel cook stoves

Figure 2:1. Classification of biomass cookstoves (Kshirsagar and Kalamkar, 2014)

## 2.3 Design Features of Cook stoves

### 2.3.1 Material of Construction

Traditional cook stoves are commonly constructed using clay, bricks, or cement materials. However, many designers of improved cook stoves opt for metal as the primary construction material. Metal offers advantages such as low thermal inertia, portability, and the ability to incorporate desirable features for improved performance. Recent high-performance cook stoves also utilize metals, sometimes complemented by ceramics for the interior lining to enhance durability in high-temperature conditions.

A metallic body in a cook stove reduces the energy stored within the stove due to its lightweight nature. However, it can also result in higher heat losses due to its higher thermal conductivity. These losses can be effectively minimized by properly insulating the cook stove, which subsequently leads to higher temperatures in the combustion chamber (De Lepeleire and Christiaens, 1983).

On the other hand, traditional mud, cement, or brick structures used in cook stoves are poorer heat conductors. However, a heavy stove body made of such materials results in a significant loss of stored energy within the stove.

A portable stove made entirely of metal is expected to have a longer lifespan for the outer body. However, a metal combustion chamber may not last as long unless high-quality, fire-resistant stainless steel is utilized. Combining a metallic body with a ceramic combustion chamber increases the likelihood of the stove having an extended lifespan.

Fixed brick or mud stoves are often preferred by low-income families due to their lower maintenance costs, although they do require regular attention. Portable stoves made of non-metallic materials may be less resistant to impact and durability.

Table 2:1 Cook stove materials (Kshirsagar and Kalamkar, 2014)

| Material type | Components | Advantages | Disadvantages |
|---|---|---|---|
| Mud | Sand, straw, mica, grass, clay, saw dust combined with organic binders | Lower cost after three-stone fire, simple construction | High maintenance needs, short lifespan |
| Ceramic | Similar to mud stoves, may have metal cladding in modern versions | High insulation, Durable construction | High maintenance needs, expensive and difficult construction, lack of flexibility in pot-stove size ratio |
| Metal | Steel<br>Cast iron | Lightweight, portable, conductive for quick heating, sturdy, low maintenance, available in various models | Prone to rusting, risk of user burns, high cost |
| Hybrid | Combination of multiple materials like metal and ceramic | High efficiency | Expensive, complex construction |

### 2.3.2 Parameters that Affect the Efficiency of the stoves

#### 2.3.2.1 Insulation

Insulating the walls of a stove can significantly enhance its performance by reducing heat loss. Baldwin (1987) highlighted that proper insulation of the combustion chamber can effectively reduce emissions. Furthermore, Baldwin (1987) emphasized that good insulation of the stove's external walls can improve efficiency by approximately 8% and decrease fuel consumption by nearly 5%. To further enhance heat retention and draft, Still and Kness (2003) recommended insulating not only the cooking stove walls but also the chimney. The inclusion of an insulated skirt serves as an additional protective layer, minimizing the risk of burns from the stove's hot surface. In addition to commonly used insulation materials such as perlite, pumice, coral, vermiculite, and aluminum foil, dry wood ash has also proven to be an effective insulator (Still and Kness, 2003).

Panwar (2009)conducted a study on multi-biofuel gasifier cookstoves, providing valuable insights into thermal efficiency, operating time, ignition time, and power rating when using various fuel sources such as sawdust, groundnut shell briquettes, cashew nuts, and babul wood. Their research demonstrated that the use of heat-resistant cement as insulation can result in approximately 35% thermal efficiency (Panwar, 2009). These findings highlight the significance of insulation in achieving optimal stove performance and efficiency, thereby emphasizing its relevance in the field of cookstove technology.

#### 2.3.2.2 Combustion chamber Grate materials

Incorporating best material into cookstove designs can decrease specific fuel consumption, emissions, and increase energy efficiency, as suggested by Boafo-Mensah et al. (2020). Their research examined the impacts of utilizing aluminum, ceramic clay, and mild steel as combustion chamber materials on the performance of an enhanced biomass cookstove. As per the findings, ceramic clay was the optimal material for the combustion chamber grate, satisfying tier 2 emission limits and tier 3 efficiency benchmarks under both high and low power conditions (Boafo-Mensah et al., 2020).

### 2.3.3 Additional tools that enhance the performance of stoves

#### 2.3.3.1 Grate

Due to an improved main air supply under the bed and greater air-fuel contact, the use of a grate often enhances the combustion quality and rate quite significantly. The use of a grate increases stove efficiency by 3-5% points, according to (Gusain, 1990). Ajunwa et al., (2021) claim that by optimizing fuel-air mixing, grate can increase efficiency and reduce emissions. The size of the grate also matters when thinking about the rate of fuel combustion (Baldwin, 1987). According to research by Ballard-Tremeer and Jawurek, (1996)the average efficiency of an open fire is just under 15%, and when a grate is employed, the efficiency of an upgraded open fire rises by 7% .

#### 2.3.3.2 Air supply

The main or secondary air that is introduced into the combustion chamber during operation of the cook stove sustains the combustion process. One of the most crucial aspects affecting the efficiency and emissions of cook stoves is the rate of air entry. To hypothetically achieve total combustion in a combustion cookstove, stoichiometric air is the minimal required. A little more air is necessary for complete combustion and to maintain low emissions, but since the mixing of volatiles and air is never perfect (Baldwin, 1987), this is essential. The cookstove will operate at close to stoichiometric circumstances with minimal extra air since this will produce high combustion temperatures that will improve heat transmission and increase the cookstove's efficiency. On the other side, too much more air could result in insufficient combustion and poor heat transmission to the vessel because the combustion chamber would be operating at a lower temperature(Gusain, 1990). As a result, for the cookstove to operate well in terms of both thermal performance and emission performance, an optimum level of air flow rate is needed.

According to De Lepeleire et al., (1981) the total air requirement for natural draft cookstoves should be 1.6-2 times the stoichiometric air requirement. By ensuring that the balance between the frictional losses and the draft through the cookstove results in the necessary air flow rate, the design of these cookstoves must take this requirement into account. This criterion is met in a forced draft cookstove by the features of the selected fan. As a result, compared to a forced draft cookstove, a natural draft cookstove's performance is significantly more sensitive to its dimensions. This is another factor in the underperformance of many improved natural draft cookstoves in real world environments compared to their laboratory performance (Barnes et al., 2012).

#### 2.3.3.3 Chimney

In order to remove flue gases from the kitchen and to draw air into the cookstove, a chimney provides draft. A bigger diameter leads in a greater mass intake of air due to a larger area and a less frictional pressure drop via the chimney, even though draft directly depends on chimney height. The chimney's diameter, rather than its height, determines the mass flow rate of air induced through it (Gusain, 1990). The height and diameter of the chimney must be chosen for each cookstove configuration in order to balance the chimney draft with the air needed for combustion and the frictional pressure drop(De Lepeleire et al., 1981), resulting in the cookstove's best performance.  According to research conducted by Memon et al. (2020), increasing the height of a cookstove's chimney enhances combustion efficiency as a result of improved draft. However, decreasing chimney height, which consequently lowers the overall height of the cookstove, is beneficial from an economic perspective (Memon et al., 2020).

The chimney plays a crucial role in facilitating the removal of flue gases from the kitchen and creating a draft that draws air into the cookstove. The diameter of the chimney significantly influences the mass intake of air, as it provides a larger area and reduces frictional pressure drop (Gusain, 1990). Surprisingly, draft primarily depends on the chimney's height, but the chimney diameter determines the mass flow rate of induced air (Gusain, 1990). To achieve optimal performance, the height and diameter of the chimney should be carefully selected for each cookstove configuration to strike a balance between the chimney draft, combustion air requirements, and frictional pressure drop (De Lepeleire et al., 1981).

Increased chimney height has been found to enhance combustion efficiency due to the higher draft it generates (Memon et al., 2020). Conversely, reducing the chimney height results in a lower overall height for the cookstove, which can be economically advantageous (Memon et al., 2020). Finding the optimal balance between chimney height and diameter is crucial for maximizing the cookstove's performance and efficiency. These insights from Gusain (1990), De Lepeleire et al. (1981), and Memon et al. (2020) shed light on the importance of chimney design considerations in cookstove technology and provide valuable guidelines for achieving optimal performance in various cooking setups.

## 2.4 Researches on Biomass Stove

### 2.4.1 Biomass Stove Internationally

Several researchers have made significant contributions to the improvement of biomass cook stoves through various design modifications and enhancements. (Amiebenomo et al., 2013; Ayo, 2009)  focused on reducing radiation heat loss and indoor air pollution by incorporating appropriate pot seats and flue gas stacks. Ayo (2009) implemented a sizable chimney on the right side of the combustion chamber, while Amiebenomo et al. (2013) positioned the chimney at the top, albeit with a shorter height. Both approaches aimed to minimize environmental pollutants, although the large chimney design was found to be heavy and inflexible. In contrast Nandish and Tewari (2015)developed a biomass cook stove without a chimney, demonstrating that its presence or absence did not impact stove efficiency.

Okino et al. (2021) explored enhancements to cooking stoves through the novel use of sawdust as an insulating material. Their prototype stove, designed for a 26 cm diameter saucepan, comprised a two-layer structure integrating sawdust and clay components. Compared to conventional cookstoves, testing showed the insulated stove decreased biomass usage and emissions, as verified via water boiling experiments. The addition of a chimney draught to the stove prototype further augmented smoke reduction and thermal efficiency gains (Okino et al., 2021).

Ajunwa et al., (2021)conducted research on wood stoves and evaluated the impact of a detachable skirt on the stove's thermal performance during water boiling tests. Results showed that the stove equipped with a skirt exhibited improved thermal efficiency and reduced specific fuel consumption compared to the stove without a skirt. The inclusion of the skirt proved beneficial in enhancing the stove's thermal performance.

Harsono et al., (2022)designed and constructed a stove fueled by coffee husk pellets. To improve air supply and complete fuel combustion, they incorporated additional components such as a battery, dimmer, and blower. The thermal efficiency of the biomass stove was evaluated by comparing the heat used to cook water with the heat produced from the coffee husk pellets. The optimal formulation of biopellets was achieved using coffee husk, tapioca flour, and molasses, resulting in favorable density, ash content, moisture content, and thermal efficiency.

Omoniyi and Ojo (2022)developed and tested a briquette cooking stove utilizing a combination of sawdust from Cordia milleni and cow dung briquettes. Their stove design aimed to improve heat retention, ash collection, and air supply. Performance evaluations, comparing the briquette stove with a kerosene stove and a metallic charcoal-burning stove, revealed shorter cooking time, higher thermal efficiency, and reduced specific fuel consumption. The appropriate design configuration of the briquette cooking stove was identified as a crucial factor for achieving optimal performance.

Overall, the studies by these researchers have contributed valuable insights and advancements to the field of biomass cook stove design, leading to improved efficiency, reduced emissions, and enhanced cooking performance.

### 2.4.2 Biomass Stove in Ethiopia

#### 2.4.2.1 Gonziye Stove

The Ethiopian Rural Energy Development and Promotion Center developed the Gonziye stove in 1994 as an accessible and cost-effective solution for rural communities to save fuel. This stove is designed to serve the dual purpose of baking and cooking. The Gonziye multipurpose stove demonstrates an efficiency rate of 23%, offering substantial fuel savings compared to traditional methods. According to Aster (2022), it has the potential to save 42% of fuel for cooking and 54% for baking. Moreover, the adaptability of Gonziye burners allows households to reposition them for various cooking tasks, such as brewing coffee and preparing Ethiopian sauce (known as wot), as mentioned by (Mekonnen, 2022).

#### 2.4.2.2 Mirt Stoves

In-depth studies conducted by Dresen et al. (2014) and Gizachew and Tolera (2018) have extensively explored the impact of mirt stoves on reducing carbon emissions and fuel wood consumption, specifically focusing on improved cook stoves in different regions of Ethiopia. Dresen et al.,( 2014)conducted their research in Ethiopia's Afromontane Forest, while Gizachew and Tolera (2018) focused on the Bale region of Oromia, Ethiopia.

Tesfaye and Nigusse (2022) took a unique approach by designing and constructing an institutional mirt stove with a waste heat recovery system. This system aimed to utilize the waste gases' heat from the institutional mirt stoves as an energy source for baking injera on the secondary mitad. Alongside this significant design improvement, they incorporated fuel supporting structures such as grates, which facilitated ash collection and allowed air to enter beneath the fuel. Ash removal openings were also included below each grate. To assess the stove's performance compared to an existing institutional mirt stove, Tesfaye and Nigusse (2022)employed a controlled cooking test method.

The improved stove showcased promising outcomes, including up to 16% reduction in fuel wood consumption and 14% decrease in cooking time compared to the existing institutional mirt stove. Moreover, it achieved fuel savings ranging from 22% to 31% in comparison to a traditional three-stone tripod stove. During the testing phase, the surface of the secondary mitad reached a temperature of approximately 216.3 °C, enabling the successful baking of injera.

In summary, the studies conducted by Dresen et al. (2014), Gizachew and Tolera (2018), and Tesfaye and Nigusse (2022) shed light on the effects of mirt stoves in Ethiopia, emphasizing the reduction of carbon emissions and fuel wood usage. Tesfaye and Nigusse's (2022) novel waste heat recovery system and other design enhancements demonstrated promising results, offering improved efficiency, reduced fuel consumption, and enhanced cooking performance for institutional mirt stoves.

#### 2.4.2.3 Lakech Stoves

The Lakech stove, introduced to Ethiopia in 1990 as part of the Cooking Efficiency Improvement and New Fuels Marketing Project by the Ministry of Mines and Energy, was designed by Kenyan Ceramic Jocko (KCJ). This stove incorporated a thinner KCJ aluminum cladding, which resulted in improved efficiency, better alignment with Ethiopian cooking preferences, and reduced construction costs. Featuring a unique double conical structure above its waist, the Lakech stove includes a clay lining. This design choice, utilizing a half liner and bell-bottom design instead of full liners, offers stability to the stove while being more cost-effective and heavier in construction (Aster, 2022). The Lakech stove boasts a thermal efficiency of 32%, outperforming traditional Ethiopian metal charcoal stoves. Notably, it can achieve fuel savings of up to 25% while emitting fewer particulate matter (PM) pollutants, contributing to a cleaner cooking environment (Aster, 2022).

#### 2.4.2.4 Tikikil Stoves

The Tikikil stoves, manufactured by local producers and distributed in collaboration with the German Society for Internationale Zusammenarbeit (GIZ), are specifically designed to cater to the cooking practices of Ethiopian households and local manufacturing techniques. These stoves, resembling rocket stoves, have been carefully developed to meet the requirements of Ethiopian families.

The design of the Tikikil stove takes into account the parameters of traditional three-stone stoves, which are widely used but inefficient. Factors such as the size of the cooking pot, ease of production, affordability, and the utilization of locally available materials and skills are considered. The fuel chamber of the Tikikil stove is made of a clay-fire-based combination, while the liner is constructed from recycled galvanized sheets (Sutar et al., 2015).

Compared to open flame stoves with three burners, Tikikil stoves can significantly reduce fuel consumption by up to 50%. These stoves exhibit a thermal efficiency ranging from 25% to 28% (Aster, 2022; Manaye et al., 2022; Senait, 2019). Therefore, Tikikil stoves offer a practical solution and play a crucial role in enhancing energy efficiency, improving the well-being of rural communities, promoting sustainable biomass resource utilization, and mitigating climate change in Ethiopia and beyond (Yibeltal T. and Adaramola, 2021).

#### 2.4.2.5 Ezy Stoves

The Ezy Stove was developed by a team of engineers and designers at the University of British Columbia in Vancouver, Canada. The stove was designed to be a simple, efficient, and affordable way to cook food in developing countries. It is an innovative wood-burning stove designed to enhance the efficiency of wood combustion while minimizing smoke production. The stove, specifically designed for household use, follows a batch-loaded rocket design. The primary goal of its creators is to mitigate the negative environmental impact of traditional cooking methods by making them more eco-friendly, healthier, and less time-consuming. EzyStoves have been successfully distributed in various countries, including Ethiopia, Ghana, India, and Kenya. These energy-efficient stoves. These energy-efficient stoves retain wood as their fuel source, yet they significantly reduce wood consumption for cooking purposes by approximately 40-50%, resulting in a notable decrease in greenhouse gas emissions measured in tons of CO2 (Aster, 2022). In comparison to conventional 3-stone fires, approximately, the Ezy stove can conserve 40% of fuel (Aster, 2022). The EzyStove comprises a fire chamber integrated into a sturdy metal support frame. This two-part system includes a fire chamber with a lifespan of 2-3 years and a pot support frame capable of lasting up to 10 years.

#### 2.4.2.6 Improved Rocket Stoves

The Rocket stove is appealing due to the simplicity of the components and ease of fabrication. Its main purposes are to accept fuel with small dimensions, such as twigs or small branches, to give great combustion efficiency, and to direct the heat produced most efficiently. In institutions, larger-scale cooking can be done with a portable stove called the Institutional Rocket Stove (IRS). The stove has the capacity to save up to 70% of fuel when compared to a three-stone fire, which has a thermal efficiency of 40–50%. In developing countries, the stove is usually available. GIZ-ECO has begun distributing stoves in Ethiopia in conjunction with stove producers (Aster, 2022).

In order to replace the traditional three-stone open fire stove (TSOFS) in institutional kitchens with an improved double skirt rocket stove (IDSRS), (Fetene et al., 2019)developed and tested the Improved Double Skirt Rocket Stove with the goal of reducing the amount of firewood needed and carbon monoxide emissions. Based on design standards established by the Aprovecho research center, every component of the stove was created. The double skirt rocket stove's construction includes structural steels, sheets, clay, and insulation materials (pumice), all of which contribute to minimize heat loss when cooking. The double skirt rocket stove differs from earlier single skirt stoves in that it is constructed using insulation materials such as pumice, loam soil, and synthetic asbestos to reduce the amount of firewood consumed and to increase the efficiency of the rocket stove by 41% over the conventional three-stone cooking method.

The upgraded double skirt rocket stove contributes in a 24.85% reduction in CO emission levels in the kitchen. For the double skirt rocket stove, the average of three experimental results shows that PM is 9.870 and CO emission is 0.603 ppm. By using the controlled cooking test (CCT) approach, the performance of the stove is assessed (Fetene et al., 2019).

## 2.5 Researches on Coffee husk as a Fuel

In Ethiopia, biomass energy constitutes more than 92% of the total energy consumption, making it one of the country's most reliant on biomass (Assefa et al., 2022). However, this heavy dependence on wood fuels and agricultural residues has negative implications for social, economic, and environmental well-being.

Researchers are actively exploring ways to convert surplus coffee, cotton, wheat, and barley residues into cleaner and alternative energy sources. Weldemedhin et al. (2014) conducted an experiment on the potential of coffee husk and pulp as a renewable energy source and found that coffee husk can be converted into briquettes to deliver clean energy for daily use. The coffee husk briquettes were found to have a calorific value of 5041.1±168.60 Cal/g and a moisture content of 6-11%, volatile matter content of 22-16%, fixed carbon content of 42-59%, bulk density of 0.44-0.65g/cc, and sulfur content of 0.06-0.16% (Weldemedhin et al., 2014).

A study reported by Rahel (2022) highlighted the annual disposal of approximately 192,000 tons of coffee husk waste in Ethiopia, with each kilogram of coffee fruit producing one kilogram of coffee husk (Wondwosen et al., 2017). Rahel (2022)also mentioned the efforts of two students who designed a machine to convert coffee husk into pellets and briquettes. The carbonized briquettes and pellets undergo a carbonization process, including heated drying, to eliminate water content and increase their strength for use as a charcoal substitute.

Sisbudi Harsono (2019)studied the characteristics of coffee husk biopellets as a solid fuel for combustion stoves and found that coffee husk can be used as an alternative energy source through a carbonization process when converted into biopellets.

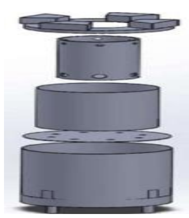
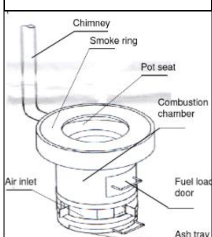
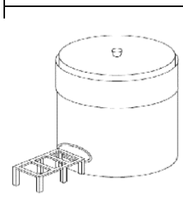
Sairoel et al., (2021)analyzed the properties of coffee husk for use in a cogeneration plant in Southwestern Ethiopia's coffee processing industries. Experimental testing with Eager 300 software at Addis Ababa University demonstrated that coffee husk has a calorific value of 18.98 MJ/kg, indicating its high energy potential for power generation.

Assefa et al. (2022)produced and characterized coffee husk briquettes using clay as a binder. Laboratory results showed that the briquettes had a moisture content of 10.03%, density of 970 kg/m3, fixed carbon content of 81%, ash content of 5.15%, sulfur content of 0%, and calorific value of 30.543 MJ/kg. These findings indicate the positive characteristics of coffee husk fuel briquettes.

Overall, these studies highlight the coffee husk's viability as a promising renewable fuel source. With proper processing like carbonization and binding, this abundant biomass waste from coffee production can be transformed into solid biofuels. As documented across multiple studies, coffee husk exhibits suitable properties including moderate moisture content, reasonably high calorific values, and the ability to be pelletized or briquetted to enhance density and combustion characteristics. While further research and development is still needed, coffee husk has clear potential for sustainable conversion from a disposal burden into an energy resource. The scalable production of next-generation biofuels from coffee husk could provide renewable, efficient cooking fuels to benefit millions of households in coffee-producing regions while also reducing agricultural waste. With appropriate technological and commercial development, coffee husk fuels could provide a small but incremental step towards modern energy access and a circular economy in the developing world.

## 2.6 Literature review summary

Table 2:2 International biomass cook stoves and fuel types

| ***Stove*** | ***Author*** | ***Title*** | ***Draft type and fuel used*** | ***Improvement made*** | ***Thermal efficiency*** |
|---|---|---|---|---|---|
|  | (Nandish and Tewari, 2015) | Performance Enhancement Of Cook Stove | Forced draft<br>12V AC fan<br>Wood and plant chips | Combustion chamber<br>• Refractory cement<br>Outer body:<br>• Galvanized iron sheet | 23% |
|  | (Pavan, H.:, 2016) | Energy Efficient Wood Stove | Forced draft<br>12V AC fan,<br>Wood and<br>Plant chips | Combustion chamber<br>• Clay outside of combustion chamber<br>• Lined by fiber glass<br>Outer body:<br>• Milled steel | 22.27% |
|  | (Ayo, 2009) | Design, Construction And Testing Of An Improved Wood Stove | Natural draft with adjustable air inlet | • Incorporation of smoke rings at the top of the stove<br>• Provision of sizable and adjustable air inlet and Incorporation of a chimney | 64.4% |
|  | (Amiebenomo et al., 2013) | Fabrication And Performance Evaluation Of An Improved | Natural draft, wood and chips | • Insulation around the combustion chamber<br>• Provision of a pot skirt | 23% |

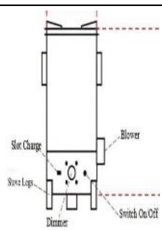
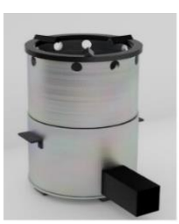
| | | | | | |
|---|---|---|---|---|---|
| | | Biomass Cook Stove | | • Provision of a graft or fuel tray | |
|  | (Pandey and regmi, 2013) | Analysis And Test Of Biomass Briquette And Stoves | Natural draft, Briquette | • Ceramic stove<br>• Grate<br>• Pot stove gap | 33.4% |
|  | (Nadine and stephan, 2016) | Dried coffee husk for cooking in gasifier stoves, Ethiopia | Natural draft, coffee husk pellet | • Fixed<br>• Use steel for the whole part<br>• No chimney, fan/ventilator instead | 35% |
|  | (Okino et al., 2021) | Performance characteristics of a cooking stove improved with sawdust as an insulation material | Natural draft, coffee husk, wood, saw dust | • Metal sheet<br>• Saw dust is used as insulation material<br>• Chimney (suggested)<br>• Grate | 25.7 ± 1.7% |
|  | (Harsono et al., 2022) | Biomass Stove With Low Carbon Monoxide Emission Fueled By Solid Fuel Coffee-Husk Biopellet | Forced draft Coffee husk bio-pellet | • Blower<br>• Dimmer<br>• Battery | 33.15% |
|  | (Omoniyi and ojo, 2022) | Development And Performance Evaluation of a Briquette Cooking Stove | Forced draft,6w rechargeable fan, Mixture of sawdust from cordia milleni and cow dung briquette | • Simple<br>• Portable | 86.34% |

Table 2:3 Domestic biomass cook stoves and fuel types

| ***Types of Stoves*** | ***Materials*** | ***Application*** | ***Thermal efficiency*** | ***Comparison*** | ***Source*** |
|---|---|---|---|---|---|
| ***Three stone open fire*** | Clay, stone<br>wood | Baking injera and cook | 10-15% | Less efficient, high emission, cause severe health problems | (Aster W.,2022, Senait.T,2019) |
| ***Metal stove*** | Metal, charcoal | For cooking | 20% | Efficient than three stone open fire<br>Consume less fuel, portable | (Aster, 2022) |
| ***Gonzuiye*** | Mud | Baking injera | 23% | Can be changed into cook stove. Flexible | (Aster, 2022) |
| ***Mirt stove*** | Cement + sand | For Baking injera | 22% | Fuel-saving potential of 40% compared to the TSOF | (Yibeltal and Adaramola, 2021) |
| ***Lakech stove*** | clay, sand, cement and sheet metal for cladding | For cooking and brewing | 32% | Save over 25% over the traditional Ethiopia metal charcoal stoves.<br>Emit less PM as compared to Traditional Metal stove | (Beyene and Koch, 2013; Senait, 2019). |
| ***Mirchaye stove*** | Made from clay, sand, cement and sheet metal | For cooking and brewing | 25% | Emit less PM as compared to Traditional Metal stove | (Senait, 2019) |

| | | | | | |
|---|---|---|---|---|---|
| ***Tikikil stove*** | Galvanized sheet metal and ceramic | For cooking and brewing | 25-28% | Fuel saving potential of up to 50% compared with a three-stone stove | (Aster, 2022; Senait, 2019) |
| ***IRS*** | Metal and clay, cement | For cooking | 40-50% | Institutional Rocket Stove(IRS) Can save fuel up to 70% compared with a three-stone stove | (Aster, 2022) |
| ***Ezy stove*** | Metal | For cooking and brewing | 27% | Reduce fuel consumption by 40-50% compared to TTSOF | Aster, 2022) |

Table 2:4 Literature summary of coffee husk as fuel

| ***Author*** | ***Title*** | ***Suggestion / Findings*** |
|---|---|---|
| ***Rahel, 2022;*** <br><br> ***Wondwosen et al., 2017)*** | Monetizing Waste: Husky Energies <br><br> Coffee Husk Highly Available in Ethiopia as an Alternative Waste Source for Biofuel Production | 192,000tons of coffee husk waste annually in Ethiopia <br><br> Coffee husk can be as alternative fuel by convert it to biofuel. |
| Weldemedhin et al., (2014) | The Potential of Coffee Husk and Pulp as an Alternative Source of Environmentally Friendly Energy | Coffee husk and pulp can be used as an alternative source of energy |
| ***Sisbudi Harsono, (2019)*** | Coffee Husk Biopellet Characteristics as Solid Fuel for Combustion Stove | Coffee husk can be used as an alternative energy source by carbonization process when converted into biopellet |
| ***Assefa et al., (2022)*** | Production and Characterization of Coffee Husk Fuel Briquettes as an Alternative Energy Source | Produce and characterize coffee husk briquettes using clay as a binder. <br><br> Concluded when large amount of clay is used for briquetting the briquette will ignite and burn poorly or not at all |
| ***Sugumaran and Seshadri, (2010)*** | Biomass charcoal briquetting | • Starch is preferred as a binder |

## 2.7 Research gaps

The literature review focuses on enhancing the efficiency and reducing emissions of cook stoves. Researchers have proposed adding components like grates, chimneys, and baffles, and designing them with materials that enhance performance. Users demand versatile stoves that can use different types of fuel to reduce fuel consumption and time spent searching for fuel. The availability of abundant fuel sources also impacts the stove's market viability. The literature review also highlights Ethiopia's abundant coffee husk, which is currently considered waste. However, coffee husk possesses the potential to provide clean energy for daily use. One significant drawback associated with coffee husk briquettes is the ignition delay, as they take a considerable amount of time to catch fire. To solve this problem eucalyptus leaves and castor seed powder were planned to be used. But for this research only coffee husk with corn flour as binder bio-briquette was prepared

Overall, the literature review emphasizes the importance of improving stove efficiency, reducing emissions, and addressing fuel and design limitations to meet user demands for multi-purpose functionality and the utilization of various fuel sources. Additionally, it highlights the potential of coffee husk as a valuable energy source in Ethiopia, suggesting solutions to overcome its specific drawbacks.

# CHAPTER 3

# 3. MATERIALS AND METHODOLOGY

## 3.1 Material selection

The materials used for the prototype had a huge effect on its weight, size, and efficiency. The stove had to be attractive, lightweight, easy to cook on, and efficient. Therefore, material selection played a crucial role in the development of this stove. Galvanized sheet metal was used for the exterior body of the stove because it is lightweight. For the interior body of the stove, stainless steel was expected to be used, but due to material shortages, galvanized sheet metal was used instead. Aluminum pots were used for cooking, and wood ash and gypsum mixed insulation material were used for insulation.

## 3.2 Methodology

### 3.2.1 Data collection

Data collection in this study involved two approaches. The first involved gathering standard data from secondary sources, while the second involved obtaining additional data through mathematical analysis and experimental testing.

#### 3.2.1.1 Data collection techniques

In this research, data was collected using the following techniques:

- Direct measurement: Data was obtained through direct measurement of relevant variables.
- Continuous recording data: Data was collected by continuously recording observations over a specified period of time.
- Laboratory test: Data was acquired through experiments conducted in a laboratory setting.
- Analysis using mathematical formulas: Data was processed and analyzed using mathematical formulas and equations.
- Review of published international journals: Data was gathered by reviewing and extracting relevant information from published international journals.

### 3.2.2 Work flow chart

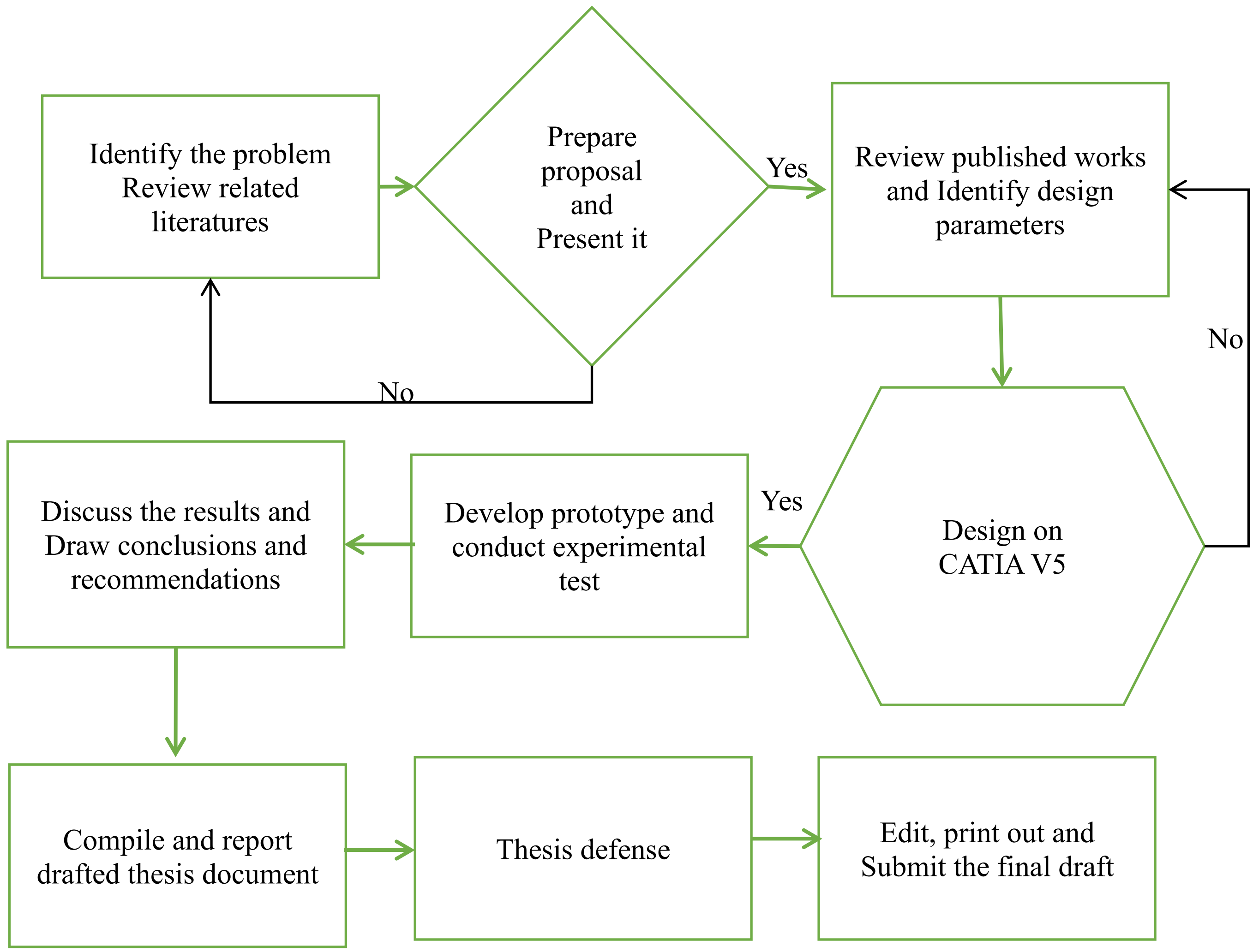



Figure 3:1. Overall work flow chart

### 3.2.3 Conceptual design

A multipurpose stove is a versatile piece of equipment that can be used for a variety of cooking tasks. The conceptual design multipurpose stove was designed by considering of several factors. First and foremost, the stove have designed to be able to accommodate different types of fuel, such as wood, charcoal, briquette and sawdust . It also designed to be portable, so that it can be easily transported to different locations. In addition, the stove was designed with safety in mind, with features such as chimney and stable legs to prevent tipping. The stove also designed to be efficient and easy to clean, with removable parts and ash trays to facilitate maintenance. Overall, the conceptual design of a multipurpose stove shown in figure 3.1 below.

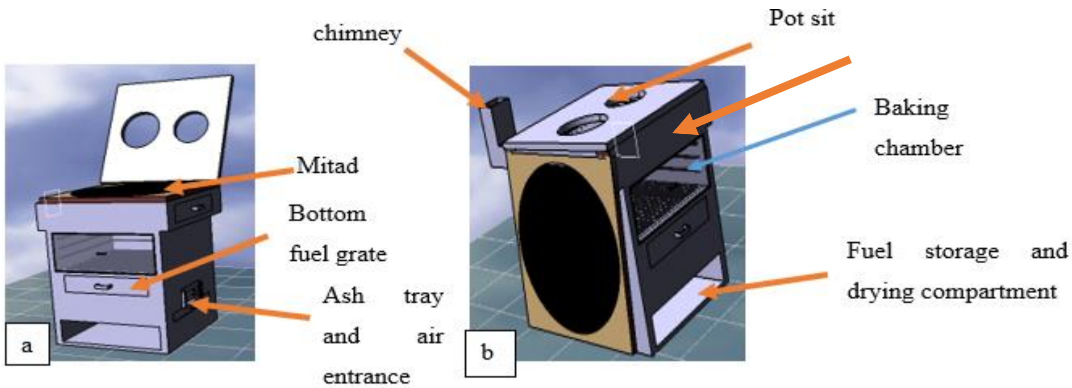



Figure 3:2 Conceptual design of multipurpose stove

### 3.2.4 Briquetting

Briquettes were made from damped waste through using following procedure:

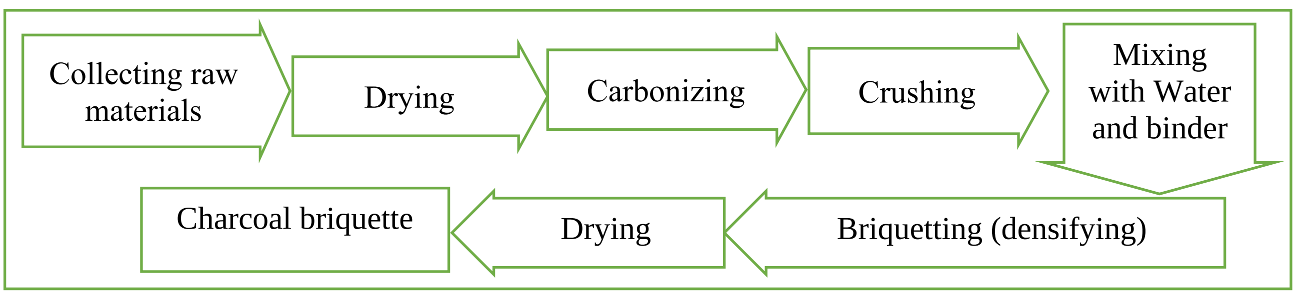



Figure 3:3. Briquette production procedures flow chart

#### 3.2.4.1 Description of study sites

Coffee husks were collected from Hidde dry coffee processing industries found in Oromia regional state, Kellem Wellega, Anfilo, sudi village. Geographically, it is located at 8.651 N latitude, 34.7059 E longitude, and at an altitude of 2206m above sea level.

#### 3.2.4.2 Sampling techniques

The raw coffee husks were collected from where the industry damp and separate foreign unnecessary materials and sun dried. The collected coffee husks were carbonized and grinded there in order to make it simple for transportation. The carbonized and grinded coffee husk were then sent to the Ethiopia Geological Survey for laboratory analysis.

### 3.2.5 Stove Development

The following procedures were followed in order to fabricate the proposed stove:

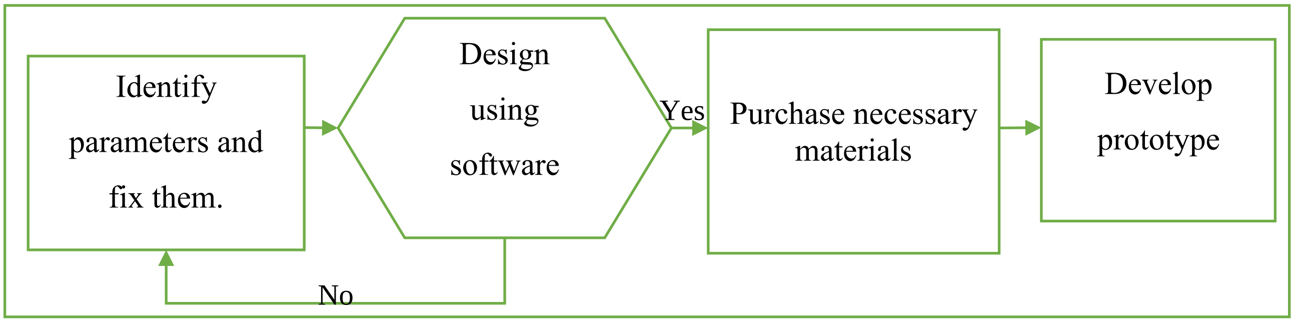



Figure 3:4. Stove development procedure flow chart

### 3.2.6 Conduct an experiment

The fuel was characterized in laboratory through proximate analysis test.

The following test were carried out to test the performance of the multipurpose stove.

- Water Boiling Test (WBT),
- Controlled Cooking Test (CCT) and

For testing measurement instruments required are:

- Thermocouples
- Thermometers
- Flue gas analyzer
- Standard pot and Different pots
- Weighing scale
- Timer(stopwatch)

# CHAPTER 4

# 4. DESIGN AND THEORETICAL ANALYSIS OF STOVE

## 4.1 Introduction

This chapter presents the design, thermal analysis, fuel proximate analysis, and performance parameters of the stove in depth. Temperature gradients between the ignited biomass and the stove body surfaces create energy transfers within the stove structure. The stove's various zonal heat transfers and energy losses have been analyzed through conduction, convection, and radiation heat transfer equations. Broadly, this section examines the design of key stove components including the combustion chamber, ash pan, and injera mitad. Furthermore, heat and energy transfer phenomena occurring within the stove, alongside heat losses stemming from conduction, convection, and radiation mechanisms present in the system, were discussed.

## 4.2 Design of the multipurpose stove

The stove design can be used for baking injera, baking bread and cooking foods in two different pots. The overall CATIA model of the multipurpose stove is indicated in Figure 4.1. The poly stove has combustion chamber with fuel holder and chimney.

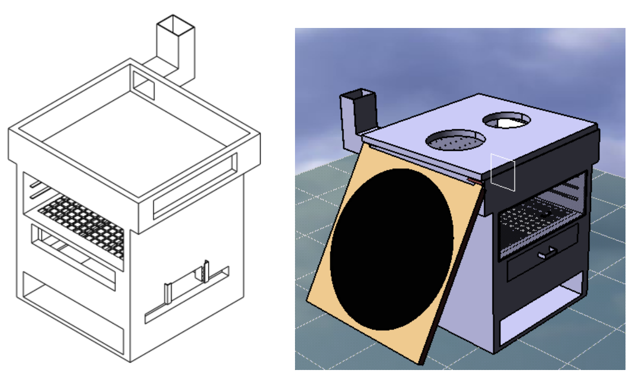


Figure 4:1 The overall CATIA V5 model of the multipurpose stove.

### 4.2.1 Combustion chamber design

Biomass stoves typically have a combustion chamber where the fuel is burned. Combustion chamber design for briquette stove is a process of designing a chamber where the briquettes are burned to produce heat for cooking. The combustion chamber design should consider the characteristics of the briquettes, such as size, shape, density, moisture content and calorific value, as well as the air supply, heat transfer and emissions of the stove. The bottom combustion chamber is shown in Figure 4.2 and 4.3 and the top combustion chamber is shown in Figure 4.4. These chambers are used to holds fuel for the design multipurpose stoves. The combustion chamber design for briquette stove can affect the performance and emissions of the stove, so it should be tested and evaluated using appropriate methods. (Segun and Onilude, 2020)

Optimum chamber size for combustion chamber of charcoal is a process of determining the best dimensions of the chamber that can achieve the desired performance and emissions of the stove. The optimum chamber size depends on several factors, such as the type and quality of charcoal, the air supply and distribution, the heat transfer and retention, and the design of the stove. For the design of combustion chamber the optimum height is ranged between 10-15 cm(Baldwin, 1987).

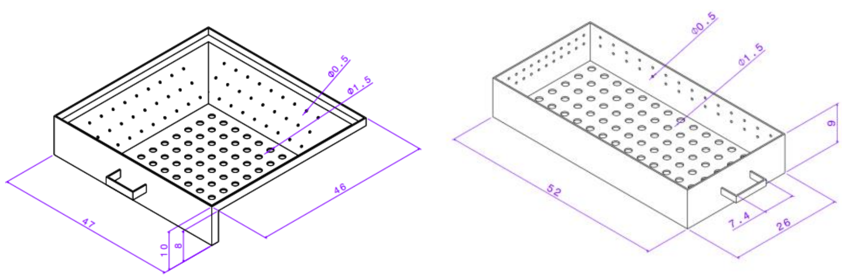



Figure 4:2 Isometric view of a)bottom combustion chamber b)upper cooking combustion chamber

The design of a combustion chamber for a coffee husk briquette charcoal stove involves considerations such as efficient fuel combustion, heat transfer, and emission control. The arrangement and configuration of the coffee husk briquettes within the combustion chamber should facilitate proper airflow and even distribution of heat. This can be achieved by optimizing the placement and orientation of the briquettes to ensure sufficient air supply and minimize unburned fuel. Additionally, adequate control of airflow is crucial for efficient combustion. The design should incorporate adjustable air vents or dampers that allow the regulation of oxygen supply to the combustion chamber. This control mechanism helps optimize the burning rate and ensures complete combustion of the coffee husk charcoal briquettes. Incorporating insulation materials in the combustion chamber design can help retain heat within the chamber and improve overall thermal efficiency. Insulation minimizes heat loss to the surroundings, allowing for better utilization of the heat generated by the burning fuel.

To facilitate the above criteria, trapezoidal grate was developed (Figure 4.2). It has several advantages compare to other type of combustion chamber grate. Some of it are

- Promotes better fuel combustion by allowing for better air distribution and fuel bed agitation. This results in more efficient and complete burning of the fuel, reducing waste and improving energy conversion (Du et al., 2019).
- Allows for more precise control of air distribution and airflow within the combustion chamber. This control enables the optimization of oxygen supply to the fuel bed, facilitating better combustion and reducing the formation of smoke and pollutants (Vanek, 2012).
- Promotes better heat transfer from the burning fuel to the surrounding environment or heat exchangers. This improves overall thermal efficiency and increases the utilization of heat generated during combustion, leading to improved stove performance and reduced fuel consumption(Kreith, 1999).

### 4.2.1 Air entrance design

1. **Stoichiometric Calculations**

The initial principles underlying the combustion of biomass rely on the chemical reactions involved and the stoichiometric conditions for effective combustion. Wang and Yan, (2008)provided a balanced equation to describe the combustion process of biomass, which is as follows:

Table 4:1 Ultimate analysis (weight%, dry basis) (Adem et al., 2022)

| Sample type | C | H | N | $O_2$ |
|---|---|---|---|---|
| Coffee husk | 43.39 | 6.37 | 1.41 | 45.08 |

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

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

2. **Theoretical air and Air-fuel ratio**

According to Adem et al., (2022) the air-to-fuel ratio necessary for achieving complete combustion of coffee husk on a theoretical basis is 5.241.

$$\frac{A}{F} = \frac{m_{air}}{m_{fuel}} = \frac{\dot{m_{air}}}{\dot{m_{fuel}}} \tag{4.1}$$

$$\frac{A}{F} = 5.241 \frac{kg\ of air}{kgof\ fuel}$$

Based on the findings of Tran and White (1992), the burning rate, denoted as , for a typical fuel wood based on the rate of mass loss, falls within the range of 2.92 $gm^{-2}s^{-1}$to 9.80 $gm^{-2}s^{-1}$.

According to research conducted by Tran and White (1992), the burning rate (denoted as dm/dt) for typical fuel wood, calculated based on mass loss over time, lies within a range of 2.92 $gm^{-2}s^{-1}$to 9.80 $gm^{-2}s^{-1}$. .

Assuming a maximum of six layers of fuel pieces, each with a rectangular cross-section of 15 x 15 mm (or more precisely, a circular cross-section with a 15 mm radius), the total surface area of the fuel exposed to combustion can be approximated as roughly fourteen times the cross-sectional area of the combustion chamber. Based on these geometrical assumptions, the mass flow rate of fuel burned per unit time can be formulated as follows:

$$\dot{m}_{fuel} = 14\ddot{m}\, a \tag{4.2}$$

Where: $\ddot{m}$-mass of fuel loss rate($\ddot{m}$ = 9.8gm$^{-2}$s$^{-1}$); $\dot{m}_{fuel}$-mass of the fuel; $a$- area of combustion chamber

The real or actual air flow rate that matches the rate at which mass is being lost during burning can also be calculated using the following equation:

$$\dot{m}_{air} = \frac{A}{F} \times \dot{m}_{fuel} \tag{4.3}$$

This gives a volume rate of air supply based on air density of 1.23 $kgm^{-3}$ ,

$$\dot{V}_{air} = 2.338 \times 10^{-2}\ m^3/s.$$

According to Parker (1969), the area of air opening, $A_{air}$, is related to the volume flow rate, , as

$$\dot{V}_{air} = 23.6\ A_{air}\sqrt{h} \tag{4.4}$$

This gives an area of air opening,

$A_{air} = 0.140\ \times 10^{-2}\ m^2$, for an air opening being rectangular in section with a vertical dimension, h = 50mm, and a horizontal dimension, l = 88.6mm. which can be taken roughly as 100mm for better combustion process.

### 4.2.2 Chimney Design

The primary purpose of chimney design revolves around determining the appropriate diameter for effective functionality. In practical applications, the following inequality is commonly employed to ascertain the chimney diameter(Adem et al., 2022):

$$Ac_{chimney} \leq 10Aair \tag{4.5}$$

where $Ac_{chimney}$ = cross-sectional area of chimney. By substituting the area of the side air opening into the inequality, width and length of the chimney, can be calculated as follows:

width ≤11.83 cm, chimney with length of 11.83cm and 10 cm X 10cm is taken for this study. And the chimney height utilized was 1.5 meters to increase the combustion efficiency and reduce incomplete combustion.

### 4.2.3 Mitad and Enclosure Dimensions

Injera mitad, the traditional Ethiopian clay plate or injera stove, is typically made from clay or a combination of clay and other materials. The exact composition may vary depending on the specific artisan or manufacturer. The diameter of an injera mitad can also vary, but it is generally around 40 to 60 in centimeter. The size of the injera mitad allows for the preparation of a relatively large injera, which is important as injera is often served in large round shapes to accompany various Ethiopian dishes(Teshome et al., 2021). In this study, a clay-made mitad with a diameter of 58cm and a thickness of 2cm was chosen. The lid cover dimension used for this study was 58cm in diameter and 0.5 mm thick Aluminum and has conical shape. The mitad combustion chamber was surrounded by a 1mm thick sheet metal enclosure, and ash and gypsum was utilized as an insulating material to minimize heat loss.

### 4.2.4 Frame and Housing

Frame was made of hollow rectangular bar of 2cmX2cm, 2cmX4cm, 3cmX3cm. All metal bar is joined together by welding. The housing is the encloser around the frame which are sheet metal of 0.5mm and it is wrapped around the frame and joined by riveting. It helps to bound the insulation material which reduce heat loss to the surrounding through conduction. And the bottom part of the body has a dimension of 54 cm x 54 cm X 69 cm and the upper part has dimension of 18cmX64cmX64 cm.

### 4.2.5 Ash pit

Properly managing ash waste is an important consideration for operating biomass stoves. Biomass fuels produces residual ash that must be collected and disposed of. Biomass ash needs to be removed from the stove periodically to maintain performance and prevent clogging. So ash pit was designed and fabricated from galvanized sheet metal and used to remove ash left easily without moving the entire body of the stove. It has a dimension of 30cm X 40cm.

## 4.3 Energy and Exergy analysis of the stove

### 1. Energy balance on mitad lid cover

Energy balance equation for lid cover is calculated from the following thermal resistance circuit.

$$Ein - Eout = \ energy\ accumulated\ in\ the\ lid\ cover \tag{4.6}$$

$$Eout \ = \ Q\ conv\ loss \ + \ Q\ rad\ loss \tag{4.7}$$

$$E_{out} = \ h_{r2}A(T_{lc} - T_a) + h_{c2}A(T_{lc} - T_a) \tag{4.8}$$

$$h_{r2} = \varepsilon_{eff}\sigma(T_{lc}^2 + T_a^2)(T_{lc} + T_a) \tag{4.9}$$

Energy gain by mitad lid cover is from the mitad by convection and radiation and neglecting the side losses.

$$E_{in} = Q_{rad} + Q_{conv} \tag{4.10}$$

$$E_{in} = h_{r1}A(T_m - T_{lc}) + h_{c1}A(T_m - T_{lc}) \tag{4.11}$$

$$h_{r1} = \varepsilon_{eff}\sigma(T_m^2 + T_{lc}^2)(T_m + T_{lc}) \tag{4.12}$$

$$m_{lc}C_{p_{lc}}\frac{dT_{lc}}{dt} = E_{in} - E_{out} = h_{r1}A(T_m - T_{lc}) + h_{c1}A(T_m - T_{lc}) - [h_{r2}A(T_{lc} - T_a) + h_{c2}A(T_{lc} - T_a)] \tag{4.13}$$

### 2. Energy Balance on Mitad

Energy balance on the mitad is given as follows:

$$E_{in} - E_{ut} - E_{loss} = \Delta E_{sys} \tag{4.14}$$

The energy gain by the mitad is from the combusted fuel through radiation and convection and given in eqn. 4.15

$$E_{in} = h_{ri}A\big(T_{fl} - T_m\big) + h_{ci}A\big(T_{fl} - T_m\big) \tag{4.15}$$

Energy lost from the mitad is in the form of convection and conduction and it is given as :

$$E_{loss} = h_{rl}A(T_m - T_{lc}) + h_{cl}A(T_m - T_{lc}) \tag{4.16}$$

Energy utilized (in joules) means the energy used to bake the injera can be calculated using the following equation 4.17.

$$E_{ut} = \frac{(\mathrm{m_b Cp_w (T_b - T_a)} + \ (\mathrm{m_b} - \mathrm{m_i})\mathrm{h_{vap}})}{t_f - t_i} \tag{4.17}$$

The general energy balance equation on mitad is given in the eqn.4.18

$$m_m Cp_m \frac{dT_m}{dt} = \Delta E_{sys}$$

$$\Delta E_{sys} = h_{ri}A\left(T_{fl} - T_m\right) + h_{ci}A\left(T_{fl} - T_m\right) - \left[h_{rl}A(T_m - T_{lc}) + h_{cl}A(T_m - T_{lc}) + \mathrm{m_b Cp_w (T_b - T_a)} + (\mathrm{m_b - m_i})\mathrm{h_{vap}}\right] \quad (4.18)$$

Where mb- mass of batter; mi- mass of injera. Tb- boiling temperature; Ta- ambient temperature; Cpw- specific heat capacity of water

**3. Energy Balance on Baking Chamber**

$$E_{in} - E_{ut} - E_{loss} = \Delta E_{sys} \quad (4.19)$$

Energy gain by the baking chamber is from the bottom fuel combustion chamber through convection and radiation modes of heat transfer.

$$E_{in} = h_{ri}A\left(T_{fl} - T_{bc}\right) + h_{ci}A\left(T_{fl} - T_{bc}\right) \quad (4.20)$$

Energy lost from the baking chamber is to the upper wall and the side walls.

$$E_{loss} = [h_{rl}A(T_{bc} - T_{uw}) + h_{cl}A(T_{bc} - T_{uw})] + 4[h_{rl}A(T_{bc} - T_{sw}) + h_{cl}A(T_{bc} - T_{sw})] (4.21)$$

$$E_{ut} = \frac{\mathrm{m_{batter} Cp_{water} (T_{boil} - T_{room}) + (m_{batter} - m_{bread}) h_{vap}}}{t_f - t_i} \quad (4.22)$$

The general energy balance equation on baking chamber is given by:

$$m_{bc} Cp_{bc} \frac{dT_{bc}}{dt} = \Delta E_{sys}$$

$$= h_{ri}A_{fl}\left(T_{fl} - T_{bc}\right) + h_{ci}A_{fl}\left(T_{fl} - T_{bc}\right) - \left[\begin{matrix} [h_{rl}A_{uw}(T_{bc} - T_{uw}) + h_{cl}A_{uw}(T_{bc} - T_{uw})] \\ +4[h_{rl}A_{sw}(T_{bc} - T_{sw}) + h_{cl}A_{sw}(T_{bc} - T_{sw})] \end{matrix}\right] + \frac{\mathrm{m_{batter} Cp_{water} (T_{boil} - T_{room}) + (m_{batter} - m_{bread}) h_{vap}}}{t_f - t_i}] \quad (4.23)$$

Where : subscript sw – side wall; bc- baking chamber, uw- upper wall, fl -fuel

**4. Energy Balance on Cooking area**

The energy balance of cooking area of multipurpose stove has two cases.

**Case 1: when two pots are used.**

$$E_{in} - E_{ut} - E_{loss} = \Delta E_{sys}$$

Energy is gained by cooking pots from the upper fuel combustion chamber by convection and radiation. The equation given as:

$$E_{in} = h_{ri}A\left(T_{fl} - T_{p1}\right) + h_{ci}A\left(T_{fl} - T_{p1}\right) + h_{ri}A\left(T_{fl} - T_{p2}\right) + h_{ci}A\left(T_{fl} - T_{p2}\right) \qquad (4.24)$$

Energy gained by the cooking both cooking pot lost the energy through radiation and convection to the surrounding  air. The energy lost by both pot 1 and pot2 is given on eqn

$$E_{loss} = [h_{rl}A\left(T_{p1} - T_a\right) + h_{cl}A\left(T_{p1} - T_a\right)]_{p1} + [h_{rl}A\left(T_{p2} - T_a\right) + h_{cl}A\left(T_{p2} - T_a\right)]_{p2} (4.25)$$

Energy utilized is the energy used to boil water in both pot 1 and pot 2.

$$E_{ut} = \frac{\mathrm{m_{wp1}Cp_w(T_b - T_a)}}{(\mathrm{t_f - t_i})_{p1}} + \frac{(\mathrm{m_{wi}} - \mathrm{m_{wf}})_{p1}\mathrm{h_{vap}}}{(\mathrm{t_f - t_i})_{p1}} + \frac{\mathrm{m_{wp2}Cp_w(T_b - T_a)}}{(\mathrm{t_f - t_i})_{p2}} + \frac{(\mathrm{m_{wi}} - \mathrm{m_{wf}})_{p2}\mathrm{h_{vap}}}{(\mathrm{t_f - t_i})_{p2}} (4.26)$$

Where : $m_{wp1}$- mass of water in the pot 1; $m_{wp2}$-mass of water in the pot 2

Subscript *i and f* indicate initial and final

**Case 2: when only one pot is used.**

The fuel grate was filled partially and the energy released from the fuel is directly towards on pot sit only. Energy balance in this case is given as follows:

$$E_{in} - E_{ut} - E_{loss} = \Delta E_{sys}$$

Energy gain by pot is from the fuel combustion chamber by radiation and convection and the equation to calculate the energy gained by the pot is given in eqn…

$$E_{in} = h_{ri}A\left(T_{fl} - T_{p1}\right) + h_{ci}A\left(T_{fl} - T_{p1}\right) \qquad (4.27)$$

Energy is lost from the cooking pot by radiation and convection. The energy lost can be calculated from eqn…

$$E_{loss} = [h_{rl}A\left(T_{p1} - T_a\right) + h_{cl}A\left(T_{p1} - T_a\right)]_{p1} \qquad (4.28)$$

Energy utilized here is the  energy used to boil water in a cooking pot and it is given as :

$$E_{ut} = \frac{\mathrm{m_{wp1}Cp_w(T_b - T_a)}}{\mathrm{(t_f - t_i)}_{p1}} + \frac{\mathrm{(m_{wi} - m_{wf})}_{p1}\mathrm{h_{vap}}}{\mathrm{(t_f - t_i)}_{p1}} \qquad (4.29)$$

## 4.4 Performance of Stove

### 4.4.1 Energy balance of stove

1. When baking alone

$$E_{in} - E_{ut} - E_{lost} = 0$$

$$E_{in} = m_{fc} \times LHV \qquad (4.30)$$

$$E_{ut} = \mathrm{m_{batter}Cp_{water}(T_{boil} - T_{room})} + \mathrm{(m_{batter} - m_{bread})h_{vap}} + m_{baker}C_{pAl}(T_{fb} - T_{ib}) \qquad (4.31)$$

$$E_{lost} = E_{in} - E_{ut}$$

$$\eta_{th_{bc}} = \frac{E_{ut}}{E_{in}} \times 100\% \qquad (4.32)$$

2. When cooking alone

$$E_{in} - E_{ut} - E_{lost} = 0$$

$$E_{in} = m_{fc} \times LHV \qquad (4.33)$$

$$E_{utilized} = \mathrm{m_{water}Cp_{water}(T_{boil} - T_{room})} + \mathrm{(m_{water\ evaporated})h_{vap}} + m_{pot}C_{pAl}(T_{fp} - T_{ip}) \qquad (4.34)$$

$$\eta_{th_c} = \frac{E_{ut}}{E_{in}} \times 100\% \qquad (4.35)$$

3. When baking and cooking simultaneously

$$E_{in} - E_{ut} - E_{lost} = 0$$

$$E_{in} = m_{fc} \times LHV \qquad (4.36)$$

$$E_{utilized} = \begin{bmatrix} [\mathrm{m_{water}Cp_{water}(T_{boil} - T_{room})} + \mathrm{(m_{water\ evaporated})h_{vap}} \\ + m_{pot}C_{pAl}(T_{fp} - T_{ip})] \end{bmatrix} + \begin{bmatrix} \mathrm{m_{batter}Cp_{water}(T_{boil} - T_{room})} + \mathrm{(m_{batter} - m_{bread})h_{vap}} \\ + m_{baker}C_{pAl}(T_{fb} - T_{ib}) \end{bmatrix} \qquad (4.37)$$

$$\eta_{th_{b,c}} = \frac{E_{utilized}}{E_{in}} \times 100\% \qquad (4.38)$$

4. When baking injera alone

$$E_{in} - E_{ut} - E_{lost} = 0$$

$$E_{in} = m_{fc} \times LHV \qquad (4.39)$$

$$E_{utilized} = \mathrm{m_{batter}Cp_{water}(T_{boil} - T_{room})} + \left(\mathrm{m_{batter}} - \mathrm{m_{injera}}\right)\mathrm{h_{vap}} + m_{pan}C_{pClay}\left(T_{fpn} - T_{ipn}\right) \qquad (4.40)$$

$$\eta_{th_{bi}} = \frac{E_{utilized}}{E_{in}} \times 100\% \qquad (4.41)$$

### 4.4.2 Exergy analysis of stove

An overall exergy balance for the system can be written as (Park et al., 2014):

$$Exergy\ input - [Exergy\ recovered + Exergy\ loss] - Exergy\ consumption = Exergy\ accumulation$$

1. Baking alone

Exergy input is given by (Tyagi et al., 2013):

$$\mathrm{E_{Xin}} = m_{fc} \times LHV\left(1 - \frac{\mathrm{T_a}}{\mathrm{T_{bf}}}\right) \times \eta_{\mathrm{cb}} \qquad (4.41)$$

where Ta is ambient temperature, Tbf is temperature of briquette burning (K), and $\eta_{cb}$is theoretical combustion efficiency of the briquette(95%,assumed).

Exergy output is given by (Tyagi et al., (2013) ); Obi et al., (2021)):

$$E_{Xo} = [\mathrm{m_{batter}}C_p\left(T_{f\omega} - T_{iw}\right) + (\mathrm{m_{batter}} - \mathrm{m_{bread}})\mathrm{h_{vap}}] \times (1 - \frac{\mathrm{T_a}}{\mathrm{T_{fw}}}) + m_{baker}C_{pAl}\left(T_{fbc} - T_{ibc}\right) \times \left(1 - \frac{\mathrm{T_a}}{\mathrm{T_{fbc}}}\right) \qquad (4.42)$$

Exergy efficiency, $\psi$ (%) defined as the ratio of output exergy to input exergy is given as (Pandey et al.,( 2012); Obi et al., (2021)).

:

$$\psi = \frac{E_{Xo}}{\mathrm{E_{Xin}}} \times 100\%$$

2. Cooking alone

$$\mathrm{E_{Xin}} = m_{fc} \times LHV\left(1 - \frac{\mathrm{T_a}}{\mathrm{T_{bf}}}\right) \times \eta_{\mathrm{cb}} \qquad (4.43)$$

$$E_{xo} = m_w C_p (T_{f\omega} - T_{iw})\left(1 - \frac{\mathrm{T_a}}{\mathrm{T_{fw}}}\right) + m_{pot} C_{pAl}(T_{fp} - T_{ip})\left(1 - \frac{\mathrm{T_a}}{\mathrm{T_{fp}}}\right) \quad (4.44)$$

$$\psi = \frac{E_{Xo}}{\mathrm{E_{Xin}}} \times 100\%$$

3. When baking injera alone

$$E_{Xin} = m_{fc} \times LHV\left(1 - \frac{\mathrm{T_a}}{\mathrm{T_{bf}}}\right) \times \eta_{\mathrm{cb}}$$

$$E_{xo} = \Bigg[\left[\mathrm{m_{batter}Cp_{water}(T_{fw} - T_a)} + (\mathrm{m_{batter}} - \mathrm{m_{injera}})\mathrm{h_{vap}}\right] \times \left(1 - \frac{\mathrm{T_a}}{\mathrm{T}_{fw}}\right) + \left[(\mathrm{m_{batter}} - \mathrm{m_{injera}})\mathrm{h_{vap}} + m_{pan} C_{pClay}(T_{fpn} - T_{ipn})\right] \times \left(1 - \frac{\mathrm{T_a}}{\mathrm{T_{fpn}}}\right)\Bigg]$$

$$\psi = \frac{E_{Xo}}{\mathrm{E_{Xin}}} \times 100\% \quad (4.45)$$

## 4.5 Fuel characterization

### 4.5.1 Proximate Analysis of Fuel

Proximate analysis is a method of determining the composition of a fuel. It is used to determine the moisture content, volatile matter, ash content, and fixed carbon content of a fuel.

#### 4.5.1.1 Moisture content

Moisture content is the percentage of water in a fuel. The moisture content of biomass fuel is an essential parameter to consider because it directly affects the combustion efficiency and overall performance of the fuel. High moisture content can lead to incomplete combustion, reduced energy output, increased emissions, and potential operational issues in combustion systems.

The ideal moisture content of biomass fuel depends on the intended use and the type of combustion system. In general, biomass fuel is considered suitable for combustion when its moisture content is below 20%.

$$MC\% = \frac{Mi - Mf}{Mf} \times 100\% \quad (4.46)$$

Where: MC% represents the percentage of moisture content on a dry mass basis present in the fuel sample. It is calculated using the initial mass of the fuel sample (Mi) before drying, and the final mass of the fuel (Mf) after drying the sample in an oven maintained at 105°C.

#### 4.5.1.2 Volatile Matter

Volatile matter in biomass fuel refers to the portion of the fuel that can be easily vaporized or transformed into gas when subjected to heat. It consists of organic compounds with low boiling points, such as water, volatile organic compounds (VOCs), and other volatile components. Volatile compounds are generated through the thermal decomposition of biomass fuels when exposed to heat. The volatile matter content of a biomass fuel has multiple salient implications. Firstly, it influences the combustion properties, with higher volatile matter correlating to faster, easier ignition per the authors. Secondly, volatile matter impacts attainable energy yield, as fuels richer in volatiles produce increased energy per unit mass. According to Assefa et al. (2022) and Sisay et al. (2020), the volatile matter (VM) percentage of the briquettes was quantified via the standard CEN/TS 15148 method. This involved heating a dried briquette sample to 950°C in an inert atmosphere for six minutes. The volatile matter percentage was calculated by comparing the initial and final sample weights after heating as a ratio of the original briquette mass. The volatile matter was mathematically formulated as:

$$VM = \frac{M1 - M2}{M} \times 100\% \tag{4.47}$$

Where: M1 = Initial mass of the briquette sample dried at 105°C, in grams M2 = Final mass of the sample after heating to 950°C, in grams; M = Total mass of the original briquette sample, in grams VM = Percentage of volatile matter present in the fuel, in percent.

#### 4.5.1.3 Ash content

Ash content in biomass briquettes refers to the amount of inorganic materials or minerals that remain after the briquette is burned. It is an important characteristic to consider when evaluating the quality and suitability of biomass briquettes for various applications.

Ash content is expressed as a percentage and higher ash content can lead to increased maintenance requirements and reduced combustion efficiency. The composition of ash residue can also affect emissions during combustion, with certain minerals contributing to particulate matter, fouling, and corrosion. Minimizing the content of these elements in biomass feedstocks is desirable to produce briquettes with lower ash content and improved combustion characteristics.

Overall, the ash content in biomass briquettes is an important parameter that affects their combustion performance, efficiency, and environmental impact. It is often considered alongside other factors, such as calorific value, moisture content, and ash composition, when assessing the suitability of briquettes for specific applications, such as heating, power generation, or industrial processes.

To determine ash content, the briquette sample was heated in a crucible at 750°C for 3 hours, following standard methods. The ash content was calculated by taking the residual mass after heating and dividing it by the initial briquette sample mass, as follows:

$$AC = \frac{M_{w950} - M_{w750}}{M_{ws}} \times 100\% \tag{4.48}$$

where $M_{w950}$ -weight of sample at 950°C, in g, $M_{w750}$ -weight of sample at 750°C, in g, $M_{ws}$ - weight of briquette sample, in g, and AC - percentage of ash content, in %.

#### 4.5.1.4 Fixed Carbon

The percentage of the fixed carbon content of the briquettes was calculated by subtracting the amount of volatile matter, ash content, and moisture content from 100, and the percentage of the fixed carbon content of the briquettes was calculated:

$$FC = 100\% - (MC + VM + AC) \tag{4.49}$$

where VM - volatile matter, in %, AC- ash content, in %, MC-moisture content, in %, and FC - fixed carbon, in %

#### 4.5.1.5 Calorific Value of the Fuel

The calorific value refers to the total heat energy obtainable from combusting a fuel, as described by the higher heating value (HHV) representing theoretical maximum heat, and lower heating value (LHV) denoting practically extractable heat. As stated, HHV indicates the absolute upper limit of thermal energy possible via complete combustion, while LHV accounts for losses from water vaporization to define usable energy. Per the source, biomass calorific values depend on moisture content and density. The LHV can be calculated via the following mathematical relations:

$$LHV = HHV - 10.55(Mc + 9H) \tag{4.49}$$

There is also another formula used to calculate the LHV (Cengel and Boles, 2015):

$$LHV = HHV - (Mc \times hvap) \tag{4.50}$$

Where: LHV = lower heating value of fuel, HHV = higher heating value of fuel, Mc = Weight % of moisture in fuel, hvap= Heat of vaporization of water (2.26MJ/kg) and H = Weight % of hydrogen in fuel (Adem and Ambie, (2017); Bantelay and Gabbiye, (2014)).

## 4.6 Performance test of multipurpose stove

### 4.6.1 Water boiling tests

The water boiling test (WBT) represents a standardized laboratory procedure for evaluating key cooking stove thermal and emissions performance indicators. Specifically, it allows quantification of a given stove design's fuel utilization efficiency in heating a measured volume of water within a representative cooking vessel to boiling temperature. Additionally, the WBT enables measurement of pollutant emissions generated throughout the defined boiling process.

The test is conducted by placing a known quantity of water inside a standardized cooking pot and igniting a specified mass of fuel within the stove. The time elapsed until boiling is attained is documented. The remaining unburnt fuel is also weighed post-test to determine total consumption. As the authors elucidate, the relatively uncomplicated and cost-effective WBT permits comparative assessment of various stoves' thermal efficiencies and emissions profiles. It further provides engineers and manufacturers with actionable data to iteratively enhance prototypes.

#### 4.6.1.1 Parameters to be calculated after WBT

1. **Time to boil**

It is a measure of how long it takes for a specified quantity of water to reach its boiling point when placed on a cookstove. It is often used as a metric to assess the performance and efficiency of the stove, particularly in the context of the Water Boiling Test (WBT).

The time to boil is an important factor because it reflects the stove's heating capacity and efficiency in converting fuel energy into useful heat. A shorter time to boil indicates that the stove can quickly and effectively transfer heat to the pot and the water, resulting in faster cooking times. The time to boil can be calculated using the formula:

$$\Delta t = t_f - t_i \tag{4.51}$$

2. **Burning rate**

Burning rate refers to the rate at which fuel is consumed and converted into heat energy in a stove. It indicates how quickly the fuel is consumed during the combustion process and determines the heat output and overall efficiency of the stove.

The burning rate is typically measured in terms of fuel mass consumed per unit of time. Common units of measurement include kilograms per hour (kg/h) or grams per minute (g/min). It represents the amount of fuel that is burned and converted into heat energy within a specific time frame.

The formula to calculate the burning rate in a stove is:

$$Burning\ Rate = Fuel\ Mass\ Consumed\ /\ Time$$

$$r_b = \frac{m_{fc}}{t_f - t_i} \tag{4.52}$$

Where:

- rb- Burning Rate; mfc-Fuel Mass Consumed; t-Time

To calculate the burning rate, you need to measure the fuel mass consumed during a specific time interval. This can be done by weighing the fuel before and after a designated period of use and subtracting the initial fuel mass from the final fuel mass. The difference represents the amount of fuel consumed during that time.

$$Fuel\ Consumed\ =\ Initial\ Fuel\ Mass\ -\ Final\ Fuel\ Mass$$

$$m_{fc} = m_{fi} - m_{ff} \tag{4.53}$$

Where:

$m_{fc}$-Fuel Consumed; $m_{fi}$-Initial Fuel Mass; $m_{ff}$-Final Fuel Mass

3. **Equivalent fuel consumed**

This is a calculation that adjusts the amount of briquette that was burned in order to account for two factors: (1) the energy that was needed to remove the moisture in the briquette and (2) the amount of char remaining unburned. The calculation is done in the following way:

$$m_{fce} = m_{fc}(1 - 1.0885MC) \tag{4.54}$$

The factor of 1− (1.0885 ∗m) adjusts the mass of briquette burned by the amount of fuel required to heat and evaporate MC *$m_{fc}$ grams of water. It takes roughly 2260 kJ to evaporate a kilogram of water, which is roughly 8.85% of the calorific value of dry briquette. Thus, if briquette consists of mc% moisture, the mass of fuel that can effectively heat the pot of water is reduced by roughly 1− (1.0885 ∗mc) because the water must be boiled away.

4. **Water vaporized**

This is a measure of the amount of water lost through evaporation during the test. It is calculated by simple subtraction of initial weight of pot and water minus final weight of pot and water.

$$m_{w_v} = m_{p_i} - m_{p_f} \tag{4.55}$$

Where: $m_{w_v}$- mass of water vaporized; $m_{p_i}$ -mass of pot with water before the test (initially)

$m_{p_f}$- mass of pot with water after the test (finally)

5. **Water remaining at the end of the test**

This is a measure of the amount of water heated to boiling. It is calculated by simple subtraction of final weight of pot and water minus the weight of the pot.

$$m_{w_r} = m_{p_f} - P \tag{4.56}$$

Where : P- mass of pot with no water in it; $m_{w_r}$- Water remaining at the end of the test

6. **Specific Fuel consumption**

Specific consumption can be defined for any number of cooking tasks and should be considered "the fuel required to produce a unit output" whether the output is boiled water, cooked beans, or loaves of bread.

$$\text{SFC} = \frac{m_{fce}}{m_{p_f} - P} \tag{4.57}$$

7. **Temperature corrected specific fuel consumption**

This corrects specific consumption to account for differences in initial water temperatures. This facilitates comparison of stoves tested on different days or in different environmental conditions. The correction is a simple factor that "normalizes" the temperature change observed in test conditions to a "standard" temperature change of 75 ºC (from 25 to 100). It is calculated in the following way.

$$T_c SFC = \frac{m_{fce}}{m_{p_f} - P} \times \frac{75}{T_f - T_i} \tag{4.58}$$

8. **Fire power**

This is a ratio of the fuel energy consumed by the stove per unit time. It tells the average power output of the stove (in Watts).

$$F_p = \frac{m_{fce} \times LHV}{60(t_f - t_i)} \tag{4.59}$$

9. **Turn down ratio**

In a stove, the turndown ratio is to the ratio of the maximum to minimum heat output of the stove. A higher turndown ratio means that the stove can be more precisely controlled, which can lead to more efficient use of fuel and a more comfortable cooking experience.

The formula for calculating the turn down ratio of a stove is:

Turn Down Ratio = Maximum Heat Output / Minimum Heat Output

$$TDR = \frac{Q_{max}}{Q_{min}} \tag{4.60}$$

$$TDR = \frac{F_{P_h}}{F_{P_s}} \tag{4.61}$$

10. **Thermal efficiency**

This is a ratio of the work done by heating and evaporating water to the energy consumed by burning fuel. It is calculated in the following way.

$$\eta_t = \frac{4.186\left(m_{p_i} - P\right) \times \left(T_{wf} - T_{wi}\right) + 2260 \times m_{we}}{m_{fc} \times LHV} \tag{4.62}$$

In this calculation, the work done by heating water is determined by adding two quantities: (1) the product of the mass of water in the pot, $(m_{p_i} - P)$, the specific heat of water (4.186 J/gºC), and the change in water temperature $(T_{wf} - T_{wi})$ and (2) the product of the amount of water evaporated from the pot and the latent heat of evaporation of water (2260 J/g). The denominator (bottom of the ratio) is determined by taking the product of the equivalent fuel consumed during this phase of the test and the LHV.

## 4.6.2 Control cooking test

The controlled cooking test (CCT) is a method of evaluating the performance of a cook stove. It is conducted by cooking a standard meal on the stove and measuring the amount of fuel used, the time it takes to cook, and the quality of the food. The CCT is a valuable tool for comparing the performance of different cook stoves and for identifying the factors that affect stove performance. It can also be used to assess the impact of cook stoves on household health and well-being.

The CCT is typically conducted in a laboratory setting, but it can also be conducted in the home. The meal that is cooked is typically a simple, local dish that is representative of the foods that are typically cooked on the stove. The amount of fuel used is measured by weighing the fuel before and after cooking. The time it takes to cook is measured by a stopwatch.

#### 4.6.2.1 Parameters to be calculated in CCT

1. **Total mass of food cooked ($M_f$)**

This is the final weight of all food cooked; it is simply calculated by subtracting the weight of the empty pots from the pots and food after the cooking task is complete:

$$M_f = \sum_{j=1}^{4} (M_{pcfj} - M_{pj}) \tag{4.63}$$

where j is an index for each pot (up to four).

2. **Equivalent fuel consumed**

This is defined as for the WBT, adjusting for the amount of briquette that was burned in order to account for the briquette that must be burned in order to vaporize moisture in the briquette.

$$m_{fce} = m_{fc}(1 - 1.0885MC) \tag{4.64}$$

3. **Specific fuel consumption (SC)**

This is the principal indicator of stove performance for the CCT. It tells the tester the quantity of fuel required to cook a given amount of food for the “standard cooking task”. It is calculated as a simple ratio of fuel to food:

$$SC = \frac{m_{fce}}{M_f} \tag{4.65}$$

## 4.7 Thermal Efficiency of The Injera Mitad by Heat Loss or Indirect Method

The energy efficiency of the system can also be expressed in terms of overall heat losses ($Q_L$) as,

$$\eta = 1 - \frac{Q_L}{Q_e} \tag{4.66}$$

The overall heat loss from the side, top and bottom of the mitad can be found as;

$$Q_L = U_L A(T_m - T_a) \tag{4.67}$$

The total heat loss coefficient ($U_L$) is the sum of the heat loss from the top ($U_t$), bottom ($U_b$) and sides ($U_s$) of the stove (Duffie and Beckman, 2013):

$$U_L = U_t + U_b + U_s \tag{4.68}$$

The top loss coefficient ($U_t$) can be estimated by considering convection heat losses (from mitad to lid cover ($h_{C_1}$) and lid cover to sky ($h_{2c}$)) and radiation heat losses (from the mitad to lid cover ($h_{1r}$) and from lid cover to sky ($h_{2r}$)) in the upward direction. Thus, the effective top heat loss coefficient is given by (Duffie and Beckman, 2013):

$$U_t = \left[\frac{1}{h_{1c} + h_{1r}} + \frac{1}{h_{2c} + h_{2r}}\right]^{-1} \tag{4.69}$$

$$h_{1c} = \frac{K_a}{L} Nu \tag{4.70}$$

The Nusselt number in terms of the Rayleigh number for air between mitad and lid cover is given by (Duffie and Beckman, 2013):

$$Nu = 1 + 1.44\left[1 - \frac{1708\, sin(1.8\beta)^{1.6}}{R_a \cos\beta}\right]\left[1 - \frac{1708}{R_a \cos\beta}\right]^{+} + \left[\left(\frac{R_a \cos\beta}{5830}\right)^{1/3} - 1\right]^{+} \tag{4.71}$$

"+" exponent means only the positive value of the square bracket is to be used. Zero is to be used for negative value. The Rayleigh number is given by:

$$R_a = \frac{2g(T_m - T_l)\, Pr\, L^3}{(T_m + T_l)\nu^2} \tag{4.72}$$

$$h_{2c} = 5.7 + 3.8V \tag{4.73}$$

$$h_{1r} = \sigma \left[\frac{1}{\varepsilon_m} + \frac{1}{\varepsilon_l} - 1\right]^{-1} \left[\frac{(T_m + 273)^4 - (T_l + 273)^4}{T_m - T_l}\right] \quad (4.74)$$

$$h_{2r} = \varepsilon_l \sigma \left[\frac{(T_l + 273)^4 - (T_\infty + 267)^4}{T_l - T_\infty}\right] \quad (4.75)$$

Neglecting the bottom convective heat loss and assuming one dimensional steady state heat flow through the bottom insulation, the bottom heat loss coefficient $(U_b)$ is expressed as:

$$U_b = \frac{K_i}{\delta_b} \quad (4.76)$$

The side loss coefficient $(U_s)$ is given by:

$$U_s = \frac{Ld}{A_{side}} \frac{K_i}{\delta_s} \quad (4.77)$$

For bottom losses, the convection and radiation film coefficient relations, respectively are

$$h_{br} = \sigma \left[\frac{1}{\varepsilon_{steel}} + \frac{1}{\varepsilon_{steell}} - 1\right]^{-1} \left[\frac{(T_{bottom} + 273)^4 - (T_\infty + 273)^4}{T_{bottom} - T_\infty}\right] \quad (4.78)$$

The property of the mitad materials needed to find the thermal efficiency of the mitad by indirect method are emittance of aluminum lid and mitad were taken as $\varepsilon_l$=0.11 and $\varepsilon_m$=0.95, respectively. The density and specific heat capacity of the mitad clay were taken to be 1900 kg/m3and 830 kJ/kg K (Gashaw, 2011).

# CHAPTER 5

# 5. EXPERIMENTAL SETUP AND PROCEDURE

## 5.1 Introduction

This chapter included the fabrication process of multi-purpose stove, coffee husk charcoal briquette, the experimental setup and procedures and also equipment used with clear description and the experimentation and its analysis.

## 5.2 Fabrication of Multipurpose Stove

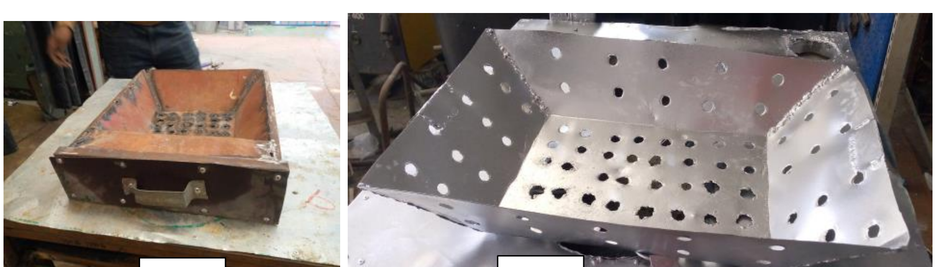
The materials used for constructing the components of multi-purpose stove and molder were purchased from the local market. Availability and cost of the materials in the local market were considered while selecting the materials for each component.

### 5.2.1 Body Frame and Housing

The material used for construction of body frame is a round hollow rectangular bar of 4cmX 4cm and 4cmX 2cm. The housing was riveted to the frame in all six directions and they were galvanized sheet metal of thickness 0.5mm.

### 5.2.2 Combustion Chamber Grates

The combustion chamber grates were made from sheet metal of thickness 2mm and their dimension is 30cmX40cmX10cm.



a b

Figure 5:1 Fabricated grate a) upper combustion chamber grate and b) bottom combustion chamber grate

### 5.2.3 Injera Baking Pan

The injera making pan was bought from market and it is made from clay and has thickness of 15mm and diameter of 58cm.

Figure 5:2 Multipurpose stove when baking pan is assembled

### 5.2.4 Top Cooking Pot Sit and Baking Chamber

The cooking area found at the top of the stove was made of sheet metal of 1mm and 2mm thickness and wood ash and gypsum mixture was used as insulation.

Figure 5:3 Multipurpose stove when cooking part is assembled

## 5.3 Preparation of Coffee husk Bio-briquette Fuel

### 5.3.1 Collection of Biomass and Drying

The process involves gathering coffee husks from the Hidde dry coffee processing industry located in the village of Sudi, Kellem Wellega, Oromia regional state. These coffee husks are then exposed to the sun for a period of 2-3 days to decrease and eliminate the moisture content in the biomass. According to Bhattacharya et al. (2002), it is crucial to attain a moisture range of 8% to 12% in the biomass material to ensure its suitability for briquetting. Although drying adds an extra cost to the briquetting process of crop residues, it is a necessary step. Among the various drying methods, sun drying is the most convenient and cost-effective for biomass. Bandara (2018) found that sun drying led to a decrease in the weight of the biomass.

(a) (b)

Figure 5:4 Collecting coffee husk a) coffee husk damped at Hidde coffee processing industry (b) coffee husk sun drying

#### 5.3.1.1 Carbonizing and Grinding

Carbonization involves converting an organic substance into carbon, typically achieved through pyrolysis. Pyrolysis is a high-temperature process carried out in an oxygen-deprived environment, often facilitated by a charcoal kiln. When producing briquettes from coffee husks, two methods can be employed: the carbonize-first method and the densify-first method. The carbonize-first method is commonly utilized in East Africa due to its technical simplicity. In this approach, the coffee husks undergo carbonization, transforming them into charcoal using a charcoal kiln. The resulting charcoal is then crushed into a powder and combined with corn starch binder. During this study, the 0.5 kg of carbonized coffee husk were obtained from 1kg of raw coffee husk. And also, 2kg of raw coffee husk was used as fuel for carbonization of 1kg of coffee husk.

(a) (b)

Figure 5:5 Coffee husk carbonization a) carbonized b) grinded carbonized coffee husk

### 5.3.2 Binder Preparation and Mixing

For briquetting, corn flour was employed as a binding agent. The ratio of corn flour to water used was 1:10, while the biomass to binder ratio was 9:1. The mixture was heated at a temperature of 65°C. The corn flour and water mixture were heated for a duration of 10 minutes, resulting in a sticky consistency solution. Continuous stirring was maintained during the gel preparation stage to avoid the formation of lumps. Subsequently, the dried biomass was added to the mixture and thoroughly mixed, enhancing the adhesion of the powder.

Figure 5:6 Mixing powder carbonized coffee husk with binder

### 5.3.3 Briquetting and drying

The biomass and the mixture with binder were made into briquettes using a briquette press. For the mechanical operation, the biomass and mixture were loaded directly into the briquetting molder to form uniform-sized cylindrical briquettes. Each briquette has a diameter of 3.5cm and a height of 4.5cm. The briquettes produced were sundried for one (1) week until the required moisture content was attained (Borres Jr and Mora, 2022) .

(a) (b)

Figure 5:7 Molding and Drying a) molding coffee husk bio-briquette b) briquette drying under sun

## 5.4 Experimental Setups


Figure 5:8 Experimental setup during a)water boiling test b) injera baking

## 5.5 Experimental Procedures

### 5.5.1 Water Boiling Test Procedures

Water boiling tests are commonly conducted to evaluate the performance of biomass stoves. In this test, a predetermined amount of water is heated until it reaches its boiling point using the stove, and the time required to achieve boiling is measured. This test serves as an indicator of the stove's thermal efficiency and its ability to transfer heat effectively to the cooking vessel.

The evaluation of the cookstove's performance involved three sets of water boiling tests, each comprising three distinct phases: cold start, hot start, and simmering phase. The initial two phases represent the cooking period, while the final phase involves maintaining the temperature of the pot's contents for 45 minutes at low power.

For each experimental set, data regarding water temperatures, fuel weight, and water weight were recorded. Based on the collected experimental data, various parameters such as thermal efficiency, firepower, mass flow rate, cooking time, specific fuel consumption, and exhaust emissions were investigated. During the assessment of thermal efficiency, the boiling point of water was measured to be 94.506°C for Adama city, located at an altitude (elevation) of 1648 meters (Waganesh, 2021).

$$T_b = \left(100 - \frac{h}{300}\right) ℃ \tag{5.1}$$

where $T_b$ is the local boiling point of water to account for the variations as a result of elevation.

#### 5.5.1.1 Cold Start

Cold start in water boiling tests is the first phase of the test, where the tester begins with the stove at room temperature and uses a pre-weighed bundle of briquette or other fuel to boil a measured quantity of water in a standard pot. This phase is intended to simulate the typical morning cooking task, where the stove is cold and needs to be ignited. The cold start test can help to evaluate the ignition time, fuel consumption, thermal efficiency and emissions of the stove[1].

#### 5.5.1.2 Hot Start

Hot start in water boiling tests is the second phase of the test, where the tester continues with the stove while it is still hot from the first phase and uses another pre-weighed bundle of fuel to boil a fresh pot of cold water. This phase is intended to simulate a typical evening cooking task, where the stove is already hot from previous use. The hot start test can help to evaluate the ignition time, fuel consumption, thermal efficiency and emissions of the stove when it is hot.

## 5.6 Equipment Description

The following are the equipment and instruments used during the experimental evaluation of the multipurpose stove.

1. **Infrared thermometer**

An infrared thermometer, also known as a non-contact thermometer or a temperature gun, is a device that measures the surface temperature of an object or a person without making direct contact. It works by detecting and measuring the infrared energy emitted by an object, which is directly related to its temperature. Here it used to measure the temperature of injera mitad surface and the temperature of the briquette (figure 6:9).

2. **Digital weight balance**

A digital weight balance, also known as a digital scale or electronic scale, is a device used to measure the weight or mass of an object. It utilizes electronic components and a load cell to provide accurate and precise weight readings. During the experiment digital weight balance is used so many times, during measuring mass of fuel, mass of water, mass of pot, and etc

Figure 5:9 digital weight balance during briquette fuel preparation

3. **Thermocouples**

Thermocouples are temperature sensors that are widely used for measuring temperature in various applications. They are composed of two different types of metal wires or alloys joined together at one end, forming a junction. The junction is exposed to the temperature being measured, while the other ends of the wires are connected to a measuring instrument, typically a thermocouple meter or a temperature controller.

4. **Stopwatch**

A stopwatch is a handheld device that measures the elapsed time of an event. it was used to measure the time it takes during water boiling tests and also for surface temperature vs time and during injera and bread baking.


Figure 5:10 Stopwatch

# CHAPTER 6

# 6. RESULT AND DISCUSSION

## 6.1 Introduction

This chapter discusses and presents the findings obtained from laboratory tests, numerical calculations, and experimental tests. The first part focuses on comparing the laboratory test results with existing literature and presenting the experimental results related to the fuel. The subsequent section presents the numerical findings concerning the fuel briquette, along with a comparison to previous research. Finally, the chapter discusses and presents the numerical and experimental results pertaining to the multi-purpose stove.

## 6.2 Bio-briquette Characterization

### 6.2.1 Physical Properties of Bio briquette

Coffee husk prepared has a diameter of 3.5 cm and height of 4.5 cm. and each weigh 27g on average. Its density is 623.6 kg/m^3.

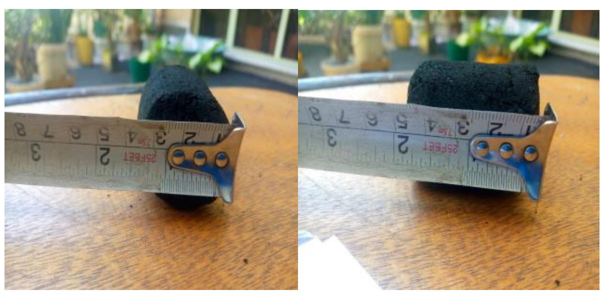


Figure 6:1 Coffee husk  bio-briquette Fuel size

### 6.2.2 Thermal Properties of Coffee Husk Bio-Briquettes

#### 6.2.2.1 Proximate Analysis and Calorific Value of Fuel

Carbonized coffee husk sample was tested in Ethiopia Geological survey laboratory (The laboratory report is on Appendix 4.) and the proximate analysis and calorific value were presented in the following table 6.1.

Table 6:1 Proximate analysis of bio-briquette fuels

| Fuel | Moisture content | Volatile matter(%) | Fixed carbon(%) | Ash content(%) | Calorific value(cal/g) |
|---|---|---|---|---|---|
| Carbonized coffee husk | 7.18 | 28.6 | 50.34 | 13.87 | 6108.99 |

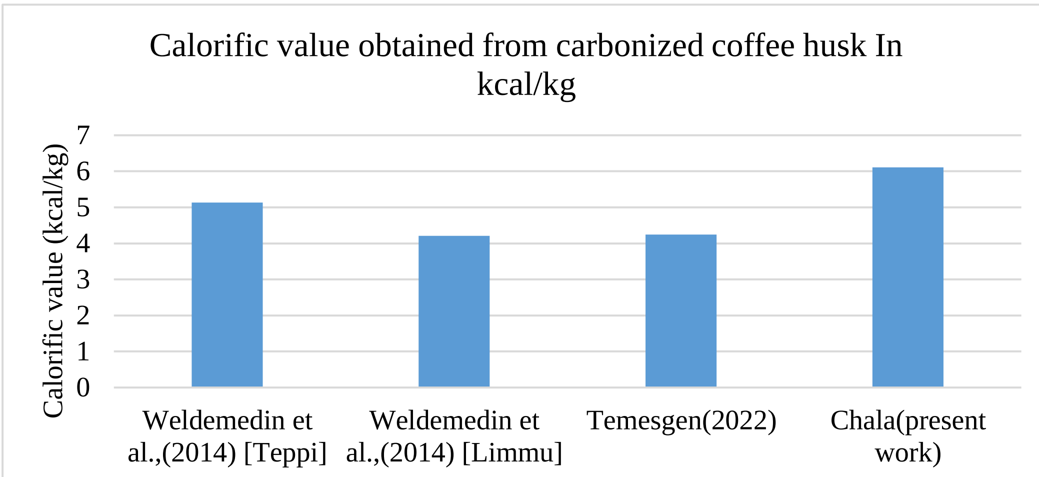



Figure 6:2 Calorific value or HHV of coffee husk bio-briquette comparison

The calorific value of carbonized coffee husk varies depending on the location and method of carbonization. The four studies you have been analyzed and show a range of calorific values, from 4.21 kcal/kg to 6.11 kcal/kg. The study by Weldemedin (2014) found that the calorific value of carbonized coffee husk was higher in Teppi (5.13 kcal/kg) than in Limmu (4.21 kcal/kg). This may be due to the different methods of carbonization or coffee bean kind.

The study by Temesgen (2022) found a lower calorific value of 4.24 kcal/kg. And the coffee husk carbonized for this research found the highest calorific value of 6.11 kcal/kg (Appendix 4). The results of these studies suggest that carbonized coffee husk has the potential to be a valuable source of energy. However, more research is needed to determine the optimal method of carbonization for maximizing the calorific value of coffee husk. Overall, the calorific value of carbonized coffee husk is a function of the location, method of carbonization, and the length of time for which the coffee husk is carbonized. The higher the calorific value, the more energy the carbonized coffee husk can produce.

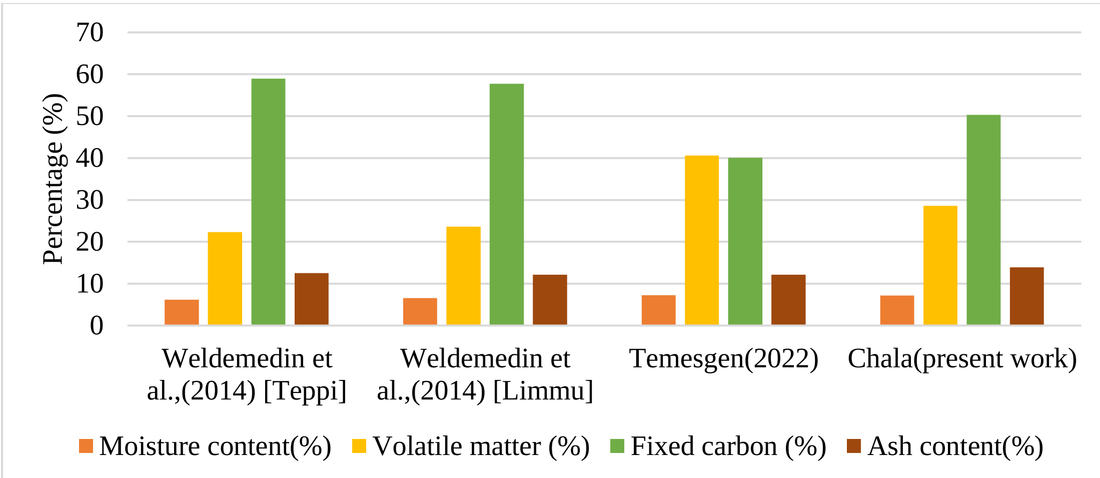



Figure 6:3 Proximate analysis of coffee husk bio-briquette comparison

The moisture content found in this research is greater than the moisture content obtained by Weldemedhin et al., (2014) which were 6.18 and 6.53%and less than moisture content obtained by Temesgen et al. (2022)which was 7.22%. This is happened due to drying techniques and kind of coffee husk and also the location where coffee husk was collected. The volatile matter of coffee husk bio-briquette found was in between the volatile matter of coffee husk prepared by Weldemedhin et al., (2014) and Temesgen et al. (2022). The more volatile matter the more smoke it produce. A study by the University of California, Berkeley found that "fuels with lower fixed carbon contents produce more smoke than fuels with higher fixed carbon contents." Further studies found that fuels with less fixed carbon burn less efficiently and produce more smoke (Basu, 2018) and also fuels with less fixed carbon produce more pollutants, including smoke, when they burn. As you can be seen in Figure 6.3, the briquettes made in this study has relatively higher moisture content, a lower volatile matter content, and higher fixed carbon content.

The higher moisture content of the briquettes found in this study could make them more difficult to ignite and burn and thus require sun drying before used as fuel. However, the higher fixed carbon content could make them more efficient as a fuel source. In the contrary, the higher calorific value of the briquettes could make them more attractive option for users who are looking for a fuel source with a high energy density. Overall, the briquettes in this work has a different proximate analysis than the briquettes from the other three research papers. The differences in the proximate analysis could be due to a number of factors, including the variety of coffee beans used, the method of processing the coffee husks, and the way in which the briquettes are made. These results indicate that the properties of carbonized coffee husk, including moisture content, volatile matter, fixed carbon, ash content, and calorific value, vary among the studies conducted by different authors. These variations could be influenced by factors such as sample characteristics, analytical methods, and processing techniques. Standardization of procedures is crucial to ensure accurate and comparable results in proximate analysis of carbonized coffee husk.

### 6.2.3 Combustion and Emission of Bio-Briquette

When coffee husk bio-briquettes are burned, they undergo a combustion process that releases energy in the form of heat. The combustion of bio-briquettes typically involves three main stages: ignition, flaming combustion, and smoldering combustion (shown in figure 6.4).

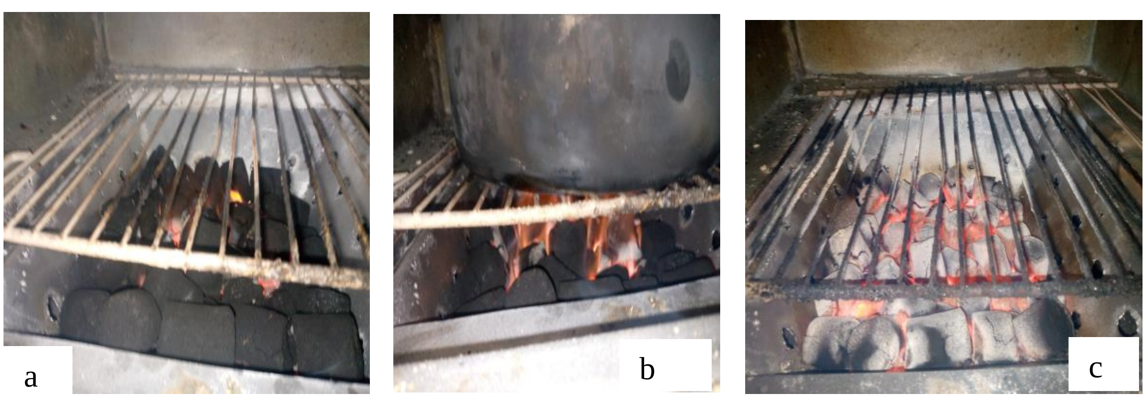


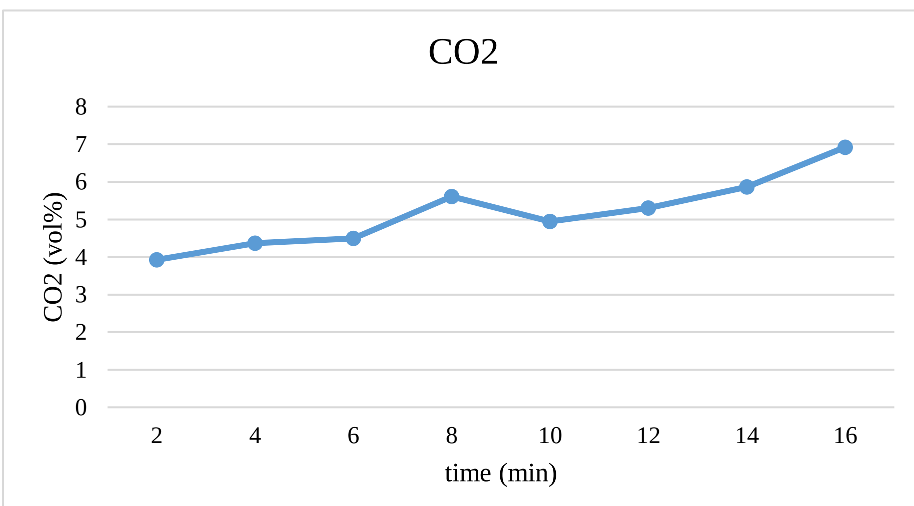

Figure 6:4 Combustion of briquette a) ignition stage b) flaming combustion c) smoldering combustion

During the ignition stage, the briquettes were heated to a temperature at which the organic matter within them starts to decompose and release volatile gases. These gases mix with oxygen from the surrounding air and undergo combustion, producing flames.

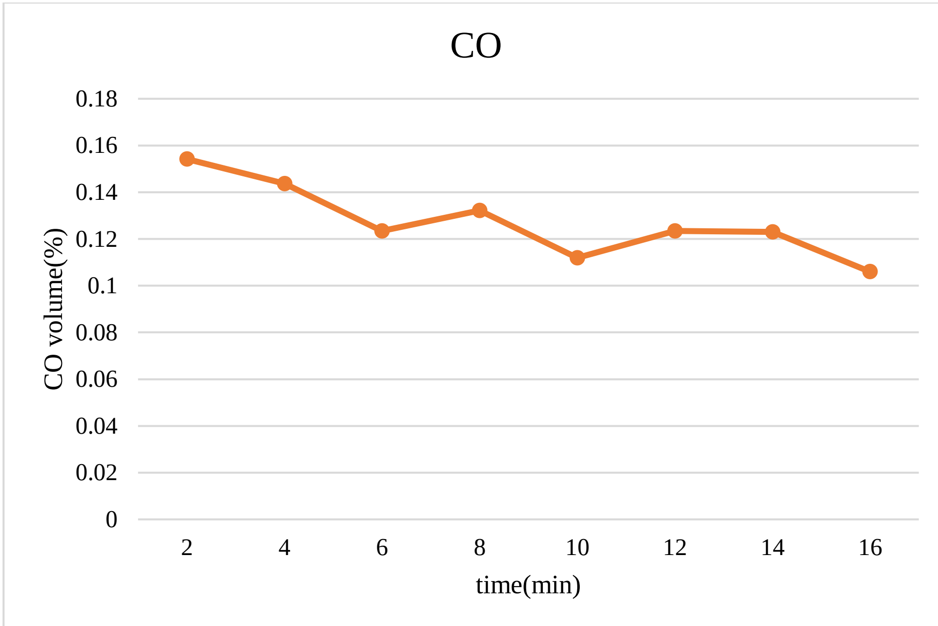
In the flaming combustion stage, the briquettes continue to burn with a visible flame. The released volatile gases, such as methane, carbon monoxide, and hydrogen, react with oxygen in the air, resulting in the generation of heat, light, and combustion byproducts, such as water vapor and carbon dioxide((R. Myrzakhanov et al. 2019).

As the flaming combustion subsides, the briquettes enter the smoldering combustion stage. In this stage, the briquettes continue to burn, but without a visible flame. The remaining solid material gradually decomposes and reacts with oxygen to release more heat, although at a lower intensity compared to the flaming combustion stage(R. Myrzakhanov et al. 2019).

The combustion of coffee husk bio-briquettes is considered a renewable energy option because coffee husks are agricultural waste products that would otherwise be discarded. By converting these husks into bio-briquettes and using them as a fuel source, it is possible to reduce waste and utilize a sustainable energy resource. Additionally, the combustion of bio-briquettes generally produces lower emissions of greenhouse gases compared to fossil fuels, making them a potentially more environmentally friendly option for heating or energy generation.




(a)




(b)

Figure 6:5 Exhaust gas composition a) $CO_2$ (vol%) and b)CO (vol%)

As shown in Figure 6.5, the flue gas was analyzed for 16 minutes, and the results indicate that the CO2 emission in volume percentage ranged between 3.924% and 6.92%, while the CO emission in volume percentage ranged from 0.106% to 0.15%. The average CO2 emission was 5.17% (517 ppm), which falls within the range of CO2 emissions recommended by the WHO. Similarly, the average CO emission from the recorded data was 0.12% (12 ppm), which also falls within the WHO's recommended limit of 35 ppm(for 1hr).

## 6.3 Water Boiling Tests

The data gather through experimentation during cold and hot start water boiling test using charcoal and bio briquette as fuel and the performance of the stove in terms of Thermal efficiency, burning rate, and Specific fuel consumption are shown in Table 6.2 and Table 6.3, respectively.

Table 6:2 Water boiling test with charcoal on the top cooking place

| | | **COLD START** | | **HOT START** | |
|---|---|---|---|---|---|
| **Calculations/Results** | Units | data | label | data | label |
| Fuel consumed | g | 372 | $f_{cm}$ | 224 | $f_{hm}$ |
| Equivalent dry fuel consumed | g | 319 | $f_{cd}$ | 192.6303 | $f_{hd}$ |
| Water vaporized from all pots | g | 596 | $w_{cv}$ | 585 | $w_{hv}$ |
| Weight of Pot # 1 with water | g | 2837.3 | $P1_{ci}$ | 2500 | $P1_{ch}$ |
| Weight of Pot # 2 with water | g | 1199 | $P2_{ci}$ | 940.56 | $P2_{ch}$ |
| Effective mass of water boiled | g | 2,950 | $w_{cr}$ | 3,051 | $w_{hr}$ |
| Time to boil Pot # 1 | min | 35 | $\Delta t_c$ | 30 | $\Delta t_h$ |
| Thermal efficiency | % | 25% | $h_c$ | 41% | $h_h$ |
| Burning rate | g/min | 9.1 | $r_{cb}$ | 6.4 | $r_{hb}$ |
| Specific fuel consumption | g/liter boiled | 108 | $SC_c$ | 63.14153 | $SC_h$ |
| Firepower | watts | 4531 | $FP_c$ | 3189 | $FP_h$ |

Table 6:3 WBT using bio-briquette carried out inside baking chamber

| | | COLD START | | HOT START | |
|---|---|---|---|---|---|
| **Calculations/Results** | Units | data | label | data | label |
| Fuel consumed | g | 283 | $f_{cm}$ | 250 | $f_{hm}$ |
| Equivalent dry fuel consumed | g | 258 | $f_{cd}$ | 228.1315 | $f_{hd}$ |
| Water vaporized from all pots | g | 766 | $w_{cv}$ | 692 | $w_{hv}$ |
| Effective mass of water boiled | g | 1,812 | $w_{cr}$ | 1,860 | $w_{hr}$ |
| Time to boil Pot # 1 | min | 25 | $\Delta t_c$ | 22 | $\Delta t_h$ |
| Thermal efficiency | % | 40% | $h_c$ | 42% | $h_h$ |
| Burning rate | g/min | 10.3 | $r_{cb}$ | 10.4 | $r_{hb}$ |
| Specific fuel consumption | g/liter boiled | 143 | $SC_c$ | 122.6829 | $SC_h$ |
| Firepower | watts | 4181 | $FP_c$ | 4196 | $FP_h$ |

The thermal efficiency of the cold start and hot start are almost similar for briquette fuel. But when it comes to fuel consumption cold start consumed more fuel which is 143 g/liter of water boiled whereas the hot start consumed less which was 122.6829 g of fuel/ liter of water boiled. Here compared to water boiling test by using charcoal on upper stove part( double pot) the thermal efficiency is high and it boiled water in short period of time compared to the upper stove test. The burning rate of cold start and hot start were the same for WBT with briquette in baking chamber while burning rate were 9.1 g/min and 6.4 g/min in case of WBT with charcoal.

## 6.4 Bread Baking

Bread baking involves the application of heat to transform the raw dough into a cooked and flavorful loaf. The bread was baked in baking chamber, involving preheating the baking chamber for 2 minutes and once the surface of the chamber become hot the bread was placed. Then the baking chamber was closed for 5 minutes and after that door was opened and the fuel level was checked, then the door was closed to restrict heat loss during door opening. The results obtained from the controlled cooking test are summarized in table 6.4.


Figure 6:6 Bread baking a)bread dough before baking b) checking while baking c) baked bread

Table 6:4 Controlled cooking test (CCT) results of the stove

| **Total weight of food cooked (g)** | **Equivalent fuel consumed(g)** | **Specific fuel consumption(g/kg of food)** | **Total baking time (min)** |
|---|---|---|---|
| 1805.2 | 227 | 87 | 14 |

The data shows that 1805.2 grams of food were cooked using 227 grams of fuel, for a specific fuel consumption of 87 grams per kilogram of food. The total baking time was 14 minutes.

## 6.5 Injera Baking and Non-Baking Tests on The Mitad

The surface temperature profiles of the stove such as mitad surface, flame and bottom surface temperature of the oven, temperature of the oven, lid cover temperature and air between lid cover and mitad were gathered for injera baking and non-baking as shown in Figure 6.7 to 6.11.

### 6.5.1 Flame Temperature During Dry Test Verses During Baking Test

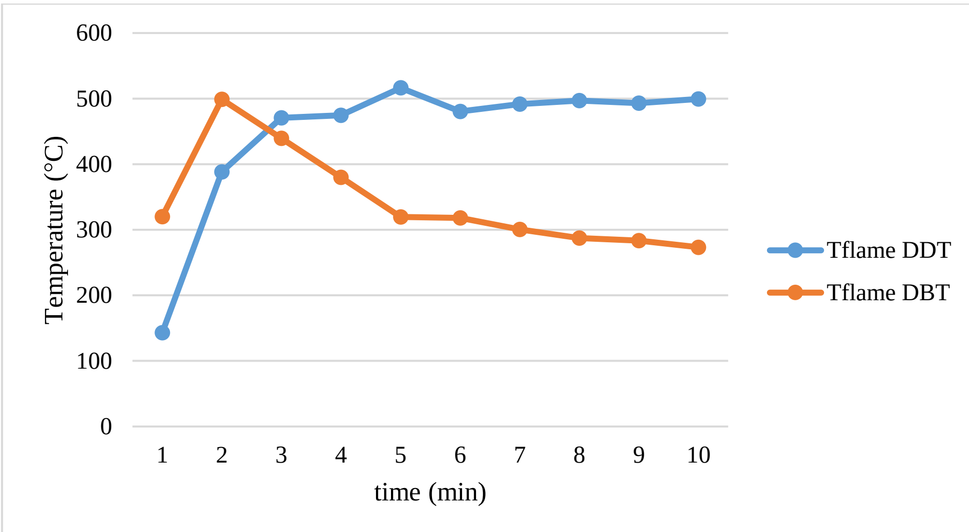



Figure 6:7 Flame temperature for dry test verses injera baking

The temperature of flame during baking is increased initially, because the temperature of the mitad must be heated up and ready for baking before the batter was poured on it. After the pouring the temperature should be sustained in baking temperature to bake injera perfectly. The temperature of flame during dry test is go to the maximum and become almost uniform after the maximum temperature is attained.

### 6.5.2 Temperature distribution on the top surface of the mitad

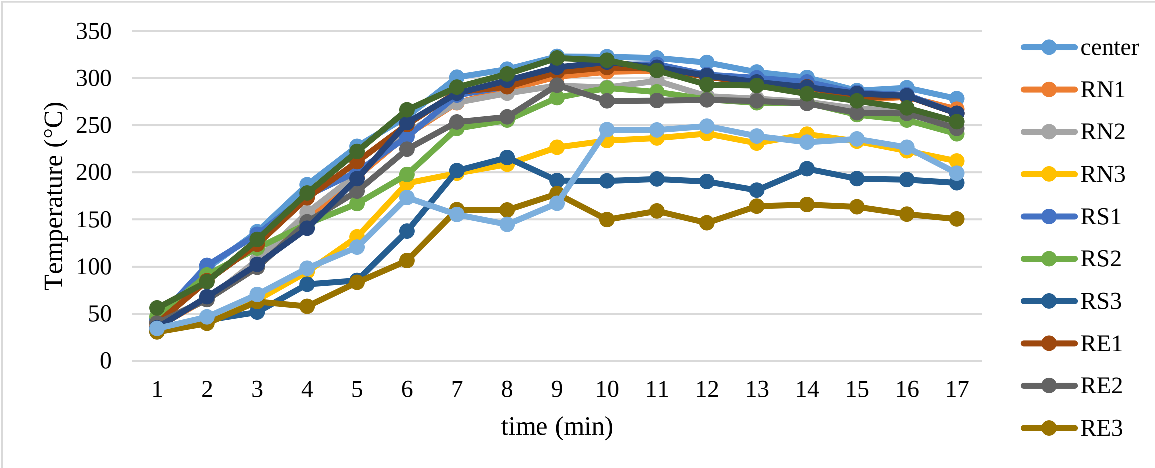



Figure 6:8 Temperature distribution of mitad during dry test radially

The temperature distribution of the mitad's surface is shown in Figure 6.8. From the figure, it can be seen that there are three points identified on each of the four sides (north, south, east, and west) of the mitad. In total, 13 points were identified including the center of the mitad, with a distance of 9cm between each point. Having a uniform temperature distribution on the mitad's surface is important for making high-quality injera. So, it is necessary to maintain uniform temperature in all directions as much as possible. During the experiment, temperature fluctuations were noticed mainly at the outermost points of the mitad's surface. These fluctuations happened because the fuel used did not burn evenly. However, when the temperature dropped, it could be fixed by moving the fire towards that area. This helped to monitor and control the temperature better, ensuring a more uniform distribution throughout the baking process.

Figure 6:9 Measuring surface temperature of mitad using infrared thermometer

### 6.5.3 Initial Heating up time

The initial heating time of the multipurpose stove mitad is shown in Figure 6.10. The temperature of the mitad increases gradually, reaches 180°C. The experimental results reveal that the mitad reaches the desired temperature within an average duration of 7.5 minutes. This is significantly faster than the traditional three-stone stoves, which can take up to 30 minutes to reach the same temperature. The mitad's quick heating time makes it a more efficient and convenient option for baking injera, a traditional Ethiopian flatbread.

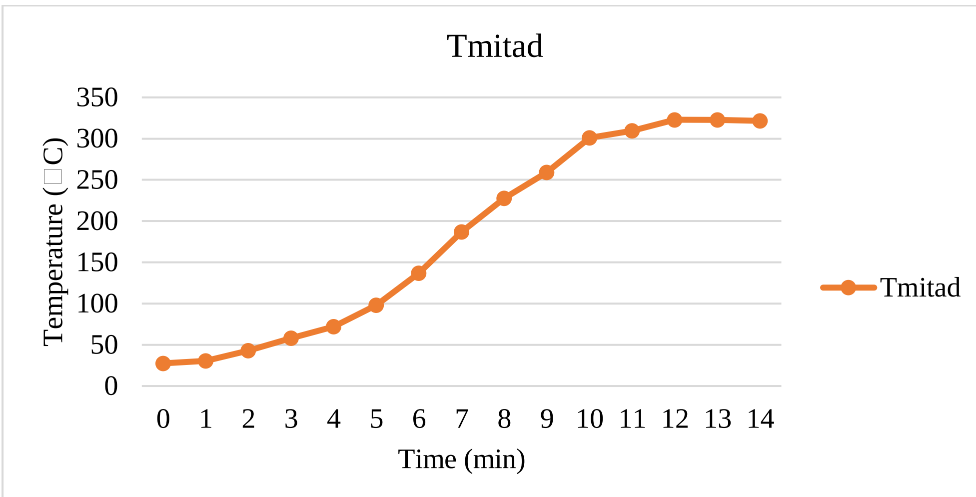



Figure 6:10 Initial Heating up time temperature profile of mitad

### 6.5.4 Temperature of mitad surface and temperature of batter during baking process

During the baking process, as shown in figure 6.11, the transfer of heat occurs from the clay mitad to the poured batter or dough, leading to an increase in the temperature of the dough until it reaches the threshold required for the formation of the characteristic spongy texture of injera. In this particular case, the final temperature of the batter typically falls within the range of 91.5-98.5°C. The average maximum temperature recorded for the injera batter is approximately 94.4°C, which signifies the temperature at which the batter coagulates and attains the desired spongy texture specific to injera. As depicted in Figure 6.11, the temperature of the mitad initially decreases when the batter is poured onto it. However, once the baked injera is removed from the mitad, the temperature begins to rise again, thus initiating a cyclical pattern.

The average duration of baking for an individual piece of injera was observed to be 1.65-2 minutes, with an additional idle time of 0.25-0.50 minutes between successive injera. It is worth noting that the utilization of biomass fuel, specifically sawdust, introduces certain variations in both the time and temperature profiles of the mitad and injera throughout the baking process. The nature of biomass fuel necessitates a continuous loading and monitoring procedure to ensure optimal performance.

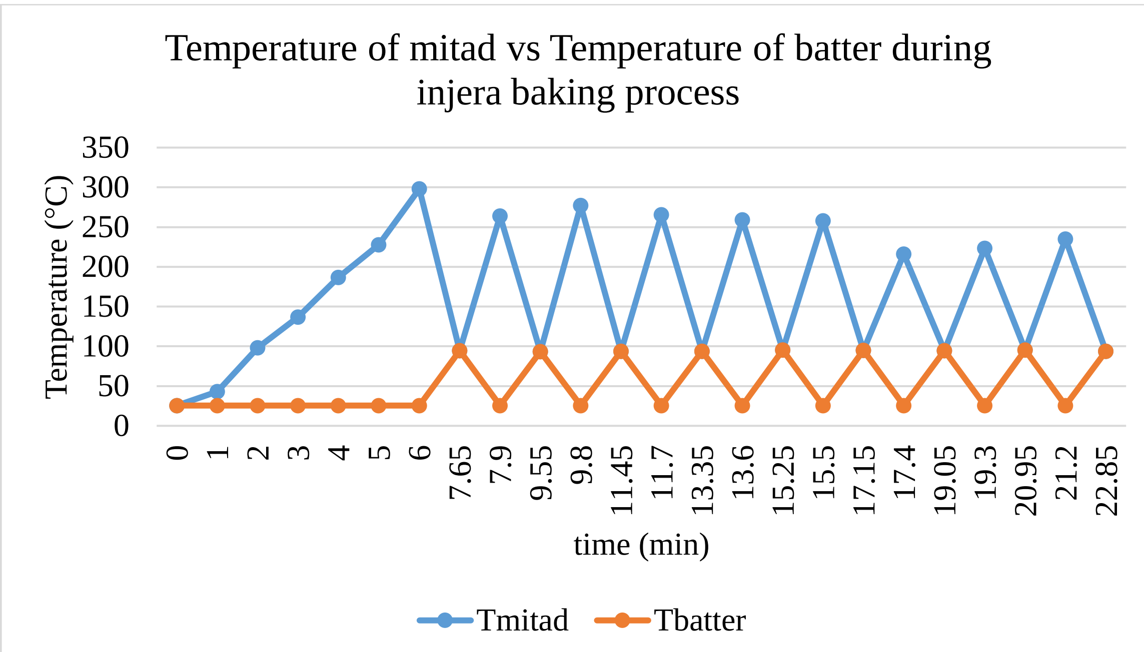



Figure 6:11 Temperature profile of injera mitad and baked batter during baking process

### 6.5.5 Injera Quality


Figure 6:12 Injera baking test a) pouring of batter b) closing the lid cover c) after the batter baked (took out) d) quality injera baked

### 6.5.6 Energy And Exergy of Baking Process Calculation Results by Direct Method

The energy utilized and overall efficiency of MS mitad for baking injera was determined after measuring the data summarized in Table 6.5. The utilized energy was found to be 6057.6 kJ and the overall efficiency of the mitad in baking 10 injera is found to be 24.86% and the overall exergy of the mitad was found to be 15.21% form direct method.

Table 6:5 Energy utilized during baking process

| | |
|---|---|
| Mass of batter(kg) | 5.99767 |
| Mass of injera(kg) | 4.12711 |
| Mass of evaporated water (kg) | 1.87056 |
| Cp water(kJ/kgK) | 4.18 |
| T_in_batter (°C) | 25.5 |
| T_final_batter (°C) | 94.8 |
| Hvap(kJ/kg) | 2260 |
| Number of injera | 10 |
| Heat utilized (kJ/kg) | 6057.594624 |
| LHV sawdust (kJ/kg) | 1.62E+04 |
| Mass of fuel initial (kg) | 2 |
| Mass of charcoal left(kg) | 0.012 |
| Moisture content of fuel (kg) | 0.18 |
| Mass fuel consumed (kg) | 1.5848 |
| Heat Input kJ/kg | 2.44E+04 |
| Efficiency (%) | 24.86 |
| Exergy input (kJ) | 1.57E+04 |
| Exergy utilized (kJ) | 2396.005987 |
| Exergy efficiency(%) | 15.21 |

### 6.5.7 Specific Fuel Consumption of Injera Mitad During Baking Test

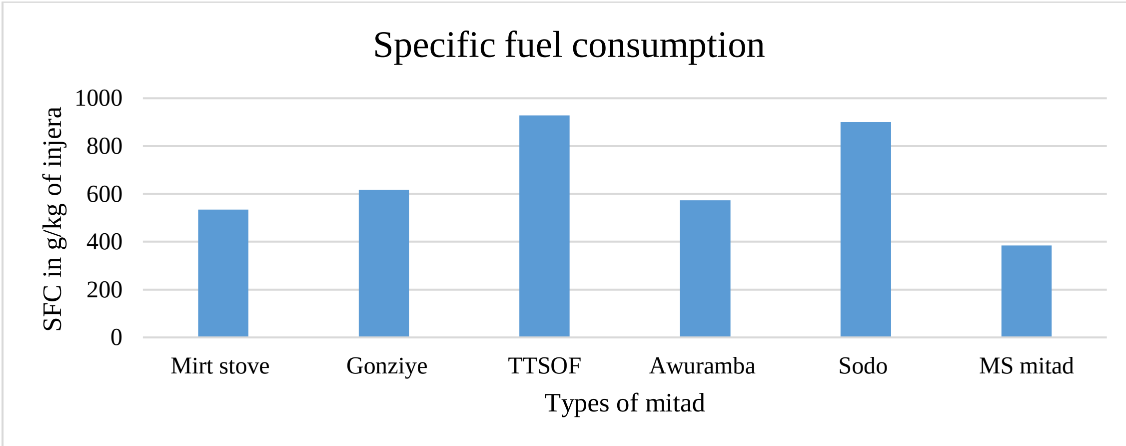



Figure 6:13 Specific fuel consumption of multipurpose stove mitad (MS mitad)compared to other (Tadesse, 2020)

From the data, it can be observed that the Multipurpose stove mitad achieved the lowest specific fuel consumption of 383.88g/kg of injera, indicating better fuel efficiency compared to the other stoves examined, meaning that it uses the least amount of fuel to bake a kilogram of injera. The Mirt Stove is the second most efficient, followed by the Gonziye and Awuramba. The TTSOF and Sodo mitads are the least efficient, meaning that they use the most fuel to bake a kilogram of injera.The MS mitad reduces fuel consumption by 47.83% compared to the TTSOF.

The MS mitad reduces fuel consumption by a significant amount compared to the other mitads. It reduces fuel consumption by 19.88% compared to the Mirt Stove, 29.97% compared to the Gonziye, 51.48% compared to the TTSOF, 17.67% compared to the Awuramba, and 51.83% compared to the Sodo. This means that the MS mitad can save users money on fuel costs, while also reducing their environmental impact.

# CHAPTER SEVEN

# 7. CONCLUSIONS AND RECOMMENDATIONS

## 7.1 Conclusion

In this study experimental investigation and performance evaluation of multipurpose stove that can bake injera, bread and cook stews was designed and experimentally tested. The design was done using CATIA V5. The experimental performance was evaluated for baking, non-baking of injera and bread and cooking test using water boiling test for hot and cold start. In addition, bio briquettes was prepared from coffee husk, using corn flour as a binder was also tested.

The main results obtained from the study are summarized in the following section.

### 7.1.1 Finds From Bio Briquette

The bio-briquette was prepared from coffee husk by carbonizing first method and the corn flour was used as a binding agent. The ratio of corn flour to water used was 1:10, while the biomass to binder ratio was 9:1. The mixture was heated at a temperature of 65°C. after molding it manually it was dried in sun for one week. The moisture content, volatile matter, fixed carbon content and ash content of the coffee husk bio-briquette were 7.18%, 28.6%, 50.34% and 13.87% respectively. The briquette dimensions were averagely 3.5 cm in diameter and 4.5 cm height. And the mass of each briquette was 30g and the bulk density of the briquette was 623.6 $kg/m^3$. The calorific value of the bio-briquette was 6108.99 cal/g.

### 7.1.2 Finds From Multipurpose Stove Experimental Performance

Cold start water boiling test was conducted by using charcoal and bio-briquette prepared. The charcoal fuel was used on the upper combustion chamber (dual pot sits) and the thermal efficiency was found to be 25% and the burning rate was 9.1 g/min. The effective mass of water boiled was 2950g and time to boil for pot#1 was 35 min. The specific fuel consumption and fire power was 108g/liter of water boiled and 4531W, respectively. The briquette fuel was used to boil water inside baking chamber and the thermal efficiency of cold start was 40%; water vaporized was 766g; time to boil was 25 minutes; burn rate, specific fuel consumption and fire power were 10.3g/min, 143g of briquette/ liter of water boiled, 1481 W respectively.

Hot start water boiling test was also conducted using charcoal and briquette. The charcoal fuel was used on the upper combustion chamber (dual pot sits) and the thermal efficiency was found to be 41% and the burning rate was 6.4 g/min. The effective mass of water boiled was 3,051 g and time to boil for pot#1 was 30 min. The specific fuel consumption and fire power was 63.14g/liter of water boiled and 3189W, respectively. The briquette fuel was used to boil water inside baking chamber and the thermal efficiency of hot start was 42%; water vaporized was 692g; time to boil was 22 minutes; burn rate, specific fuel consumption and fire power were 10.4g/min, 122.7g of briquette/ liter of water boiled, 4196 W respectively.

Injera mitad:

- The utilized energy was found to be 6057.6 kJ and the overall efficiency of the mitad in baking 10 injera is found to be 24.86% and the overall exergy of the mitad was found to be 15.21% form direct method.
- The mitad temperature distributions were studied by collecting temperature data from 12 radial nodes and one central node for 17 minutes and the average temperature of the mitad was found 210.8°C.
- The overall heat loss was calculated using indirect method using thermal resistance diagram and found to be 6.653 kW and overall efficiency was 26.3%.
- The specific fuel consumption of mitad was found to be 383.88gof sawdust/kg of injera.

Bread baking:

- Bread of mass 1.8kg was baked within 14 minutes inside baking chamber using briquette and the specific fuel consumption was found to be 126 g of fuel / kg of bread baked.
- Equivalent fuel consumed during baking was found to be 227 g of briquette.

## 7.2 Recommendations

Multipurpose stove is capable of being fired by different biomass commonly used in Ethiopia such as saw dust, fire wood, and charcoal. However, conducting further experimentation is needed in baking injera, bread and water boiling test by charcoal, sawdust and briquette in each stove. In addition, since the assembling of the mitad and the cook pot seat is detachable, mechanically robust and convention mechanics such as three hundred six degrees of freedom can be integrated.

- For the insulation ash and gypsum mixture was used, however it increases the weight of the stove and researchers can improve it using other less weight and available insulation materials.
- During baking test flue gas was higher, that indicate incomplete combustion in combustion chamber, this may be due to two things, first more moisture in the air or more air is required, so further research is required to reduce the flue gas.
- Bio-briquette emissions should also be performed extensively.
- Additional Ash tray may be important in case of reducing ash accumulation while baking injera.

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# APPENDIX 1.

## 1. Baking chamber losses

The baking chamber losses heat by conduction through all walls(four side walls and upper wall).

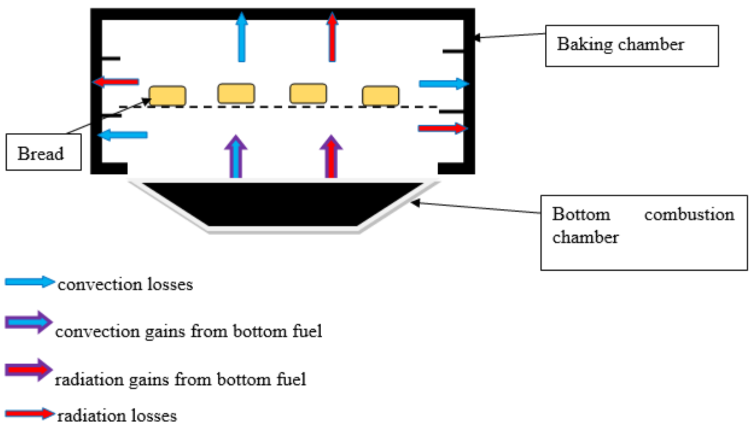



Figure A: 1 Schematic diagram of heat transfer of baking chamber

Conduction losses through the wall of baking chamber is the summation of convection loss and radiation loss.

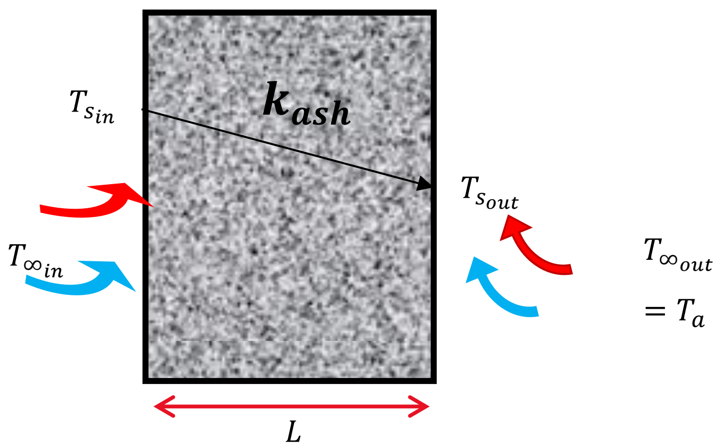



Figure A: 2 Schematic diagram of heat transfer through wall of baking chamber

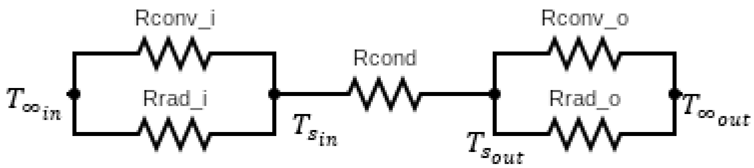



Figure A: 3 Thermal resistance circuit of side loss of baking chamber

$R_{conv_i} = \frac{1}{h_{c_i}A}$ ;$R_{conv_o} = \frac{1}{h_{c_o}A}$

$R_{rad_i} = \frac{1}{h_{r_i}A}$; $R_{rad_i} = \frac{1}{h_{r_o}A}$

$R_{cond} = \frac{L}{k_{ash}A}$,

$$R_{tot_{bs}} = \frac{R_{conv_i} \times R_{rad_i}}{R_{conv_i} + R_{rad_i}} + R_{cond} + \frac{R_{conv_i} \times R_{rad_i}}{R_{conv_i} + R_{rad_i}}$$

$$\dot{Q}_{sideloss} = 4 \times \frac{[T_{\infty_{in}} - T_{\infty_{out}}]}{R_{tot_{bs}}}$$

Top loss of baking chamber thermal resistance circuit

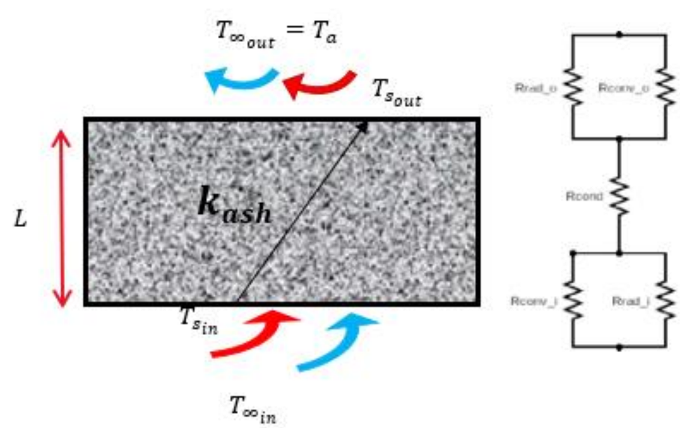
$R_{conv_i} = \frac{1}{h_{c_i}A}$ ;$R_{conv_o} = \frac{1}{h_{c_o}A}$

$R_{rad_i} = \frac{1}{h_{r_i}A}$; $R_{rad_i} = \frac{1}{h_{r_o}A}$

$R_{cond} = \frac{L}{k_{ash}A}$,

$R_{tot_{bt}} = \frac{R_{conv_i} \times R_{rad_i}}{R_{conv_i}+R_{rad_i}} + R_{cond} + \frac{R_{conv_o} \times R_{rad_o}}{R_{conv_o}+R_{rad_o}}$.

$\dot{Q}_{toploss} = \frac{[T_{\infty_{in}} - T_{\infty_{out}}]}{R_{tot_{bt}}}$.




## 2. Combustion chamber losses

$$\dot{Q}_{b\ cond_{loss}} = \frac{(T_{s_i} - T_{s0})}{R_{thcond\_b}},$$

$$R_{thcond\_b} = \frac{L_{ins}}{k_{ins}A_{bw}} + \frac{L_{metal}}{k_{metal}A_{bw}},$$

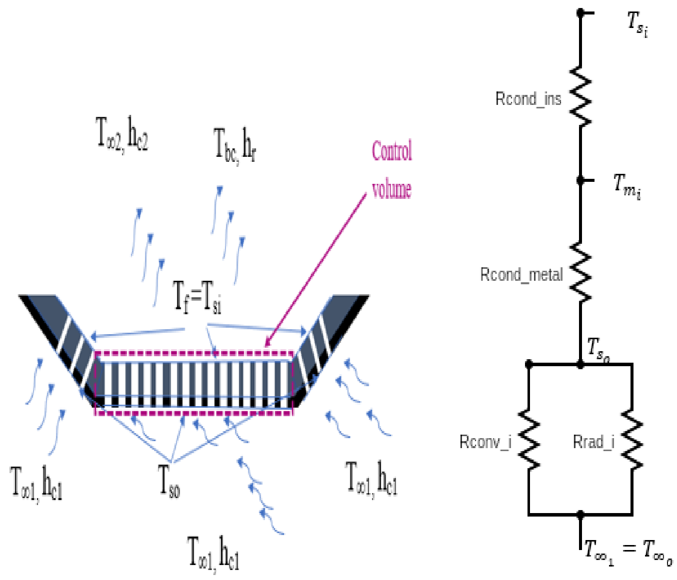
$$\dot{Q}_{trapezoidal\ walls_{loss}} = 4 \times \frac{(T_{s_i} - T_{s0})}{R_{thcond_{tra}}};$$

$$R_{thcond_{tra}} = \frac{L_{ins}}{k_{ins}A_t} + \frac{L_{metal}}{k_{metal}A_t};$$

$$\dot{Q}_{b\ rad_{gain}} = \frac{(T_{so} - T_{\infty o})}{R_{rad_o}};$$

$$R_{rad_o} = \frac{1}{h_{rad_o}}[\frac{1}{A_{bw}} + \frac{1}{A_t}];$$

$$h_{rad_o} = \varepsilon\sigma((T_{so}^2 + T_{\infty o}^2)(T_{so} + T_{\infty o});$$




$$\dot{Q}_{b\ conv_{gain}} = \frac{(T_{so} - T_{\infty o})}{R_{conv_o}}$$

$$R_{conv_o} = \frac{1}{h_{conv_o}}[\frac{1}{A_{bw}} + \frac{1}{A_t}]$$

$$\dot{Q}_{lost_{bc}} = \dot{Q}_{b\ cond_{loss}} + \dot{Q}_{trapezoidal\ walls_{loss}} - [\dot{Q}_{b\ rad_{gain}} + \dot{Q}_{b\ conv_{gain}}]$$

# APPENDIX 2

## A. Thermal resistance circuit and thermal efficiency of MS mitad

All temperatures are in Kelvin.

$$T_{sky} = T_{\infty} - 6$$

$$h_{rad_2} = \sigma \times \varepsilon_{lc} \times (T_{lc}^2 + T_{sky}^2)(T_{lc} + T_{sky})$$

$$h_{rad_1} = \sigma \times \left[\frac{1}{\varepsilon_m} + \frac{1}{\varepsilon_l} - 1\right]^{-1} \times (T_m^2 + T_{lc}^2)(T_m + T_{lc})$$

$$h_{rad_0} = \sigma \times \varepsilon_{st} \times (T_{cc}^2 + T_m^2)(T_{cc} + T_m)$$

$$h_{rad_s} = \sigma \times \varepsilon_{st} \times (T_{ow}^2 + T_{\infty}^2)(T_{ow} + T_{\infty})$$

$$h_{rad_{bt}} = \sigma \times \varepsilon_{st} \times (T_{bt}^2 + T_{\infty}^2)(T_{bt} + T_{\infty})$$

Convective heat transfer coefficient can be obtained from McAdams's equation given below for convective heat transfer on lead cover by considering wind speed 2m/s.

$$h_{c_2} = 5.7 + 3.8V$$

Convective heat transfer between mitad and lid cover can be obtained using Nusselt number of convective heat transfer between parallel plate ((Duffie and Beckman, 2013)

$$h_{c1} = \frac{K_a}{L} Nu$$

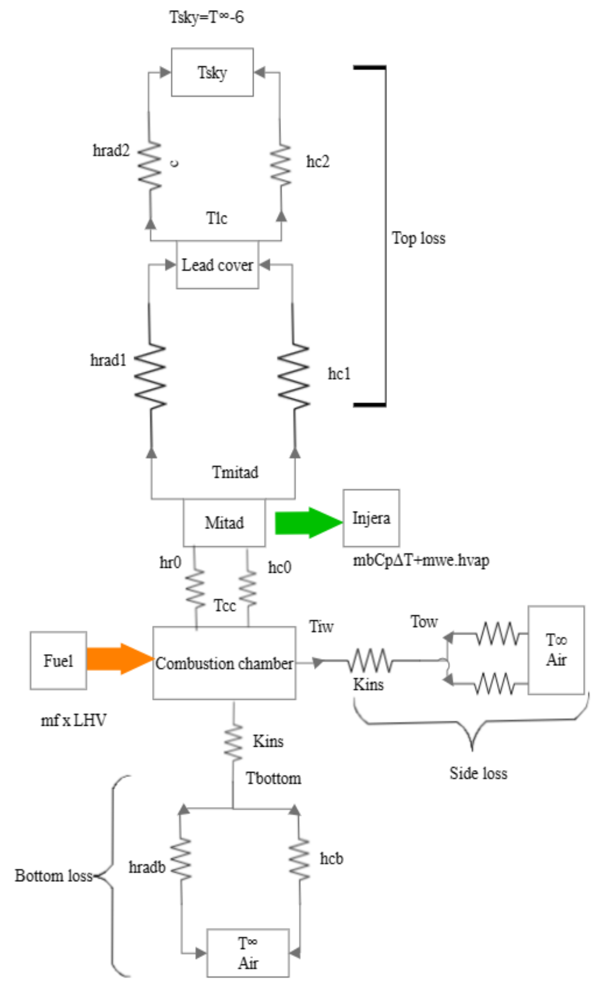



Figure A1: 1 thermal resistance circuit diagram of MS mitad

$$Nu = 1 + 1.44\left[1 - \frac{1708\,sin(1.8\beta)^{1.6}}{R_a\,cos\,\beta}\right]\left[1 - \frac{1708}{R_a\,cos\,\beta}\right]^{+} + \left[\left(\frac{R_a\,cos\,\beta}{5830}\right)^{1/3} - 1\right]^{+} \text{….A.1}$$

a "+" exponent symbol  indicates that only the positive value within the square bracket should be taken into account, while any negative value should be treated as zero. The formula for the Rayleigh number is given as follows:

$$R_a = \frac{2g(T_m - T_l)\,Pr\,L^3}{(T_m + T_l)\nu^2}$$

Where properties of gas between mitad and lead cover and mitad and combustion chamber are obtained at film temperature(Cengel and Boles, 2015).

Table A2: 1 Properties of gas at film temperature

| Properties | units | Mitad and lead cover (LOSE) | Mitad and combustion (GAIN) |
|---|---|---|---|
| Temperature film | K | 422.02 | 621.635 |
| Coefficient of expansion | 1/K | 0.00236956 | 0.001608661 |
| Prandtl number | | 0.70275 | 0.6937 |
| Kinematic viscosity | m^2/s | 2.86E-05 | 5.48E-05 |
| Thermal conductivity of gas | W/mK | 0.03411 | 0.0472 |
| Characteristic length | m | 0.57 | 0.15 |

For convective heat transfer between combustion chamber and mitad, the Nusselt number can obtained from equation A.1.  Rayleigh number is calculated using the following formula:

$$R_a = \frac{2g(T_{cc} - T_m)\,Pr\,L^3}{(T_{cc} + T_m)\nu^2}$$

Then $\quad h_{c_0} = \frac{Ka}{L} Nu$

Convective heat transfer coefficient on bottom surface can be calculated using McAdams's rule by taking zero wind speed since it is closed system.

$$h_{c_b} = 5.7 + 3.8V \; and \; V = \frac{0m}{s} no \; wind \; inside \; the \; bottom \; chamber.$$

And convective heat transfer coefficient of side walls also calculated by using McAdams's equation by taking wind speed of 2m/s.

$$h_{s_w} = 5.7 + 3.8\,V, V = 2m/s$$

Specification of clay mitad used (assumed and measured):

- $k$ = 0.5$w/m.\,k$
- $cp$ = 830$J/kg\,.\,k$
- $\rho$ = 1900$kg/m$3 (Gashaw, 2011).
- Thickness 15mm
- Diameter 58cm

Calculation was done on Microsoft excel 2021, and the overall heat loss and overall efficiency through indirect method are given by:

- $Q_{side_{loss}} = 2.11kW$ (23.3%)
- $Q_{bottom_{loss}} = 1.01kW$(11.2%)
- $Q_{top_{loss}} = 395.26W$(4.38%)
- $Q_{fluegass_{loss}} = 2.312kW$(25.6%)
- $Q_{moisture_{loss}} = 831.2W$ (9.01%)
- $Q_{overall_{loss}} = 6.653\ kW$
- $Q_{input} = 9.03\ kW$

$\eta = 1 - \frac{Q_L}{Q_e} = 1 - \frac{6.653}{9.03} = 0.263$ so, efficiency by indirect method is 26.3% and by direct method is 24.86%.

# APPENDIX 3

## A. Insulation

An insulation mixture of gypsum and wood ash in a volume proportion of 1:2 has been used and its thermal conductivity was 0.28 W/mK.( Rokiah Hashim, et al.2017).

### B. Calibration of thermocouples and thermometer

For this research purpose seven thermocouples were used. In this the thermocouples were calibrated using boiled water (100°C). Thermocouples were tagged with number from 1-7 including letters.

Figure A3: 1 Thermocouple calibration using boiled water

Table A3: 1 Data from thermocouples recorded during calibration process

| No. | Thermocouples | Boiled water(100°C) | Uncertainty |
|---|---|---|---|
| 1 | 99.2 | 100 | 0.8 |
| 2 | 99.8 | 100 | 0.2 |
| 3 | 99.3 | 100 | 0.7 |
| 4 | 99.2 | 100 | 0.8 |
| 5 | 99.5 | 100 | 0.5 |
| 6 | 99.6 | 100 | 0.4 |
| 7 | 99.7 | 100 | 0.3 |
| | | Average | 0.528571429 |

# APPENDIX 4.

## Proximate analysis and calorific values of Raw coffee husk and carbonized coffee husk

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|---|---|---|---|
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| Document Title:- | Hydrocarbon Analysis Report | Effective date: | Nov. 2022 |

Customer Name:- Chala Workneh Negari
Issue Date:- 26/05/2023
Sample type: -Row Coffee Husk
Request No:-GLD/RN/1255/23
Sample Preparation:- 60 Mesh
Report No:- GLD/TR/1854/23
Date Submitted:-09/05/2023
Number of Sample: -One (01)
Elements to be determined:-(Moisture,Volatile matter, Fixed carbon and Ash) & Calories .
Method of analysis:- Proximate Analysis, Adiabatic Calorie Metter and Gravimetric Method

| Collectors' Code | Moisture % | Volatile Matter % | Fixed carbon % | Ash % | Calorific Value Cal/gm. | Weight of Sample |
|---|---|---|---|---|---|---|
| Coffee Husk (Row) | 9.69 | 69.77 | 16.29 | 4.25 | 4192.92 | 12.00gm |

**Note**: - This result represent only for the sample submitted to the laboratory.

Analysts
Bethelhem Tefera
Shashe Haile

Approved By
Alemnesh Abate

Quality Control
Negash Worku

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| Document Title:- | Hydrocarbon Analysis Report | Effective date: | Nov. 2022 |

Customer Name:- Chala Workneh Negari

Issue Date:- 26/05/2023

Sample type: -Row Coffee Husk

Request No:-GLD/RN/1256/23

Sample Preparation:- 60 Mesh

Report No:- GLD/TR/1855/23

Date Submitted:-09/05/2023

Number of Sample: -One (01)

Elements to be determined:-(Moisture,Volatile matter, Fixed carbon and Ash) & Calories .

Method of analysis:- Proximate Analysis, Adiabatic Calorie Metter and Gravimetric Method

| Collectors' Code | Moisture % | Volatile Matter % | Fixed carbon % | Ash % | Calorific Value Cal/gm. | Weight of Sample |
|---|---|---|---|---|---|---|
| Carbonized Coffee Husk | 7.18 | 28.60 | 50.34 | 13.87 | 6108.99 | 19.00 gm |

**Note:** - This result represent only for the sample submitted to the laboratory.

Analysts
Bethelhem Tefera
Shashe Haile

Approved By
Alemnesh Abate

Quality Control
Negash Worku

Geochemical Laboratory Desk

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# APPENDIX 5.

## MOISTURE TEST FOR SAWDUST


Figure A5: 1 sawdust weight measurement

Figure A5: 2 Sawdust sample in oven for moisture content test