Addis Ababa University College of Technology and Built Environment School of Mechanical and Industrial Engineering Thermal Stream Addis Ababa, Ethiopia

Experimental Investigation of An Improved Biogas Injera Baking Stove with Conical Burner

A Dissertation Submitted for Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy (PhD) in Mechanical Engineering (Thermal and Energy Conversion Engineering).

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APPROVAL

The Dissertation entitled "Experimental Investigation of an Improved Biogas Injera Baking Stove with Conical Burner" by Taha Abdella meets the regulation governing the award of the degree of Doctor of Philosophy (PhD) in Mechanical Engineering (Thermal and Energy Conversion Engineering) from the University of Addis Ababa in College of Technology and Built Environment, Addis Ababa, Ethiopia and is approved for its contribution to knowledge and literary presentation.

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I hereby declare that this Dissertation entitled “Experimental Investigation of An Improved Biogas Injera Baking Stove with Conical Burner’’ has been written by me, in the School of Mechanical and Industrial Engineering. It is a record of my own research work and all quotations and sources of information are fully acknowledged by means of references.

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ABSTRACT

This research presents the design, development, and performance evaluation of an improved biogas-powered injera baking stove, engineered to address the limitations observed in earlier biogas stove technologies used in Ethiopia and building on shortcomings identified in previous models. This study incorporates targeted engineering enhancements aimed at improving heat distribution, combustion efficiency, and overall stove usability. Key innovations include a 45° conical burner configured to enhance air–biogas mixing, a modified 45 cm diameter clay baking pan with a reduced thickness of 15 mm to improve thermal response, and a 3 cm gypsum-based insulation layer to minimize heat loss. These modifications collectively enabled the stove to achieve a significantly higher thermal efficiency of 33.7%.

Experimental results revealed strong operational improvements. The improved stove reduced preheating time by 20% (20 minutes compared to the earlier 25-minute baseline), lowered baking time per injera by 25% (3 minutes instead of 4 minutes), and shortened idle time between successive baking cycles by 25% (3 minutes vs. 4 minutes). Energy consumption was notably efficient, requiring only 706 kJ of biogas energy per injera, demonstrating its suitability for households with limited biogas yield. Thermal distribution across the mitad/pan surface was uniform, with temperature variations maintained within ±25°C, producing injera of consistent quality in terms of texture, color, and porosity—key parameters for user acceptance.

Combustion analysis confirmed the presence of a stable blue flame throughout operation, indicating improved mixing and near-complete methane combustion. This not only enhances thermal performance but also ensures cleaner operation with minimal indoor emissions.

Overall, the findings position the improved biogas injera stove as a viable, efficient, and user-friendly alternative within Ethiopia's clean cooking energy transition. Its enhanced performance, reduced energy demand, and improved user experience increase its potential for widespread household adoption, contributing to national goals for health, environmental sustainability, and renewable energy utilization.

Key Words: Biogas stove; Injera baking; Thermal efficiency; Baking pan ; Clean cooking; Burner; Performance improvement.

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ABBREVATIONS

Anaerobic Digestion : AD, 22

Artificial Intelligence: AI, 54

Carbonmonoxide: CO, 1

Chemical Oxygen Demand: COD, 23

Climate Resilient Green Economy (CRGE): CRGE, 26

Computational Fluid Dynamics: CFD, 54

Degree Centigrade: °C, 18

Deutsche Gesellschaft Für Internationale Zusammenarbeit Gmbh.: GIZ, 37

Electric Light & Power Authority: EELPA, 40

Hydraulic Retention Time: HRT, 18

Hydrogen Sulfide: H_2S, 14

Inlet Pressure From Biogas Plant: P1, 88

International Energy Agency: IEA, 56

Kilowatt: Kw, 58; Kw, 58

Liter Per Hour: L/H, 64

Liter Per Injera: L/Injera, 66

Lower Heating Value: LHV, 65

Mega Joule Per Meter Cube: MJ/M^3, 14

Methane: CH_4, 14

Miligram Per Liter: Mg/L, 20

National Biogas Programme of Ethiopia: NBPE, 26

Nitrogen Dioxide: NO_2, 2

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PVC: Polyvinyl Chloride, 87

Specific Gravity: S, 88

The National Biogas Programe Of Ethiopia: NBPE, 26

Water Column: WC, 53

Water Vapor: H_2O, 14

CHAPTER ONE

INTRODUCTION

1.1 Background

Injera, a traditional spongy flatbread, holds significant cultural and nutritional value in Ethiopia, where it is consumed daily as a staple food. Traditionally, injera is prepared using wood-fired stoves, a process that is both energy-intensive and detrimental to the environment(1). The energy landscape in Ethiopia is characterized by a heavy reliance on biomass, with 88% of the population dependent on bioenergy, including wood and other forms of biomass, for cooking and heating (2). Despite this reliance on bioenergy, Ethiopia suffers from one of the highest energy access deficits in Sub-Saharan Africa, with nearly half of the population lacking reliable electricity(3,4). The current use of firewood and fossil fuels for injera baking has resulted in both environmental pollution and the depletion of forest resources, exacerbating deforestation in the country(5,6).

Traditional stoves, such as the three-stone open-fire stove, have thermal efficiencies as low as 14%, leading to significant fuel consumption and emissions(7). These stoves also emit high levels of carbon monoxide (CO) and particulate matter (PM), which pose severe health risks to both users and surrounding communities(8,9). Consequently, there is an urgent need for alternative, more sustainable energy solutions to address both energy poverty and environmental degradation in Ethiopia.

Biogas, generated through the anaerobic digestion of organic waste such as agricultural residues and livestock manure, has emerged as a promising renewable energy source. Biogas production offers numerous benefits, including the reduction of greenhouse gas emissions, waste management, and the provision of renewable cooking fuel(1,10). In addition, biogas technology can produce valuable byproducts such as digestate, which can be utilized as organic fertilizer, providing a sustainable alternative to chemical fertilizers (11).Studies on improved biomass stoves, such as the Mirt and Gonzie stoves, have shown some improvements in heat distribution compared to traditional three-stone stoves. However, these stoves still struggle with achieving uniform heat distribution across the baking pan. For instance, the biogas injera baking stove, while more efficient than the three-stone stove, still exhibits temperature variations of up to 55°C across the pan surface(12). This inconsistency can lead to unevenly baked injera, with some parts being overcooked and others undercooked. Electric stoves, used in some urban households, offer more controlled heat distribution compared to biomass stoves.

However, they are often impractical for rural areas due to limited access to electricity and higher operational costs. Solar cookers have been explored as an alternative for injera baking, but they face challenges related to inconsistent heat supply and dependence on weather conditions. Solar cookers typically require longer cooking times and may not achieve the high temperatures needed for injera baking, making them less suitable for this purpose(13).

This study aims to explore the development of an improved biogas stove specifically designed for injera baking. The proposed stove seeks to optimize thermal efficiency, reduce emissions, and provide a more sustainable cooking solution compared to traditional wood-fired stoves. By leveraging locally available biogas, the design hopes to contribute to Ethiopia's broader goals of sustainable development, including ensuring universal access to affordable, reliable, and modern energy services. The integration of such technologies can play a key role in the transition to a cleaner, more sustainable energy system in Ethiopia, enhancing both environmental and socioeconomic outcomes.

1.2 Statement of the Problem

Injera baking is known for its high time and energy consumption. Traditional three-stone stoves, commonly used for baking injera, exhibit a high specific fuel consumption rate of 929g/kg, with an efficiency ranging from 5% to 10%(5). The inefficiency of cooking stove not only leads to significant deforestation but also contributes to environmental degradation, including global warming(1,14). The widespread use of these traditional stoves also results in the emission of harmful pollutants such as soot, carbon monoxide (CO), nitrogen dioxide (NO_2), and fine particulate matter, which severely affect the environment and pose substantial health risks to those living in affected households(1,8).

Indoor air pollution caused by traditional cooking methods is a major concern, as the exposure to these pollutants can cause respiratory diseases, cardiovascular problems, and other health issues, particularly among women and children who spend prolonged periods near the cooking stoves. Despite efforts to improve the performance of traditional injera-baking methods, the existing wood-fired stoves still consume excessive fuel and operate with low efficiency levels (16% to 21%)(5,6).This not only exacerbates the problem of deforestation but also contributes to air pollution and climate change.

To mitigate environmental impact, there is a growing need for the adoption of clean energy sources in cooking technologies. Biogas, solar energy, and electricity offer promising alternatives to traditional biomass fuels, providing an opportunity to reduce the harmful emissions associated with traditional stoves. However, despite the potential benefits of these clean energy solutions, their application in injera baking has faced challenges. Previous studies on biogas-powered injera stoves have been unsuccessful due to issues such as uneven temperature distribution over the baking pan, low stove performance, and poor quality of the baked injera.

Ethiopia, with the largest livestock population in Africa, has a significant potential for biogas production. As of 2020, Ethiopia's livestock population included 65 million cattle, 40 million sheep, 51 million goats, 8 million camels, and 49 million chickens (15). Livestock plays a critical role in biogas production, making it a feasible and sustainable energy source for cooking. The adoption of clean energy solutions for injera baking could significantly reduce deforestation, air pollution, and health risks, while also improving energy efficiency and the quality of the food prepared. However, overcoming the technical and performance barriers remains a critical challenge for widespread implementation.

However, the transition to biogas for injera baking has faced persistent technical failures. Previous attempts to develop biogas-powered injera stoves have been unsuccessful due to critical design flaws, primarily:

1. Uneven temperature distribution across the large, flat baking pan (mitad), leading to poorly cooked injera.
2. Incompatibility with the low gas pressure from small-scale, rural biogas plants.

These two issues are intrinsically linked. Conventional burners designed for higher-pressure gases cannot function effectively with the low-pressure biogas typical of household-scale digesters. This pressure mismatch results in insufficient heat output, poor flame structure, and an inability to achieve the uniform and intense heating profile required for proper injera baking. Consequently, existing stoves either fail to work entirely or exhibit unacceptably high biogas consumption rates, making them impractical for daily use.

Therefore, the central problem is the absence of a technically viable biogas injera stove system that is specifically designed to operate efficiently at low pressures. Overcoming this barrier requires an integrated approach that addresses the core of the failure: the synergistic design and optimization of both the burner and the baking pan to ensure even heat distribution and stable performance under low-pressure conditions. Without this critical innovation, the significant potential of biogas to reduce deforestation, improve health, and provide a clean cooking solution for Ethiopia's staple food will remain untapped.

1.3 Objectives of the Research

1.3.1 General Objective

The general objective of this study is to design, develop, and optimize a biogas-fueled injera baking stove capable of operating efficiently under low-pressure biogas conditions typical of small-scale rural digesters. The study aims to achieve stable and uniform heat distribution across the baking pan by integrating an optimized low-pressure burner with a thermally efficient pan design. Through this approach, the study seeks to enhance thermal efficiency, reduce biogas consumption, and ensure the production of high-quality, culturally acceptable injera. Ultimately, the goal is to create a technically viable and energy-efficient stove system that addresses the limitations of existing designs and promotes wider adoption of biogas technology in rural Ethiopia. The goal is to reduce energy consumption and shorten baking time without compromising the quality of injera.

1.3.2 Specific Objectives

The specific objectives of this research are:

1. To analyze the performance limitations of existing biogas injera baking stoves
2. To design and fabricate a low-pressure-compatible burner that ensures stable combustion, adequate flame structure, and efficient heat transfer for injera baking.
3. To optimize the geometry and thermal properties of the baking pan (including diameter thickness) to achieve uniform heat distribution and minimize heat losses.
4. To evaluate the thermal efficiency, energy consumption, temperature and injera quality of the developed stove and compare its performance with existing biogas injera baking stove and conventional pan.
5. To validate the integrated design experimentally under realistic operating conditions and determine its suitability for rural biogas applications in Ethiopia.

1.4 Significance of the Research

Energy poverty remains a major challenge in Ethiopia, particularly in rural areas where access to modern and efficient cooking technologies is limited. A substantial portion of the population relies on traditional biomass fuels such as firewood, animal dung, and crop residues(2,4). This reliance leads to inefficient energy use, deforestation, and increased greenhouse gas emissions.

The collection of firewood also imposes significant time and labor burdens, particularly on women and children, reducing productivity and educational opportunities. These challenges underscore the need for alternative cooking technologies that are efficient, sustainable, and appropriate to local cooking practices(10,16).

Biogas has emerged as a viable alternative energy source for cooking, offering higher combustion efficiency and lower environmental impact. In Ethiopia, small-scale biogas plants produce low-pressure gas that poses a design constraint for achieving efficient and high-temperature baking, particularly for foods like injera that require consistent and intense heat(17,18).

This research addresses the performance gap by developing a biogas-powered injera baking stove specifically optimized to operate under the low-pressure conditions of typical household biogas systems. The stove integrates a conical burner and a reduced-diameter baking pan to enhance combustion efficiency, improve heat transfer, and minimize fuel consumption and baking time while maintaining injera quality.

In addition to improving stove performance, the system contributes to climate change mitigation by reducing reliance on firewood and other carbon-intensive biomass fuels. The substitution of traditional fuels with biogas reduces CO_2 emissions both directly by avoiding combustion of wood—and indirectly—by helping to preserve forest biomass that serves as a carbon sink(17,19). Quantifying these reductions provides a metric for evaluating the environmental benefits of the proposed system in relation to national and global emission reduction targets.

The outcomes of this study contribute to the broader goals of enhancing energy efficiency in the residential sector, reducing deforestation, and supporting Ethiopia's commitments under the Paris Agreement. By addressing the technical interface between biogas supply conditions and thermal energy demand in injera baking, the research presents a targeted engineering solution with measurable environmental benefits.

1.5 Scope of the Research

This research focuses on the design, development, and experimental evaluation of an improved biogas-powered injera baking stove equipped with a conical burner. The study primarily investigates how burner geometry, pan characteristics, and operating conditions influence the stove's thermal efficiency, heat distribution, and overall baking performance. The work is confined to the experimental and thermal performance domains, emphasizing measurable engineering parameters such as temperature uniformity, fuel consumption rate, heat loss distribution, and baking time. The experiments were conducted under controlled laboratory conditions using biogas as the sole fuel source, following the Controlled Cooking Test (CCT) method to ensure consistency and comparability of results. The prototype design includes a conical burner, a 45 cm diameter clay pan, and thermal insulation layers, all optimized to enhance combustion stability and energy utilization.

The study does not extend to large-scale field deployment, socio-economic adoption, or long-term durability assessments. It also excludes advanced computational modeling or simulation of fluid flow and combustion dynamics. Instead, the focus remains on practical experimentation and empirical analysis to generate reliable performance data and design insights that can guide future optimization efforts. The findings are therefore intended to establish a technical foundation for improving the efficiency and environmental performance of biogas injera baking stoves in Ethiopia, paving the way for subsequent studies on large-scale implementation, CFD modeling, and community-level validation.

1.6 Limitation of the Study

This study focuses specifically on the design, fabrication, and performance evaluation of biogas stoves for Injera baking. The experiments were conducted using cow dung as the primary biogas substrate. However, the findings may not fully represent the performance of the stove when using different feedstock materials or under varying biogas plant operating conditions.

1.7 Novelty and Contributions

This is study to develop an improved biogas injera baking stove with novel conical burner of manifold diameter 450mm size, with a clay baking pan of 450mm diameter and 15mm thickness that can improve heat distribution with full-fledged performance values and applicable for household biogas plant. A full-size Injera of 40cm in diameter was baked successfully.

This study contributes to the existing literature by introducing the design of conical burner for complete mixing of air and biogas as a critical variable in biogas injera baking application using optimized clay baking pan of 45cm diameter and 15mm thickness. While previous studies, such as those focused solely on multiple burner port on burner which demonstrates that burner shape and size significantly impacts the quality and consistency of the final product (12,20).Additionally, this study introduces a systematic approach to optimizing baking pan, pressure and fuel consumption, which has not been extensively explored in prior research.

1.8 Research Questions

- How does the conical burner and baking pan design improve combustion efficiency and heat distribution?
- What is the thermal efficiency of the biogas Injera baking stove with the conical burner, and how does it compare with existing injera baking stove?
- What is the specific energy demand (MJ/kg) required to bake Injera using the conical burner biogas stove?

1.9 The Research Organization and Design Overview

The research design is adopted to design, optimize, and evaluate a biogas-powered stove specifically developed for injera baking applications. The study integrates both experimental and analytical approaches to ensure that the developed stove meets the technical, economic, and cultural requirements of Ethiopian households. The process followed a systematic and iterative design approach, comprising five distinct phases: literature review and field assessment, conceptual design, prototype fabrication, experimental testing, and optimization. Each phase was designed to build upon the preceding one, ensuring that empirical findings and user-centered insights directly informed the final optimized stove configuration. This dissertation is organized into five main chapters, followed by references and appendices. Chapter 1 introduces the study by presenting the background and context of Ethiopia's energy landscape, the statement of the problem, research objectives, significance, scope, limitations, and the novelty of the research. It also outlines the key research questions and presents an overview of the research design and structure of the dissertation. Chapter 2 provides a comprehensive literature review that examines global and national perspectives on biogas technology, including its development, composition, influencing factors, benefits, and future prospects. The chapter also reviews Ethiopia's biogas potential, historical progress, and challenges. Furthermore, it discusses injera baking technologies, from traditional three-stone fires to modern electric, solar, gasification, and improved biomass stoves. Special emphasis is placed on biogas injera baking stoves, burner designs, thermal performance parameters, material science, environmental impacts, health implications, and socioeconomic considerations. The chapter concludes by identifying critical research gaps that this dissertation addresses. Chapter 3 describes the research methodology, including the design and manufacturing processes of the biogas injera baking stove, the materials and instruments used, the geometry and thermo-physical properties of the baking pan, and the experimental setup. It also outlines the optimization approach, stove functionality testing, cold and hot start procedures for injera baking, moisture content analysis, and the overall experimental framework used to evaluate system performance. Chapter 4 presents the experimental results and provides an in-depth discussion of the findings. This includes energy analysis, heat transfer mechanisms, heat loss assessments, thermal efficiency calculations, combustion stoichiometry, equivalence ratio evaluation, flame quality observations, and temperature distribution during baking. The chapter further analyzes energy savings, injera baking quality, pan size effects, and compares the developed stove's performance with traditional and improved stoves. Chapter 5 concludes the research by summarizing the major findings and highlighting the technical, environmental, and socio-economic contributions of the improved biogas injera baking stove. It also provides recommendations for future research, policy interventions, capacity-building, and the expansion of biogas infrastructure necessary to support widespread adoption. The dissertation ends with a complete list of references and appendices that contain supplementary information such as detailed calculations, raw data, and technical drawings relevant to the study.

1.9.1 Research Design Overview

The research adopted an applied experimental design with empirical and analytical components. The study was structured to bridge the knowledge gap between theoretical stove modeling and real-world injera baking performance. A mixed-method approach was employed, combining qualitative data from field observations and user feedback with quantitative data obtained through controlled laboratory experiments. This allowed for a holistic understanding of both the technical efficiency and socio-cultural acceptability of the biogas injera baking stove.

The overarching objective of this methodological framework was to enhance the thermal performance of the stove while minimizing biogas consumption and maintaining injera quality comparable to traditional baking methods.

Phase I: Literature Review and Gap Identification

A comprehensive literature review was undertaken to assess the current state of biogas stove technologies and their applicability for injera baking. Sources included peer-reviewed journals, conference proceedings, government reports, and documentation from development organizations such as GIZ, SNV, and the Ethiopian Ministry of Water, Irrigation, and Energy.

The review focused on identifying key performance challenges in existing technologies—such as low thermal efficiency, uneven heat distribution, excessive gas consumption, and inadequate adaptation to injera baking conditions. The analysis also examined factors influencing user adoption, including cultural preferences, stove ergonomics, and material durability.

Findings from the review revealed that most biogas stoves were adapted from general-purpose cooking designs and lacked optimization for the high, uniform heat required in injera baking. These insights guided the development of targeted design criteria for the new stove prototype.

Phase II: Field Surveys and User-Centered Design Inputs

To complement the literature review, field surveys and public hearings were conducted among households, stove users, and local artisans in rural and peri-urban Ethiopian communities. The surveys aimed to gather qualitative data on user experiences, preferences, and pain points with existing biogas and biomass stoves.
Key variables studied included:

- Typical injera baking frequency
- Perceived challenges with current stoves such as uneven baking and fuel waste
- Acceptable stove dimensions and ergonomics
- Cultural expectations for injera texture and appearance.Feedback obtained from these surveys played a pivotal role in shaping the design requirements of the stove, ensuring alignment between technical design and end-user needs.

Phase III: Prototype Design and Fabrication

Based on the identified gaps and user feedback, specialized biogas stove prototypes were developed using durable materials and precision metal fabrication techniques. The design emphasized three core objectives:

- Heat Distribution Efficiency: Ensuring uniform thermal flux across the mitad (baking pan) surface to produce consistently baked injera.
- Biogas Pressure Optimization: Maintaining optimal pressure at Combustion chamber to ensure complete combustion.
- Fuel Consumption Reduction: Minimizing gas consumption without compromising baking speed or quality.

The prototype incorporated an optimized conical burner arrangement, and heat retention mechanisms. Material selection prioritized thermal conductivity and manufacturability.

Phase IV: Experimental Testing and Performance Evaluation

Experimental evaluation of the prototype was conducted using a Controlled Cooking Test (CCT) in accordance with internationally recognized stove testing protocols. The tests were performed under standardized indoor laboratory conditions to ensure consistency and comparability of results.

Test Parameters

The following performance parameters were measured: biogas consumption rate (m^3/h), thermal efficiency (%), baking time per injera (min), surface temperature, distribution of the mitad (°C) and humidity of baked injera (%).

Data Collection and Instrumentation

A U-tube water manometer was utilized to measure the biogas supply pressure from the digester to the stove. The manometer operates on the principle that the difference in water column height between the two arms is directly proportional to the pressure difference between the biogas supply and atmospheric air. The biogas pressure was determined using the height difference (Δh) in the water column as shown in Figure 43. To assess the thermal characteristics of the stove, a thermal imaging camera and an infrared (IR) thermometer were used instead of conventional thermocouples. The thermal imaging camera provided a detailed surface temperature map of the baking pan (mitad), allowing visualization of heat distribution and identification of hot and cold zones. The infrared thermometer was employed to measure surface temperatures at specific radial and circumferential points to validate the thermal image readings and ensure uniformity.

A digital weighing scale was used to measure the mass of baked injera and assess energy utilization efficiency. A digital stopwatch was employed to accurately record the baking duration for each injera.

Experimental Procedure

Each test began with the stabilization of the gas flow and ignition of the burner. The pan was preheated until a target surface temperature was reached. Injera batter was then poured and baked under controlled conditions while data were continuously recorded. Multiple replicates were performed to establish repeatability and statistical validity.

Phase V: Data Analysis and Optimization

Collected data were analyzed and Key performance indicators (KPIs) such as specific fuel consumption, and uniformity index were used to evaluate the design.

1.10 Methods of Review on Injera Baking Technologies

Historically, evaluation of injera baking technologies has been limited by an overreliance on biomass-based or generic biogas stoves. To address this, the present study conducted a chronological review spanning over three decades of technological evolution.

Data were systematically gathered from government publications, NGO project reports, and peer-reviewed studies, focusing on metrics such as: specific fuel consumption, thermal efficiency and stove user acceptability.

The chronological organization of findings enabled the identification of key milestones—such as the introduction of the Mirt stove, the emergence of biogas-fired stoves, and the integration of thermal insulation and combustion control systems. This structured review also revealed persistent challenges, including inadequate burner design for injera baking and limited local production capacity for precision components.

By synthesizing these insights, the review established a robust foundation for innovation and guided the development of the optimized biogas injera baking stove presented in this research.

This study employed a systematic methodology to design, optimize, and evaluate biogas stoves specifically for injera baking applications. The research began with a comprehensive review of existing literature and field surveys through public hearings to identify key gaps in current biogas stove designs, particularly focusing on inefficiencies in fuel consumption and heat distribution in baking cultural accepted quality injera preparation. Based on these findings, we developed specialized stove prototypes with optimized fuel consumption and heat distribution systems tailored to the unique requirements of injera baking. The manufacturing process utilized durable materials and metal fabrication to ensure consistent performance. Experimental testing was then conducted with Controlled Cooking Test, where we measured critical parameters including biogas consumption rates, thermal efficiency, and cooking times under controlled conditions. Collected data underwent thorough statistical analysis to identify performance trends and relationships between design variables. Through an iterative optimization process, we refined the stove design to minimize biogas consumption while maintaining baking efficiency, ultimately delivering a solution that addresses both technical performance and user needs identified during the initial gap analysis phase. This end-to-end approach ensured that the final optimized stove design was both scientifically validated and practically relevant to real-world injera baking applications. This study employed a systematic five-phase approach to develop an optimized biogas injera baking stove, addressing key limitations of traditional wood-fired and existing biogas stoves as mentioned in Figure 1. The procedure focused on three critical parameters: heat distribution efficiency, biogas pressure optimization, and fuel consumption reduction.

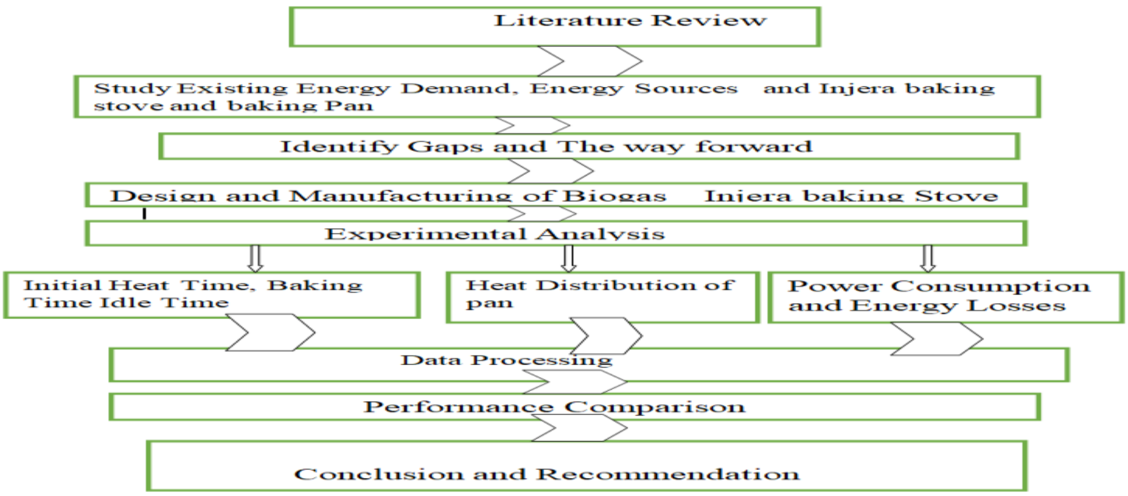

Figure 1.Conceptual Frame Work

CHAPTER TWO

LITRATURE REVIEW

2.1 Ethiopia Energy Landscape and Overview on Biogas Technology

2.1.1 Current Status of Energy Consumption in Ethiopia

Ethiopia's energy landscape remains heavily reliant on traditional sources, with the majority of the national energy supply derived from biomass and waste, similar to many other Sub-Saharan African countries. According to the Ministry of Water, Irrigation and Energy, the household sector is the dominant consumer, accounting for approximately 88% of total energy consumption, followed by the transportation sector (8.4%) and industry (3%) as shown in Figure 2 (4,21). The widespread reliance on traditional biomass fuels in Ethiopia has led to several serious challenges. One of the most critical issues is indoor air pollution, which arises from the use of open fires and inefficient stoves in poorly ventilated spaces. This exposure is a major cause of respiratory and eye diseases, particularly among women and children who spend the most time near cooking areas. Additionally, the high demand for firewood contributes to environmental degradation, especially deforestation, which in turn leads to soil erosion, loss of biodiversity, and disruption of local ecosystems. Beyond health and environmental concerns, there are significant gender and social burdens associated with traditional fuel use. In many rural communities, women and children are primarily responsible for collecting firewood—a time-consuming and physically demanding task that limits opportunities for education, income-generating activities, and overall well-being(1,22). Addressing these interconnected issues requires a transition to cleaner, more sustainable energy solutions like biogas technology(23).

Within the household sector, energy needs—particularly for cooking—are primarily met through traditional biomass sources such as firewood, charcoal, and agricultural residues. In contrast, the transportation sector is largely reliant on imported petroleum fuels.

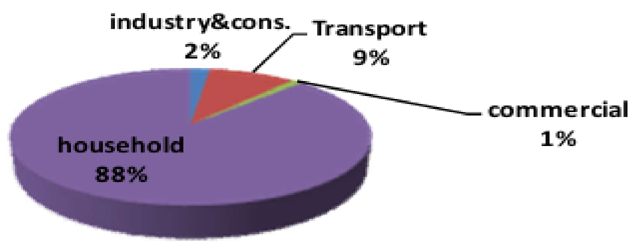

Figure 2. Energy Consumption

2.2 Relevance of Biogas Technologies and the Biogas Injera Baking Stove

Biogas technology presents a sustainable and clean alternative that directly addresses Ethiopia's energy challenges(17). Biogas is produced from organic waste—such as animal dung, food scraps, and agricultural residues—which are abundantly available in rural areas. It offers a renewable, low-emission cooking fuel that can significantly reduce the negative health and environmental impacts of traditional biomass use(23,24).

One promising innovation in this domain is the Biogas Injera Baking Stove, specifically designed to meet local baking needs. The Biogas Injera Baking Stove offers several key advantages that make it a practical and sustainable alternative to traditional cooking methods. One of its most notable benefits is fuel efficiency, as it significantly reduces the reliance on firewood, or other biomass fuels, thereby conserving natural resources and lowering household energy costs. In addition, the stove enables cleaner cooking, producing far less smoke than open fires or traditional stoves. This improvement greatly reduces indoor air pollution, which is a major health hazard in many Ethiopian households, particularly affecting women and children(10,25). The stove also offers time-saving benefits, with faster ignition and heating that lead to shorter baking times for injera—a staple food in Ethiopian cuisine. The biogas stove supports environmental sustainability by utilizing locally available and renewable inputs such as animal dung and organic waste. This not only minimizes waste but also reduces dependence on imported fuels, contributing to a more resilient and eco-friendly household energy system(26).

By integrating biogas systems into rural and peri-urban households—especially those already involved in livestock farming—the biogas injera stove can provide a culturally appropriate, health-conscious, and environmentally friendly solution to Ethiopia's energy poverty. In the long term, wider adoption of such technologies could help shift the energy mix in the household sector away from unsustainable biomass, fostering greater energy security and resilience.

2.2.1 Development of Biogas Technology

Biogas is a renewable energy gas produced through the natural breakdown of organic matter in the absence of oxygen; a process known as anaerobic digestion. This combustible gas mixture consists primarily of methane (CH_4, 50-70%) and carbon dioxide (CO_2, 30-50%), with trace amounts of other gases including hydrogen sulfide (H_2S), nitrogen (N_2), and water vapor (H_2O)(17,26). As a clean and sustainable energy source, biogas can be used for cooking, heating, electricity generation, and even as vehicle fuel, offering a practical alternative to conventional fossil fuels(27). The production of biogas occurs in specially designed digesters where microorganisms decompose organic materials such as animal manure, agricultural residues, food waste, and sewage sludge. This biological process not only generates valuable energy but also produces nutrient-rich digestate that can be used as organic fertilizer, creating a circular economy model that benefits both energy production and agricultural systems(26,28).

Biogas technology has gained global attention as an environmentally friendly solution that addresses multiple challenges simultaneously: it provides renewable energy, reduces greenhouse gas emissions by capturing methane that would otherwise escape into the atmosphere, and offers sustainable waste management. In developing countries like Ethiopia, where access to modern energy services remains limited and organic waste is abundant, biogas presents particular promise for rural energy provision and sustainable development(24,29).

The principal source of energy in the world is natural gas, a mixture of hydrocarbons. Currently, it has become increasingly rare and expensive, so it is necessary to find alternative energy resources to overcome these problems. In this context, biogas represents a valid option to obtain new energy carriers and then fresh fossil fuels for use in industrial and commercial fields(24,30).Biogas is one of the cleanest sources to generate electricity and for cooking and heating applications. The preferable technology used for biogas generation is anaerobic digestion(30,31). It is a renewable energy source and can be produced from raw materials such as biomass; agricultural, municipal, green, or food waste; manure; plant material; and sewage.

2.2.2 Characteristics and Composition of Biogas

Biogas is primarily composed of methane (CH_4, 50-70%) and carbon dioxide (CO_2, 30-50%),with trace amounts of other gases including hydrogen sulfide (H_2S), nitrogen (N_2), water vapor (H_2O), and minor constituents like ammonia (24,30).

The methane content determines most of biogas's fuel properties, giving it a calorific value between 18-25 MJ/m^3, which is about 60% of natural gas's energy value (32,33). This energy density makes biogas suitable for various energy applications, though the presence of CO_2 dilutes its heating value and affects combustion characteristics. Carbon dioxide, while non-combustible, plays a crucial role in maintaining pH balance during the anaerobic digestion process (28). However, for certain high-efficiency applications like vehicle fuel or grid injection, CO_2 removal through upgrading processes becomes necessary to achieve methane concentrations above 95% (34,35).

Hydrogen sulfide represents one of the most problematic contaminants in biogas, typically present in concentrations ranging from 0.1-3%(36,37) . This corrosive gas not only damages equipment through the formation of sulfuric acid but also poses health risks at concentrations as low as 10 ppm(1,38). Various removal techniques have been developed, with biological desulfurization using Thiobacillus bacteria proving particularly effective for large-scale operations, while chemical scrubbing with iron compounds remains common for smaller systems (38,39). The presence of water vapor, while less critical, can lead to condensation issues in gas storage and distribution systems, necessitating proper gas drying.

The physical properties of biogas significantly influence its practical applications. With a density slightly lower than air (1.2 kg/m^3), biogas will readily disperse if leaked, reducing explosion risks compared to heavier gases like propane (38). Its flammability range (6-12% in air) and relatively high auto-ignition temperature (650-750°C) make it safer to handle than many other fuel gases (30). However, these safety characteristics are strongly influenced by the exact gas composition, particularly the methane-to-CO_2 ratio, which affects both the lower and upper explosive limits (38,40).

Process parameters during anaerobic digestion play a crucial role in determining biogas composition. Temperature regimes significantly impact microbial activity, with mesophilic digestion (35-40°C) generally producing biogas with higher methane purity compared to thermophilic operation (50-60°C), though at slower digestion rates (34,41). The pH level must be carefully maintained between 6.5-7.5 to support methanogenic archaea, while the carbon-to-nitrogen ratio of the feedstock should ideally range between 20-30:1 for optimal microbial growth and gas production (30,42). Retention time represents another critical factor, with longer digestion periods generally resulting in higher methane yields but requiring larger digester volumes (43).

For many energy applications, raw biogas requires upgrading to remove CO_2, H_2S, and other impurities. Various technologies have been developed for this purpose, each with specific advantages. Water scrubbing, while energy-intensive (0.25-0.35 kWh/m^3), can achieve methane purities of 96-98% and simultaneously remove H_2S (30,34,35). Membrane separation offers lower energy consumption (0.20-0.30 kWh/m^3) but may require multiple stages to achieve similar purity levels. Pressure swing adsorption

(PSA) systems provide high-purity methane (96-99%) but at slightly higher energy costs (0.30-0.40 kWh/m³) (44,45). The choice of upgrading technology depends on factors including plant scale, required gas purity, and available resources.

Recent research has focused on optimizing biogas composition through co-digestion of multiple feedstocks. Studies show that mixing animal manure with crop residues or food waste can enhance methane production by 15-30% while improving the carbon-to-nitrogen balance (28,46). Pretreatment methods such as mechanical, thermal, or enzymatic hydrolysis have also demonstrated potential to increase biogas yield and quality by improving feedstock biodegradability (47,48). These advancements contribute to making biogas a more reliable and efficient renewable energy source.

The unique composition and characteristics of biogas present both opportunities and challenges for its utilization as a renewable energy source. While its variable quality requires careful consideration in system design and operation, proper understanding and management of its properties enable effective use across multiple applications from household cooking to electricity generation and vehicle fuel (30,49). Continued research into process optimization and upgrading technologies promises to further enhance biogas quality and broaden its applications in the transition to sustainable energy systems(41,45).

Principal gases produced are methane and carbon dioxide. Biogas is about 20% lighter than air and has an ignition temperature in the range of 50°C to 750°C (35,36). The Composition of biogas is as shown in Table 1. The composition of gas varies with raw material used(39,46).

Table 1. Composition of Biogas

Compound	Chemical Symbol	Content
Methane	CH4	50-75
Carbon dioxide	CO2	25-45
Water vapor	H_2O	2-7
Oxygen	O_2	<2
Nitrogen	N_2	<2
Ammonia	NH_3	<2
Hydrogen	H_2	<2
Hydrogen Sulfide	H_2S	<2

2.2.3 Factors Affecting Biogas Composition

The composition of biogas is influenced by multiple interrelated factors that can be broadly categorized into feedstock characteristics, operational parameters, and environmental conditions. Understanding these variables is essential for optimizing biogas quality and production efficiency in anaerobic digestion systems.

Feedstock Characteristics

The type and quality of organic substrate used represent the primary determinant of biogas composite in anaerobic digestion systems.

Different feedstocks contain varying ratios of carbohydrates, proteins, and lipids, which degrade into distinct proportions of methane and carbon dioxide(36) as shown Table 2. For instance, lipid-rich materials like slaughterhouse waste yield biogas with higher methane content (70-75%) compared to carbohydrate-dominated agricultural residues (50-55% methane)(30,36,46). The particle size and biodegradability of feedstock also significantly impact gas composition, with smaller particle sizes and higher lignin content generally resulting in slower digestion rates and altered gas profiles (30). Co-digestion of complementary substrates has been shown to improve the carbon-to-nitrogen balance and enhance methane production by 15-30% compared to single-substrate systems (51).

Table 2. Types of Feed Stocks and Gas Composition

Feedstock Type	CH_4 Content (%)	CO_2 Content (%)	H_2S (ppm)
Cattle manure	55–65	35–45	100–3000
Pig manure	60–70	30–40	500–4000
Food waste	50–60	40–50	500–1500
Sewage sludge	60–65	35–40	1000–5000
Agricultural waste	45–55	45–55	100–500

Process Parameters

Operational conditions within the digester profoundly influence microbial activity and consequently biogas composition. Temperature represents one of the most critical factors, with mesophilic digestion (35-40°C) typically producing biogas containing 55-65% methane, while thermophilic systems (50-60°C) often yield slightly lower methane concentrations (50-60%) but with faster conversion rates(23,30,50) . The pH level must be carefully maintained between 6.5-7.5 to support methanogenic archaea, as values outside this range favor acid-producing bacteria that increase CO_2 production (23,26,46). Hydraulic retention time (HRT) also affects composition, with longer retention generally increasing methane percentage but requiring larger digester volumes - typical HRTs range from 15-30 days for mesophilic systems treating agricultural waste (26,52).

Microbial Community Dynamics

The composition and activity of microbial consortia within the digester directly determine biogas quality. A balanced population of hydrolytic, acidogenic, acetogenic, and methanogenic microorganisms is essential for efficient methane production. Factors such as organic loading rate (OLR), nutrient availability, and presence of inhibitors can shift microbial populations, thereby altering gas composition. For example, excessive OLR may lead to acid accumulation and subsequent inhibition of methanogens, resulting in biogas with elevated CO_2 content. Trace element availability, particularly nickel, cobalt, and iron, is crucial for maintaining healthy methanogen populations and consistent methane production(31,34,53).

Environmental and System Design Factors

External conditions and reactor configuration play significant roles in determining biogas composition. Seasonal temperature variations in unheated digesters can cause fluctuations in microbial activity and gas quality(26,46). Mixing intensity affects substrate-microbe contact and volatile fatty acid distribution, with optimal mixing producing more uniform biogas composition compared to unmixed systems (50). The type of digestion system (e.g., continuous stirred-tank versus plug-flow) also influences gas composition through differences in substrate flow patterns and retention time distribution (43). Additionally, oxygen intrusion must be minimized as even small amounts can inhibit methanogens and promote aerobic decomposition that increases CO_2 production (44,53).

Inhibitors and Contaminants

Various substances present in feedstock can adversely affect microbial populations and biogas composition. Ammonia inhibition becomes significant at concentrations above 1500 mg/L, particularly in systems processing nitrogen-rich substrates like poultry manure, leading to reduced methane content (37,54,55). Sulfate-reducing bacteria compete with methanogens for substrates and produce H_2S instead of methane, with sulfate concentrations above 500 mg/L potentially decreasing methane yield by 20-40% (26,56). Other inhibitors including heavy metals, antibiotics, and disinfectants can similarly alter microbial dynamics and gas composition, necessitating careful feedstock selection and pretreatment (30).

Understanding these multifaceted influences on biogas composition enables better system design and operation. By controlling key parameters and optimizing process conditions, operators can consistently produce biogas with desired characteristics suitable for various energy applications, from household cooking to electricity generation and vehicle fuel. Continued research into microbial ecology and process engineering promises further improvements in biogas quality and production efficiency.

Process Parameters Affecting Biogas Production and Composition

The anaerobic digestion process is governed by several critical parameters that collectively determine both the quantity and quality of biogas produced. Among these, temperature stands as one of the most influential factors, with most commercial digesters operating in either mesophilic (30-40°C) or thermophilic (50-60°C) ranges (26). Mesophilic digestion offers optimal balance between energy efficiency and process stability, typically yielding biogas with 55-65% methane content at hydraulic retention times (HRT) of 15-30 days(43). Thermophilic systems, while achieving faster conversion rates (HRT 10-15 days), often produce biogas with slightly lower methane content (50-60%) and demonstrate greater sensitivity to operational fluctuations.pH maintenance represents another crucial parameter, requiring careful control within the narrow range of 6.8-7.4 to support methanogenic archaea while preventing acid accumulation from volatile fatty acids (VFAs) (24,53). The system's buffering capacity, measured as alkalinity (2000-5000 mg/L as $CaCO_3$), plays a vital role in maintaining this pH stability, with the VFA-to-alkalinity ratio serving as a key indicator of process health. Organic loading rate (OLR) and hydraulic retention time (HRT) form an interdependent pair of parameters, where typical agricultural digesters operate at OLRs of 1-5 kg volatile solids/m³/day with HRTs of 15-30 days (36,53). Co-digestion strategies can push OLRs higher (up to 7 kg VS/m³/day) by improving the substrate's carbon-to-nitrogen ratio, which optimally should be maintained between 20-30:1 to prevent either nitrogen limitation or ammonia toxicity (35,47).

Mixing intensity significantly impacts process efficiency by ensuring uniform temperature distribution, preventing stratification, and enhancing substrate-microorganism contact (23,46). However, excessive mixing can disrupt microbial flocs and unnecessarily increase energy consumption, making intermittent mixing (10-30 minutes per hour) the preferred operational strategy. The process is particularly sensitive to various inhibitors, including free ammonia (>150 mg/L), hydrogen sulfide (>100 mg/L), and heavy metals (>50 mg/L), all of which can severely impair methanogenic activity (35). Trace elements such as iron (1-10 mg/L), nickel (0.1-1 mg/L), and cobalt (0.1-0.5 mg/L) are equally critical for maintaining healthy microbial populations and consistent biogas production (53).

Redox potential must be carefully maintained between -300 to -400 mV to ensure strictly anaerobic conditions, as even minimal oxygen intrusion (>0.1 mg/L) can inhibit methanogens and shift microbial community dynamics (58). Proper system start-up and acclimation are equally vital, requiring gradual OLR increases over 4-8 weeks and careful monitoring of alkalinity ratios, with microbial adaptation typically requiring 2-3 complete HRTs (41). Advanced monitoring and control strategies, including online measurement of key parameters and model-based predictive control, have demonstrated significant improvements in process stability and biogas yields in modern digestion systems (28). These parameters collectively form a complex, interconnected system where optimal biogas production requires careful balancing of multiple factors based on specific feedstock characteristics and operational objectives.

2.2.4 Global Benefits of Biogas Technology

Biogas technology offers numerous environmental, economic, and social benefits that contribute to sustainable development worldwide. The anaerobic digestion process not only generates renewable energy but also addresses critical issues such as waste management, greenhouse gas emissions, and energy poverty. Below is a detailed analysis of the global benefits supported by scientific literature and case studies.

The current global energy supply is highly dependent on fossil sources (crude oil, lignite, hard coal, natural gas). These are fossilized remains of dead plants and animals, which have been exposed to heat and pressure in the Earth's crust over hundreds of millions of years. For this reason, fossil fuels are non-renewable resources which reserves are being depleted much faster than new ones are being formed(14).

Furthermore, the increases in human population as well as the overall industrial development have led to an exponential increase in global energy demand(32). Particularly, energy reserves will be depleted in the coming decades due to the increase in energy demand. Therefore, worldwide energy sectors have to identify new alternative sources of energy for replacing fossil-derived fuels. This is also fundamental from an environmental point of view. It is, in fact, well documented that fossil-derived fuels are the most important sources of pollution and global warming, which are mainly caused by the production of CO_2 and sulfur compounds(14) . Recent energy crises and the prospect of the near depletion of fossil or nonrenewable fuel reserves have led industrialized countries to promote renewable energy production, distributed generation and energy efficiency interventions. Currently, a global priority for sustainable development is access to renewable energy and other energy issues. A transition to more efficient energy systems requires actions involving all political levels, from the local one to the global one. It is clear that the issue of reducing climate-altering gas (GHG) emissions has now become an issue of paramount importance. Circular economy and bio-economy are the prospects for addressing these challenges and achieving environmental and socioeconomic goals around the world(39,45,46) .

Another relevant issue related to biogas production concerns the by-product of the process, i.e., digestate. Digestate is the residue of the anaerobic digestion process. It can result from the digestion of livestock manure, plant biomass (waste or dedicated), animal by-products, sewage sludge or organic fraction of municipal solid waste. Promising applications for digestate have been found in the agricultural sector, where it is used both as a soil amendment and a fertilizer (46,51,59).

2.2.4.1 Economic Benefits

Biogas technology enhances energy security and creates economic opportunities, particularly in rural areas. Small-scale biogas systems can provide a 10-30% return on investment (ROI) for farmers by reducing energy and fertilizer costs(24,25,60). In developing countries, biogas adoption has been shown to increase household incomes by 15-20% due to savings on fuelwood and kerosene (14,21).

Large-scale biogas plants also contribute to national energy security by diversifying the energy mix. Germany, for example, generates over 5,000 MW of electricity from biogas, reducing reliance on imported natural gas (32).

2.2.4.2 Social Benefits

Biogas adoption improves living standards, particularly in developing regions. The WHO (2020) reports that replacing traditional biomass stoves with biogas reduces indoor air pollution, preventing 4 million premature deaths annually linked to respiratory diseases. In Nepal and India, national biogas programs have improved women's health and education by reducing smoke exposure and labor burdens (32,61).

2.2.4.3 Climate Change Mitigation

Biogas systems contribute to carbon neutrality by recycling organic waste into energy. The European Biogas Association (31)estimates that biogas could supply 30-40% of the EU's natural gas demand by 2050, reducing fossil fuel dependence.

2.2.5 Global Biogas Production from Diverse Feedstocks

Biogas technology has gained significant traction worldwide as a sustainable solution for organic waste management and renewable energy generation. The anaerobic digestion (AD) process converts various organic feedstocks into methane-rich biogas and nutrient-dense digestate. This review examines biogas production from four key sources - agricultural waste, municipal wastewater, food waste, and industrial byproducts - supported by recent scientific literature.

2.2.5.1 Agricultural Waste as a Biogas Feedstock

Agricultural residues represent one of the most abundant and widely used feedstocks for biogas production globally. Animal manure from cattle, pigs, and poultry serves as an excellent substrate due to its high biodegradability and balanced nutrient profile. The co-digestion of manure with crop residues has been shown to enhance biogas yields by 20-40% compared to single-substrate digestion (28,39). However, the increasing use of dedicated energy crops like maize silage has raised concerns about land-use competition with food production. Germany has emerged as a leader in agricultural biogas, with over 9,500 plants primarily using maize silage and livestock manure, contributing significantly to the country's renewable energy mix (21,32). In developing nations like China, small-scale household digesters processing livestock manure have improved rural energy access while addressing waste management challenges (32).

2.2.5.2 Municipal Wastewater Treatment and Biogas Recovery

The treatment of municipal wastewater presents a dual opportunity for environmental protection and energy recovery through biogas production. Anaerobic digestion of sewage sludge can achieve methane recovery rates of 60-70% while significantly reducing greenhouse gas emissions compared to conventional sludge disposal methods. Recent advancements in pretreatment technologies, particularly thermal hydrolysis, have been shown to increase biogas production from sewage sludge by 30-50% (37,54).

2.2.5.3 Food Waste Valorization through Anaerobic Digestion

The anaerobic digestion of food waste has gained prominence due to its high organic content and methane potential. Research revealed that food waste can yield 400-600 m^3 of biogas per ton, significantly higher than many other organic substrates(46,50). However, challenges such as oil and salt content require careful management through pretreatment or co-digestion strategies (37,46). Several countries have implemented innovative approaches to food waste digestion, with South Korea's mandatory food waste recycling program standing out as a comprehensive system that combines regulatory measures with advanced AD technology(32).These systems not only address waste management challenges but also contribute to circular economy objectives by recovering both energy and nutrients from discarded food(46).

2.2.5.4 Industrial Waste-to-Biogas Conversion

Industrial organic wastes represent a significant and often underutilized resource for biogas production. Studies have shown that effluents from food processing, breweries, and slaughterhouses contain high chemical oxygen demand (COD) levels, making them ideal substrates for anaerobic digestion(24,33,45). Industrial biogas systems are gaining momentum worldwide, particularly in Europe where policies like the Renewable Energy Directive have created favorable market conditions. Successful implementations include Denmark's Carlsberg breweries, which have integrated biogas production from wastewater into their sustainability strategy , and India's sugar mills that utilize bagasse and vinasse for combined heat and power generation (40). These industrial applications demonstrate how biogas technology can transform waste liabilities into energy assets while improving environmental performance.

2.2.6 Future Perspectives and Research Needs On Biogas Development

While biogas technology has demonstrated significant potential across various feedstocks, several areas require further research and development. The optimization of pretreatment methods for lignocellulosic materials remains a critical challenge for agricultural biogas systems (57,62). In municipal applications, the development of more efficient sludge digestion processes could enhance energy recovery rates (37,63). For food waste systems, standardization of collection and pretreatment protocols would facilitate wider adoption(26,50). Industrial biogas would benefit from more case-specific techno-economic analyses to demonstrate financial viability (64). Additionally, emerging concepts such as biogas upgrading biomethane and integration with hydrogen production systems present exciting opportunities for future research and implementation. As nations worldwide strive to meet climate goals and transition to circular economies, biogas technology will likely play an increasingly important role in sustainable waste management and renewable energy production.

2.3 Potential of Biogas Development in Ethiopia

Ethiopia possesses significant potential for biogas development due to its abundant organic waste resources, including livestock manure, agricultural residues, kitchen waste, industrial byproducts, and municipal solid waste. With over 60 million cattle, 30 million sheep, and 30 million goats (15), Ethiopia ranks among Africa's top livestock producers, generating substantial amounts of manure that could be harnessed for renewable energy. The country's predominantly agrarian economy also yields considerable crop residues, while rapid urbanization is increasing organic waste generation in cities. This analysis examines Ethiopia's biogas potential across key feedstock categories, supported by scientific studies and development reports.

2.3.1 Potential Development of Biogas in Ethiopia

Ethiopia possesses significant potential for biogas production due to its large livestock population, abundant agricultural residues, and growing need for sustainable energy solutions. With over 65million cattle, 42 million sheep, and 52 million goats, the country has one of the largest livestock populations in Africa, generating vast quantities of manure that can serve as a reliable feedstock for biogas production. In addition, crop residues such as maize stalks, teff straw, and other organic wastes contribute to the biomass resource base, creating favorable conditions for decentralized biogas energy systems.

Biogas development in Ethiopia is further supported by the urgent demand for alternative cooking energy sources. More than 90% of Ethiopian households rely on traditional biomass fuels such as firewood, charcoal, and crop residues, which has contributed to deforestation, indoor air pollution, and associated health risks. Biogas offers a renewable and clean alternative that can reduce household dependence on unsustainable fuels while providing additional benefits such as organic fertilizer from the digested slurry, which improves soil fertility and agricultural productivity.

Geographically, Ethiopia is well-suited for biogas adoption, as many rural households maintain livestock in close proximity to their homes, ensuring easy access to manure feedstock. Moreover, the relatively warm climate in much of the country is favorable for anaerobic digestion, minimizing the need for costly heating systems to maintain digester efficiency.

At the policy level, the Ethiopian government has recognized the importance of renewable energy, including biogas, in achieving national development and climate goals. Initiatives such as the National Biogas Programme of Ethiopia (NBPE), launched in 2009, have laid the groundwork for household-level biogas digesters, though adoption remains lower than expected due to financial, technical, and institutional barriers. Nonetheless, the potential remains immense, especially when considering integration with productive uses such as biogas-powered injera baking stoves, small-scale electricity generation, and agro-processing applications.

If harnessed effectively, Ethiopia’s biogas resources could contribute significantly to energy security, reduce greenhouse gas emissions, improve rural livelihoods, and align with the country’s commitments under the Sustainable Development Goals (SDGs) and its Climate Resilient Green Economy (CRGE) strategy.

2.3.2 Livestock Manure: The Most Promising Feedstock

Ethiopia's vast livestock population presents the most immediate opportunity forbiogas expansion. Research estimates that the annual biogas potential from cattle manure alone exceeds 1.2 billion m^3, enough to provide clean cooking fuel for approximately 5 million households(46,65). Traditional manure management practices, particularly in rural areas where 80% of the population resides (14), currently lead to methane emissions and lost energy potential. The National Biogas Programe of Ethiopia (NBPE) has installed over 15,000 household biogas plants since 2008, primarily using cattle dung, demonstrating technical feasibility (49,66).

2.3.3 Agricultural Residues: An Underutilized Resource

Ethiopia generates approximately 50 million tons of crop residues annually, primarily from teff, maize, wheat, and barley production (32,67). These residues currently serve as animal feed or are burned, representing wasted energy potential. Studies show that pretreatment of lignocellulosic materials like cereal straws could yield 200-300 m³ of biogas per ton (55,67). The Ethiopian Bioenergy Development Strategy(10) identifies agricultural residues as key feedstocks for medium-scale biogas plants serving rural communities. The integration of crop residues with livestock manure in farm-based digesters could particularly benefit Ethiopia's smallholder farmers by providing both energy and organic fertilizer, Municipal and Kitchen.

2.3.4 Waste: Addressing Urban Energy Needs

Ethiopia's rapidly growing urban centers generate increasing amounts of organic waste, with Addis Ababa alone producing over 1,400 tons of municipal solid waste daily, 60% of which is organic (15). Food waste from markets and households in major cities has a high biogas potential of 400-500 m³ per ton. Pilot projects like the Koshe landfill power plant in Addis Ababa showcase the technical viability of municipal waste-to-energy conversion (2,55). However, key challenges including inadequate waste segregation, limited collection systems, and lack of institutional coordination. Community-based biogas systems using kitchen waste, similar to successful models in India and Nepal, could be adapted for Ethiopian urban neighborhoods(2,29).

2.3.5 Industrial Waste: Untapped Potential

Ethiopia's growing Agro-processing industries (coffee, leather, sugar, breweries) generate substantial organic wastewater and byproducts suitable for anaerobic digestion. The sugar industry alone produces over 1 million tons of bagasse and 500,000 m³ of vinasse annually (3,68). Biogas recovery from coffee processing wastewater could meet 30-40% of a factory's energy needs while solving environmental pollution issues(69). Tannery waste, though challenging due to high salinity and chromium content, has been successfully digested in pilot plants with proper pretreatment (70).

2.4 Challenges and Opportunities of Biogas Development

Despite Ethiopia's abundant resources, several barriers hinder biogas development. Technical capacity gaps in operation and maintenance persist, as noted in evaluations.

Climate variability affects feedstock availability, requiring adaptive designs. However, emerging opportunities include carbon financing mechanisms, pay-as-you-go business models, and integration with Ethiopia's Climate Resilient Green Economy strategy(71). Ethiopia possesses all necessary feedstocks to develop a robust biogas sector addressing energy access, waste management, and climate change mitigation. Strategic priorities should include: scaling successful household manure-based systems, developing municipal waste-to-energy projects in major cities, promoting industrial biogas recovery, and supporting research on optimized co-digestion mixtures. With proper policy support and investment, biogas could contribute significantly to Ethiopia's renewable energy targets while creating rural employment and improving agricultural productivity through digestate use. The coming decade presents a critical window to harness this distributed, sustainable energy resource that aligns perfectly with Ethiopia's development priorities.

Ethiopia has the largest livestock population in Africa, with 65 million cattle, 40 million sheep, 51 million goats, 8 million camels and 49 million chickens in 2020 (15,55). In addition, the country uses massive chemical fertilizers to improve agricultural yield, however, biogas will have the potential to replace artificial fertilizer with bio slurries. Moreover, the country has enough locally available materials to develop domestic biogas technologies.

2.5 Development of Domestic Biogas in Ethiopia (1960–2025)

Access to clean and reliable household energy remains one of the most pressing challenges in Ethiopia, where the majority of rural and peri-urban households still depend on traditional biomass fuels such as firewood, charcoal, and agricultural residues for cooking and heating. This heavy reliance on biomass not only accelerates deforestation and land degradation but also contributes to indoor air pollution, which is a major health risk, especially for women and children who spend long hours near open fires. At the same time, the collection and use of fuelwood impose a significant time and labor burden on households, limiting opportunities for education, income generation, and improved livelihoods.

Domestic biogas technology offers a sustainable alternative by converting animal manure and other organic wastes into clean combustible gas through anaerobic digestion. The gas can be used for cooking, lighting, and small-scale productive uses, while the residual bio-slurry serves as a nutrient-rich organic fertilizer, enhancing agricultural productivity. Beyond household benefits, domestic biogas contributes to climate change mitigation by reducing greenhouse gas emissions from both biomass burning and unmanaged organic waste.

Ethiopia possesses considerable potential for domestic biogas development due to its large livestock population, widespread availability of organic feedstock, and the urgent need for clean cooking solutions. Over the past two decades, national initiatives such as the National Biogas Programme of Ethiopia (NBPE) and NBPE+ have demonstrated the technical feasibility and socio-economic benefits of household biodigesters. However, adoption has faced challenges, including high upfront investment costs, inconsistent technical quality, limited after-sales service, and socio-cultural barriers. Despite these constraints, domestic biogas remains a vital component of Ethiopia's strategy to expand access to modern energy, improve rural livelihoods, and meet its climate and development commitments.

2.5.1 Early Beginnings (1960s–1990s)

The first biogas plant in Ethiopia was installed in October 1960 at Ambo Agricultural College, 115 km west of Addis Ababa. This floating-drum system had a 7m³ digester and processed 100 liters of dung-water mixture daily (1:1 ratio)(66).

In the 1970s, small-scale biogas digesters—mostly fixed-dome designs adapted from China and India—were introduced (66). However, adoption was limited due to high costs and lack of technical expertise.

2.5.2 National Expansion (2000s–2010s)

A major breakthrough came in 2007 with the National Biogas Programme Ethiopia (NBPE), a partnership between the Ethiopian government, SNV Netherlands(69). The NBPE introduced the Ethiopian Modified Fixed-Dome Digester (EMFDD), optimized for local conditions, along with microcredit schemes to improve affordability(66).

By the early 2010s, Ethiopia had made notable progress in promoting biogas technology, with over 8,000 domestic biogas plants installed, primarily in the Amhara, Oromia, and Southern Nations, Nationalities, and Peoples' (SNNP) regions (72). These installations brought a range of documented benefits. One significant advantage was the reduction in indoor air pollution, which improved household health conditions, especially for women and children(1,29). Additionally, the use of bio-slurry, a by-product of biogas production, contributed to enhanced crop yields, offering farmers a valuable organic fertilizer and reducing reliance on chemical inputs (10). Another important outcome was the time savings achieved, as biogas reduced the need for firewood collection and shortened cooking times, allowing women and children to engage in more productive or educational activities. These early successes demonstrated the potential of biogas technology to improve both livelihoods and environmental sustainability in rural Ethiopia. However, despite its potential, the widespread adoption of biogas technology in Ethiopia faces several significant challen1ges. One of the main barriers is the high upfront cost, with the installation of a single biogas digester ranging from USD 500 to 1,000(73), which is often unaffordable for many rural households. Additionally, there is a lack of regular maintenance and technical support, resulting in a high failure rate—around 60% of installed biogas plants are reported to be non-operational(72,74). Another major issue is the shortage of feedstock, particularly in drought-prone regions, where limited availability of water and animal dung undermines the consistent production of biogas (1,29). These challenges highlight the need for targeted interventions, including financial support, technical training, and context-specific solutions to improve the sustainability and scalability of biogas initiatives in Ethiopia

2.5.3 Recent Progress (2020–2025)

By December 2023, Ethiopia had made considerable strides in expanding its biogas sector, with a total of 46,160 household biogas plants installed across 11 regions (72). The Sinidu Fixed Dome model remained the most widely used design, with 7,024 units already built by 2013(72). Between 2020 and 2025, several key developments have shaped the trajectory of biogas adoption in the country. The Ethiopian Biogas Sector Development Strategy set an ambitious goal of reaching 100,000 domestic biogas installations by 2025, with a focus on high-potential regions such as Amhara, Oromia, SNNP, and Tigray (17,72).

While there has been gradual market growth, the private sector's role remains limited, necessitating stronger policy interventions and financial incentives to attract investment and improve service delivery (72). However, the sector continues to face operational challenges, with an estimated 60% of installed digesters reported as non-functional, mainly due to maintenance and technical support deficiencies (72). In response, government and development partners are intensifying efforts to enhance after-sales services and end-user training.

In terms of system specifications, around 80% of the biogas digesters are 6 m^3 in size, followed by 8 m^3 (16%), 4 m^3 (2%), and 10 m^3 (1%). The Sinidu model accounts for

70% of the systems installed, with the remaining 30% comprising the Sinidu 2008 variant. Additionally, 78% of systems are equipped with two slurry pits, while the rest have one, facilitating better management of the bio-slurry by-product.

From an environmental and economic perspective, the biogas program has contributed significantly to reducing reliance on firewood and animal dung, which are traditionally used for cooking (75). Furthermore, it has helped in cutting greenhouse gas (GHG) emissions by replacing traditional fuels, improving manure management, and lowering the need for chemical fertilizers, thereby supporting both climate goals and sustainable agriculture (76).

2.5.4 Future Outlook of biogas development (Beyond 2025)

Looking beyond 2025, the future of biogas development in Ethiopia hinges on addressing key structural and operational challenges through targeted interventions. Policy support will be crucial, particularly in strengthening financing mechanisms such as subsidies, microcredit schemes, and results-based financing to make biogas technology more accessible to rural households. In parallel, there is a pressing need to expand technical training programs aimed at enhancing local capacity for the construction, maintenance, and repair of biogas systems. This would help reduce the high rate of non-functional digesters and improve long-term sustainability. Moreover, addressing feedstock shortages—especially in drought-prone regions—will require promoting integrated farming systems that ensure a steady and reliable supply of animal dung. Finally, for the biogas sector to thrive and scale, it is essential to foster private sector participation by supporting local enterprises involved in the manufacturing and distribution of biogas components. Such efforts will not only enhance supply chains but also create jobs and stimulate local economies, positioning biogas as a key pillar of Ethiopia’s clean energy future(23).

2.6 Functionality of Biogas Plants in Ethiopia

The operational status of biogas plants in Ethiopia presents a mixed picture of progress and persistent challenges. According to the National Biogas Program Ethiopia (NBPE+) baseline study conducted in 2018, only 54% of installed biogas digesters remained functional nationwide (NBPE+, 2018). This concerning functionality rate indicates that nearly half of the country's biogas infrastructure fails to deliver intended benefits, undermining Ethiopia's renewable energy goals and rural development objectives.

Multiple interrelated factors contribute to this low functionality rate. Technical deficiencies in construction emerge as a primary constraint, with common issues including dome cracks (often caused by substandard materials or improper curing), pipe leakages (resulting from poor installation or material degradation), and drainage problems. These construction flaws frequently stem from inadequate quality control during installation and limited technical capacity among local masons. Equally problematic are operational challenges related to feedstock management, where households struggle with irregular feeding patterns, improper dung-to-water ratios, and seasonal shortages of cattle manure - particularly in pastoralist communities and drought-prone regions.

The sustainability of biogas systems is further compromised by systemic weaknesses in maintenance support. Many rural households lack access to replacement parts for damaged components such as gas valves, pipes, or burners, while the absence of local repair services leaves technical problems unresolved. Water scarcity compounds these difficulties, as adequate water supply proves essential for proper slurry preparation but remains unreliable in various regions. Promotional shortcomings also play a role, with insufficient user education leading to improper operation and maintenance practices among adopting households.

These challenges manifest differently across Ethiopia's diverse regions. While areas with strong agricultural extension services and reliable water access (particularly in the Amhara and Oromia regions) demonstrate better functionality rates, arid zones and pastoralist communities face greater obstacles(2). The variation underscores the need for geographically tailored solutions that account for local environmental conditions, livelihood patterns, and infrastructure limitations.

Addressing these barriers requires a multi-pronged approach. Strengthening construction quality through enhanced mason training and rigorous quality assurance protocols could reduce technical failures. Establishing decentralized maintenance networks and spare part supply chains would improve repair accessibility. Complementary measures should include targeted user education programs, optimized feeding protocols for low-manure households, and integrated water management solutions. As Ethiopia continues to expand its domestic biogas sector, prioritizing these operational sustainability factors will be crucial for transforming biogas potential into lasting energy and agricultural benefits for rural communities(77).

2.7 Injera Baking Technologies in Ethiopia

2.7.1 Introduction

Injera, a soft, spongy flatbread made primarily from teff, is not only Ethiopia's staple food but also a central element of its cultural heritage. Traditionally prepared on a clay griddle known as a mitad, injera baking is an energy-intensive process that depends heavily on biomass fuels such as firewood, animal dung, and crop residues. This widespread reliance on traditional fuels has contributed to numerous environmental, health, and social problems—including deforestation, indoor air pollution, and the burden of fuel collection on women and children. In response to these challenges, a variety of injera baking technologies have been developed over the years, including improved biomass stoves, electric mitads, and more recently, biogas-based injera baking systems. Among these innovations, the Biogas Injera Baking Stove has emerged as a particularly promising solution. It is designed to address both the energy and environmental concerns of traditional baking methods while maintaining cultural cooking practices. By utilizing biogas generated from organic waste, this stove offers a clean, renewable, and locally available energy source, reducing reliance on firewood and minimizing harmful emissions during cooking. The development of the Biogas Injera Baking Stove represents a significant advancement in sustainable cooking technologies in Ethiopia. It combines traditional food preparation methods with modern, eco-friendly energy solutions, offering multiple benefits such as improved fuel efficiency, reduced indoor air pollution, shorter baking times, and the productive use of bio-slurry as organic fertilizer. This review explores the evolution of injera baking technologies with a focus on the role and potential of biogas-based solutions. It also examines key research achievements, user acceptance, and implementation challenges, aiming to guide future innovation and policy support for widespread adoption of sustainable injera baking technologies across Ethiopia.

This review discusses the following issues: i) early development of injera baking stoves, ii) current research, iii) the way forward in terms of research and development regarding injera baking stoves. Since the information collected is mostly from reports from governmental and non-governmental institutions in the country, most of the references are not published in peer reviewed journals. Hence, this effort will open a door way for reaching a wider public and also be a starting point for researchers who will be working on the design, manufacturing and testing of stoves particularly for baking applications not only in Ethiopia but also elsewhere in the world.

2.7.2 Injera and Its Baseline Baking Technology

Injera, Ethiopia's traditional flatbread, is an integral part of the country's daily diet and cultural identity. It is made primarily from teff, a highly nutritious, gluten-free grain, and is characterized by its unique texture, size, and appearance. The ideal injera has a soft, spongy texture with a slightly sour taste, which is the result of fermentation. One of its most defining features is the formation of small holes (eyes) across the surface, which are created by the fermentation process and are essential for its characteristic softness and absorbency. These holes serve to soak up the various stews and sauces that are served with injera, making it a versatile and functional food item. The size of the injera typically ranges from 50 to 60 cm in diameter, although this can vary depending on the cooking method and regional preferences(71).

The quality of injera is assessed based on several factors, including its texture, evenness of the eyes, size, and flavor. Uniformity in the texture and the formation of consistent eyes are particularly important indicators of high-quality injera. Thinness and flexibility are also considered desirable, as they enhance its usability for scooping food(78).

The traditional method of injera baking involves the use of a clay griddle known as a mitad, where the batter is poured and cooked over an open flame. This process, while effective, is energy-intensive and relies heavily on biomass fuels, such as firewood. Traditional baking technologies often lead to uneven heating and excessive fuel consumption, contributing to environmental degradation and health issues due to indoor air pollution (1). To address these challenges, there has been significant interest in improving the baking process, such as through the development of improved stoves and the Biogas Injera Baking Stove, which offer cleaner, more efficient cooking methods while maintaining the traditional quality of injera.

Figure 3. Injera Picture

The majority of Ethiopians still bake injera using a three-stone fire. Since the 1980's efforts have been undertaken to improve biomass injera baking stoves and to introduce electric injera baking stoves for urban areas. Injera stoves can be classified based any source: Biomass Stove, Solar Stove, Electric stove as shown in Figure 4.

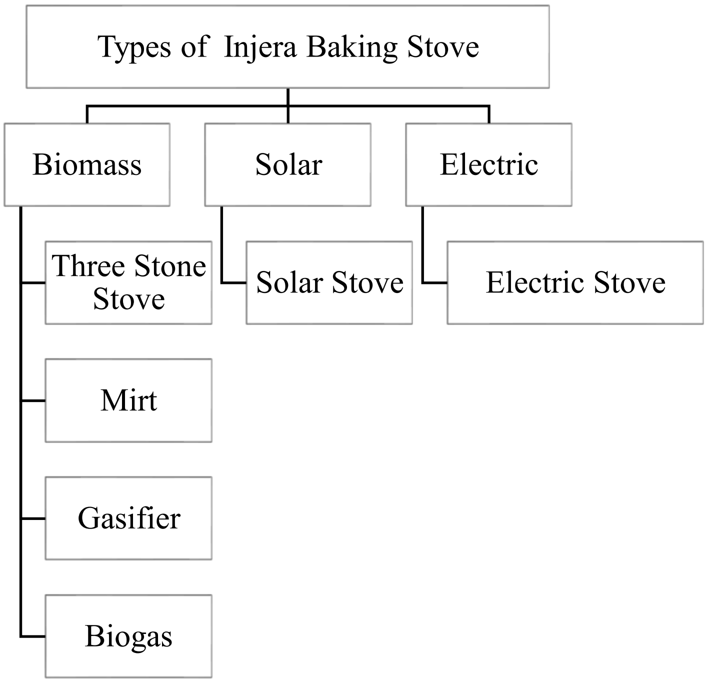

Figure 4. Types of Stoves

2.7.3 Three-stone fire for baking injera

The three stone open-fire stove uses three separate stones which can be placed as required for supporting the mitad (clay plate) for baking. The types and size of stones used varies according to the availability of the stones. Usually three (10 – 15 cm), high stones are used to support the mitad Figure 5.

Figure 5. Three Stone Open fire Stove

A number of developers used three-stone open-fire injera baking stove as a reference for showing the improvements with various versions of Mirt stove. The specific fuel consumption of three-stone open-fire injera baking stove on average is 929 g of wood /kg of injera (Table 3).

2.7.4 Early Research and Development Efforts to Improve Injera Baking Stoves

2.7.4.1 Burayou injera baking stove

The need for efficient injera baking stoves had not been addressed for a long time until governmental institutions laid the foundation in the 1980s . Early activities include manufacturing of mud injera baking stoves by the Burayou Basic Technology Center (BTC), under the Ministry of Education in the early 1980s. The name of the injera baking stove was ‘Burayou mud-stove’. The then Ethiopian Science and Technology Commission (now Ministry of Science and Technology of Ethiopia) hired a consultant in 1981 to assess traditional closed stove in selected areas of the country. The major aim of this study was to make a survey of the types of stoves in use in the country. The numbers of stoves surveyed were 113 with a diameter of 60-65 cm and thickness of less than 2.5 cm earthen plate (mitad). Out of the total 109 types stoves were identified for further evaluation. Then, depending on the similarities of the stoves, the stoves were reduced into 20 stove types and finally, six stoves were selected for further testing. The performance evaluation was made based on water boiling test. It was performed at the Appropriate Technology Center of the Adult Education Department of Ministry of Education. The report indicated that a pit type stove (Stove E) was found out to be the most efficient stove. This stove was constructed out of a mixture of clay, and chid (teff straw).

The total weight of the stove is about 100 kg. The stove is massive and fragile, and it needs at least two persons for installation. This also makes transportation very difficult. The sketch of the Burayou injera baking stove is shown in Figure 6.

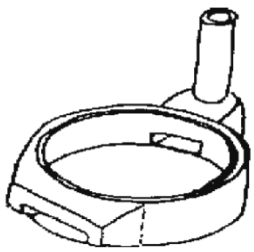

Figure 6. Burayou Injera Baking Stove

2.7.5.2 Ambo injera baking stove

In 1986, the Ambo team modified the Burayou mud-stove and come-up with the Ambo mud-stove used for injera baking. In the early 1990s a team of experts at the then Ethiopian Energy Authority with consultants from abroad started a survey to make a starting point for the development of injera baking stove in the country. The assessment made throughout the country revealed that the Burayou, Ambo and Tigrian mud stoves were the more efficient stoves at the time of the study . When tests were conducted on the above mentioned three injera baking mud stoves, the variation in performance was associated with thickness and seasoning skill of the mitad(71).

2.7.5.3 Tigrian injera baking stove

Enclosed traditional injera baking stoves are commonly used in the northern part of Ethiopia, mostly in Tigray (Tigray National Regional State) and Wollo (Amhara National Regional State). They are named after the area where they are most popular which Tigray and hence, commonly referred as Tigrian stoves. These stoves, unlike the three stones injera baking stoves, are permanently built on the ground or on a raised platform made up of mud and stones. Users build the stove according to ones estimate of dimensions. In some places the height of the stove varies from 28 to 40 cm with one or two smoke outlets. A typical Tigrian injera baking stove has usually two smoke outlets and a height of about 35cm.

The efficiency of a well-built enclosed Tigrian injera baking stove is about 12%(71).Compared to the three stone open fire injera baking stove, it consumes less fuel, is easier to used and protects from burns.

2.7.5.4 Tehesh injera bakin g stove

Tehesh injera baking stove was developed by GIZ (previously GTZ) and the Rural Technology Promotion Center of Mekele . The idea of designing Tehesh came from improving the existing Tigran injera baking stove. Figure 7 shows Tehesh injera baking stove.

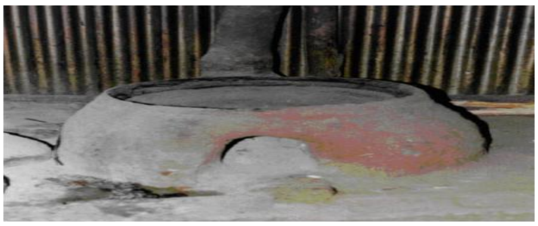

Figure 7. Tehesh Injera Baking Stove

The raw materials needed for the production of Tehesh are mud, stones, and straw. Small amount of fresh dung is mixed together with mud to increase its adhesion. This mixture is smeared over the vertically stacked stone from inside and outside. The straw is used as insulation by placing it between the outer and inner walls of the stove and under the combustion chamber.

2.7.5.5 Sodo Injera Baking Stove

Sodo injera baking stove is made by the Rural Technology Promotion Center in Sodo. The name of the stove is taken from the place it was first designed. It is an enclosed stove made of 1mm sheet metal. The sodo injera stove can support mitad sizes between 54 to 56 cm. The total height of the stove is 42cm. The combustion chamber has 60cm diameter and 15cm height. It has an ash-collecting box under the perforated metal grate Figure 8. The controlled cooking test conducted by Sodo RTPC on a 45cm diameter mitad shows that the average fuel wood consumption of the stove was 0.343 kg wood per injera (MoA/GTZ 1999).

Figure 8. Sodo Injera Baking Stove

2.7.5.6 Mirt Injera Baking Stove

Tests were conducted on the Burayou, Ambo and Tigrian stoves, and Ambo was found to be the efficient compared to the other two injera baking stoves, but fuel use saving was not satisfactory. Later on, important modifications were made and the team of experts came up with a mud injera baking stove which is efficient, and named ‘Mirt’, which means ‘best’.

Consequently, the mud structure of Mirt is changed into cement-mortar mixture to build the structure as shown in Figure 9. This injera baking stove is widely promoted by the GIZ-Energy Bureau Office in Ethiopia and named Mirt.

Figure 9. Mirt Stove With Cooking Pot

The specific fuel consumption of Mirt stove has been determined by a number of researchers and developers. The average specific fuel consumption of Mirt stove is 535 g of wood per kg of injera as shown in Table 3. Mirt stove was tested at Approvecho Research Center, the test was conducted using water boiling test procedure where the time to boil is 35.8 min and 6407 g fuel was used. The CO(g) observed was 192 and PM(g) was 5322(78) as shown in Figure 10.

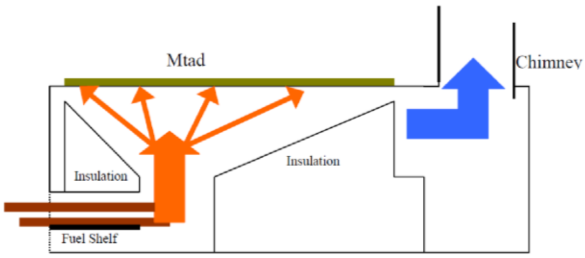

Figure 10. Modified Mirt Stove

2.7.5.7 Gonziye Injera Baking Stove

The other improved injera baking stove is made out of clay. The name of the injera baking stove is Gonziye as shown in
Figure *11*. It is a multipurpose improved cooking stove to be used both for injera baking and other types of cooking such as water heating, coffee brewing and wot[1] preparation. The specific fuel consumption of Gonziye injera baking stove is 617 g/kg of injera (79).

Figure 11. Gonziye Injera Baking Stove

Gonziye injera baking stove is a multipurpose stove with cooking as additional advantage. The stove is entirely constructed from clay which makes it cheaper than Mirt stove. The specific fuel consumption is comparable with Mirt stove. Although it is not widely disseminated, the very reason of Gonziye injera baking stove is that it could be made without industrial supply of raw material for manufacturing the product.

2.7.5.8 Awramba Injera Baking Stove

The name of this injera baking stove is associated with the name of the community in one of the regional states of Ethiopia, Amhara Regional State where it was developed. This injera baking stove has been in use in the community since 1971. This stove also integrates other cooking applications in addition to injera baking. It has a specific fuel consumption reduction of 35% compared to open-fire injera baking stove. Figure 12 shows the simultaneous operation of the injera baking and cooking using Awramba injera baking.

Figure 12. Awramba Injera Baking Stove

2.7.5.9 Electric Injera Baking Stoves

Electric injera baking stove (Electric injera Mitad) was introduced to Ethiopia 40 years earlier through the then Ethiopian Electric Light & Power Authority (EELPA). In order to disseminate Electric injera stove various government and private organizations produced the stove and sold to the market. Since Electric injera baking stove is not standardized, the performance of Electric injera baking stove depends on the quality of the producers.

The average power demand of a single household Electric injera baking stove is in the range of 3kW to 4kW. Figure 13 shows a commonly manufactured Electric injera baking stove. Currently, the private sector is involved in the manufacturing of Electric injera stove. The number of Electric injera stove is estimated to reach 850,000 in the year 2020 (EEA), this demands a corresponding energy efficiency measures to improve the peak hour load created by households.

Figure 13. Electric Injera Baking Stove

The Ethiopian Energy Authority is in the process of preparing Ethiopian standards for labeling Electric injera baking stoves to create awareness for the users to select their preference according to their interest based on the performance of the stove. A preliminary test result shows that Electric injera baking stove in the market has efficiency in the range of 57 -79 %.(80,81)

2.8 Research Efforts Towards Improving Injera Baking Stoves

2.8.1 General Recent Research Outputs

Research on improving the performance of injera baking stove has increased in recent years following the environmental and health concerns in addition to the possible reduction in the amount of energy lost during injera baking. As shown in Figure 14, the path followed in recent researches consists of numerical approaches with experimental validation to come up with an improved injera baking plate - ceramic material. This propelled the research efforts towards the possible baking of injera using both thermic fluid and steam power supply.

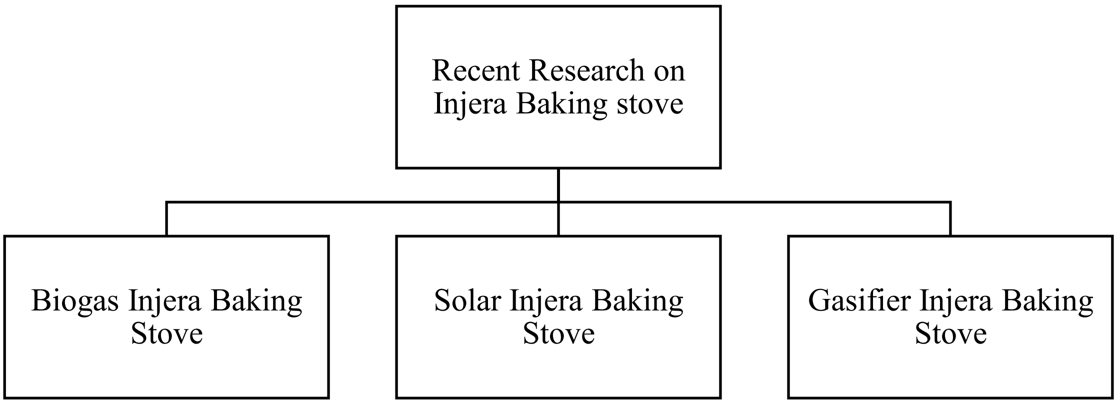

Figure 14. Recent Areas of Research

2.8.2 Electric and Heat Transfer Fluid Injera Baking Stoves

Electric injera baking stoves have wider application in urban areas where grid electricity is available. Numerical and empirical investigation of electric injera baking was conducted by many researchers. A 2D transient Finite Element Method is used to see the temperature distribution during baking of injera with conventional clay plate and new ceramic plate. Both showed a reasonable heat-up and baking time during the test. When the numerical investigation was compared with experimental results for various power supplies and oil temperature, the result showed a minimal error. The experimental result on electric injera baking stove with clay pan (thickness:20mm) and ceramic pan(thickness:8mm) has been compared and the result showed a thermal efficiency of 53% for the clay baking pan and 66% for the ceramic plate baking pan . Similarly, the thermal efficiency for baking 10-15 injera was 53 - 66% for the clay pan and 66-72% for the ceramic pan(80). The ceramic plate was manufactured at a ceramic factory in Ethiopia (Tabor Ceramic Factory). In these studies, the output of the numerical computations cannot directly be compared with electric injera baking stove efficiency.

2.8.3 Solar Powered Injera Baking Stoves

Injera baking stove operated by solar was another option investigated by various researchers. The major outputs obtained by experimental investigation are mainly the possible use of steam for baking injera in a temperature range of 135 -160 ^{0}C and direct solar radiation with a reflector to bake injera at 180 ^{0}C using frying pan. Numerical investigation of solar assisted injera baking showed a promising result. The experiment conducted was based on a simulated electric heater to heat the thermic fluid circulating in the baking process. A researcher also made effort to come up with a new injera baking plate made of metal (82) . The quality of injera baked on metal is not comparable with the clay plate. The metal plate has a higher thermal conductivity compared to clay plate which allows heat transfer rapidly generating small amounts of burn and less ‘eyes’ in the bake injera .

The other effort undertaken was on the possibility of using indirect heating for baking injera using thermic-fluid and steam as a working fluid mentioned in Figure 15. This was verified experimentally at two locations in Ethiopia (Addis Ababa and Mekele). In the first experiment, the solar energy was simulated with electric heater to supply heat to the thermic-fluid so that injera is baked before the whole system is connected to the parabolic trough since the overall objective of the project was baking injera using solar energy using thermic-fluid. The surface temperature of the baking pan was in the range of 180 – 220 ^{0}C. The proposed injera baking system for the thermic-fluid is shown in

Figure 16. The test result showed a reasonable injera texture with surface temperature of 215 ^{0}C (83).

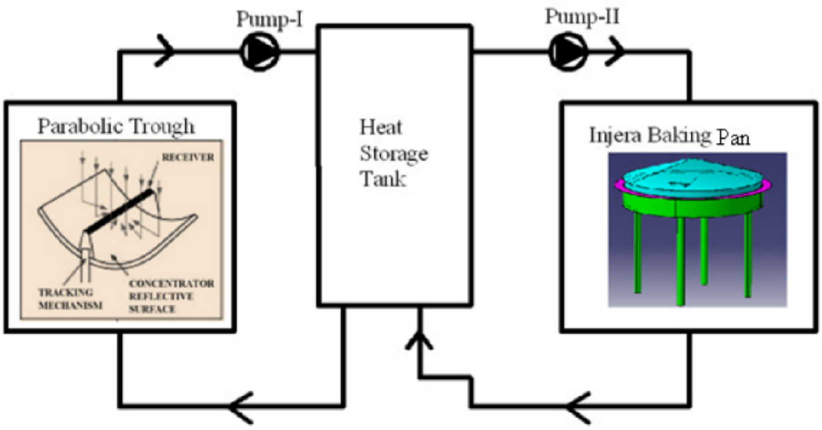

Figure 15. Solar Parabolic Stove

The second experiment was a solar thermal stove which is operated using water as a working fluid Figure 16. The important conclusion drawn from this study was the possibility of baking injera using indirect steam in temperature range from 135 to 160 ^{0}C. The indicated temperature was less than the literature or experimental values obtained earlier by other researchers or developers working on injera baking stove (84).

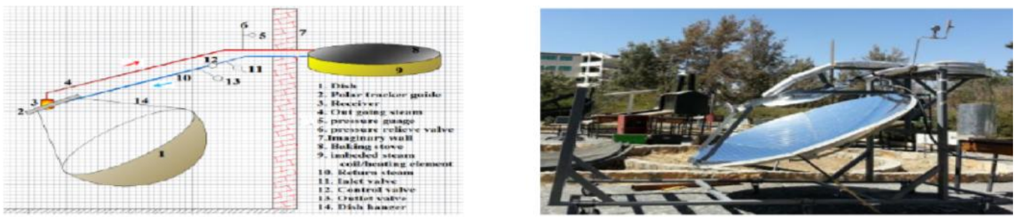

Figure 16. Parabolic Dish Solar Stove

The usual operation temperature was around 250 ^{0}C to obtain a well-baked injera. As it has been stated in this study, it requires further testing and verification which leads to investigation on this area.

Direct solar radiation through mirror was also tried in USA using frying pan for baking Injera. A prototype was tested with a diameter of the baking pan to be 45cm and baking capacity of 4kg per hour. Figure 17 shows a frying pan Injera baking prototype apparatus. The reported baking time was 2min. The researcher states that the design is scalable to any required. It is a good attempt to be explored and verified for a larger scale application.

Figure 17. Injera Baking frying pan

2.8.4 Biomass Gasification Injera baking stoves

As the improved injera baking stove's primary purpose is to reduce fuel consumption for economic and environmental reasons, specific fuel consumption has been used as a tool for comparison. The maximum reduction in specific fuel consumption of improved injera baking stoves recorded in Ethiopia is 49% while the minimum is 34%. Similarly, the percentage reduction in CO during the test period was 91% while that of PM was 19.3% in comparison with open-fire injera baking stove.

This research showed that gasification technology can be applied for baking injera and other cooking applications. Injera baking biomass gasifier stove and micro-gasifier were designed, manufactured, and tested and have a better performance.

A research review on injera baking technologies showed that injera was baked using three-stone fire and then improvements were made to increase its efficiency. The recent achievement in terms of the use of biomass for baking injera was the production of Mirt stove which is enclosed stove with a better performance in terms of fuel use and indoor air pollution and emission. As gasification is the right direction in the development of biomass cook stoves, this concept was followed to design the injera baking biomass gasifier stove. This injera baking biomass gasifier is similar with the one designed at the Asian Institute of Technology for rice cooking (85).The Injera baking stove modified the cross-draft biomass gasifier stove to suit the injera baking plate-mitad which has nearly a diameter of 60cm as shown in Figure 18. The injera baking biomass gasifier stove exhibited a thermal efficiency of 16% which is less than the rice cooking biomass gasifier stove 27%(9). However, better than all the previously reported injera baking stoves and also with little modification could have a higher efficiency. Both gasifiers were operated using wood chips. The modification area could be the heating-up time losses generated during consecutive injera baking processes and other heat loses. The injera baking plate-mitad is heated continuously while injera was baked which means there is time gap in between two injera baking processes. If we sum up the total time that injeras were baked for a single session which is 25 – 30 pieces for a single household, quite a large amount of heat is lost to the ambient air, justifying that the efficiency could be comparable with the water heating processes observed for rice cooking. In addition, other researchers also confirmed that increasing the number of injera to be baked could substantially increase performance, decreasing fuel use for injera baking stoves(16). The injera baking biomass gasifier stove showed a remarkable improvement in terms of indoor air pollution, CO and PM(71).

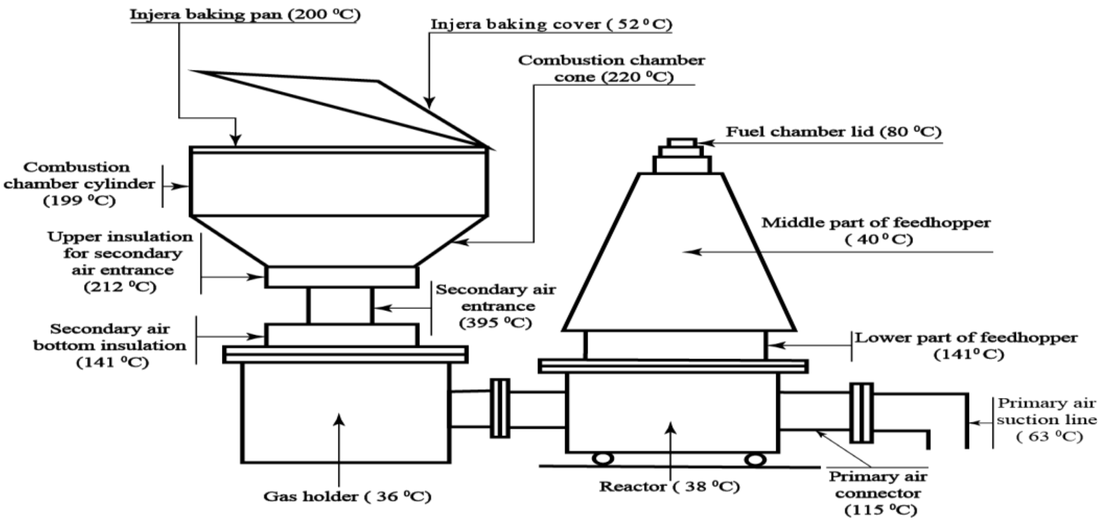

Figure 18. Biomass Gasification Stove

2.8.5 Metal Sand Improved Wood Stove

The study on the improved metal sand pan stove for Injera baking in Ethiopia addresses a critical challenge faced by over 90% of the country's population, who rely on biomass fuels—primarily firewood—for cooking. This dependency has led to alarming deforestation rates, estimated at 50 million cubic meters annually. In response, the study introduces a new stove design that integrates a metal pan with a sand enclosure, aiming to combine the superior heat conductivity of metal with the insulating and heat-retention properties of sand.

The objective of the research was to test whether the improved stove could reduce fuelwood use, shorten baking time, and offer a more sustainable alternative to traditional cooking methods. Two stove types were evaluated: a traditional clay pan (serving as the control) and a metal sand pan constructed from 1.5–2 mm sheet metal. Results showed that the metal sand pan stove significantly outperformed the traditional clay pan. It consumed an average of 2,349 grams of dry wood per baking session, compared to 2,953 grams for the clay pan, representing a 20.5% reduction in fuel use. Specific fuel consumption was also lower by 141 grams per kilogram of food baked. In terms of baking speed, the metal sand pan baked 15–20 Injera in 77 minutes—8 minutes faster than the traditional pan as shown in Figure 19.

Thermal efficiency was slightly higher for the metal sand pan at 17.5%, compared to 16.5% for the clay pan. More importantly, the sand layer around the metal pan significantly improved heat retention and distribution, addressing one of the primary drawbacks of using metal pans alone, which typically lose heat rapidly. These findings suggest that the improved stove not only reduces household firewood consumption but also minimizes cooking time and labor, particularly benefiting women who are primarily responsible for cooking in rural Ethiopian households.

The study concludes that the metal sand pan stove is a viable and efficient alternative to traditional clay pans, with tangible benefits for both energy savings and environmental conservation. To maximize impact, the authors recommend scaling up production and promoting adoption through community outreach and awareness campaigns. Further research is encouraged to optimize the design by testing different metal types and sand layer configurations. Additionally, policymakers are urged to incorporate this improved stove into national clean cooking strategies to combat deforestation and improve household energy efficiency across Ethiopia.

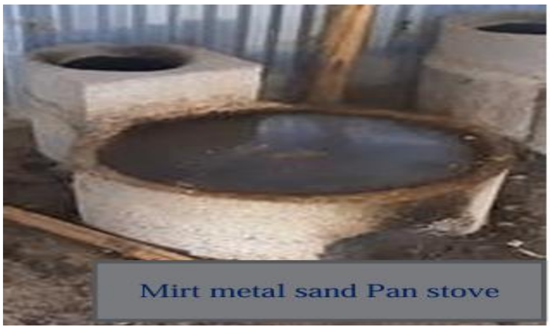

Figure 19. Mirt Sand Pan Stove

Table 3 provides a summary of different types of injera baking stoves, highlighting their energy sources, specific fuel consumption, and thermal efficiency. The table includes traditional firewood stoves, improved firewood stoves such as the Mirt stove, biogas stoves, and biomass gasifier stoves. For each stove type, the specific fuel consumption is indicated, representing the amount of fuel required to produce a unit of injera. The thermal efficiency of each stove is also provided, showing the proportion of energy effectively used for cooking.

Table 3. Performance of Biomass Injera Baking Stove

Energy Source	**Specific Fuel Con**	**Eff.**	**Ref.**
Firewood Stove	929g /kg of Injera	5-10%	(2,79)
Firewood Stove	535g /kg of Injera	18%	(7)
Biogas Stove	193 L/4.5gm injera	16%	(71)
Biomass Stove	818g/kg of Injera	16%	(9)

2.9 Benefits of The Improved Injera Baking Stoves

The improved injera baking stoves offer significant benefits, particularly in terms of indoor air pollution reduction and fuel efficiency. Research by Yosef highlighted a 91% reduction in carbon monoxide (CO) emissions and a 19.3% reduction in particulate matter (PM) during testing, demonstrating a significant improvement in air quality compared to traditional open-fire stoves(5). These reductions are crucial in addressing the health hazards posed by indoor air pollution, which has long been associated with respiratory and eye diseases, particularly in rural households.

In terms of fuel efficiency, the improved stoves show a notable reduction in specific fuel consumption. Studies have reported that the Mirt stove—a type of improved injera baking stove—reduces fuel consumption by 30% to 49% when compared to traditional open-fire stoves. This reduction in fuel use not only makes cooking more cost-effective for households but also helps in conserving valuable biomass resources, which are increasingly scarce due to deforestation.

2.10 Biogas-Fueled Cooking Stoves

2.10.1 Introduction

Access to clean cooking energy remains a major challenge in many developing countries. Traditional biomass stoves contribute significantly to indoor air pollution, health issues, and deforestation. Biogas, a renewable and clean-burning fuel, offers a sustainable alternative. Biogas-fueled cooking stoves have been developed to utilize methane-rich gas derived from organic waste, offering significant environmental and health benefits. However, the real-world performance of these stoves often falls short of manufacturers' claims. This review consolidates studies and test reports to critically analyze the performance of biogas cooking stoves and explore improvement and strategies for optimization.

In a study by Chandra (1991), several biogas burners were tested using a steady-state method to investigate the effects of various parameters on the efficiency of biogas stoves(86). Key factors such as biogas flow pressure, pan size, and the position of the pan over the burner head were studied extensively to determine an optimal operating range for these parameters. The goal was to select conditions that would yield the best possible thermal performance for the biogas burner. The research provided valuable insights into the relationships between these variables and their impact on stove efficiency, paving the way for more effective biogas stove designs.

The experimental setup for this study is depicted in Figure 20, which illustrates the layout of the biogas stove test rig used for the experiments. This setup enabled Chandra to conduct precise measurements and gather data on how different operational conditions influence the performance of biogas burners. The findings from this study contribute to understanding how to optimize biogas stove systems for better energy use, improved heat distribution, and ultimately higher-quality cooking performance. The study by A. Chandra and colleagues evaluates the performance of biogas burners in India, highlighting discrepancies between manufacturers' claims and actual efficiency. The research compares unsteady-state and steady-state testing methods, finding that steady-state assessments—which account for evaporative heat loss—provide more accurate efficiency measurements (37–54%) compared to unsteady-state methods (32–49%). Key factors affecting performance include gas flow pressure (optimal at 3–6 cm water column), pan height (peak efficiency at 2.2–4.2 cm above the burner), and pan size (smaller surfaces reduce heat transfer efficiency). The study reveals widespread overestimation of burner capabilities by manufacturers and emphasizes the need for standardized testing protocols and design improvements. Recommendations include optimizing operational parameters and adopting steady-state testing to enhance real-world performance, ensuring better energy utilization for biogas cooking technologies.

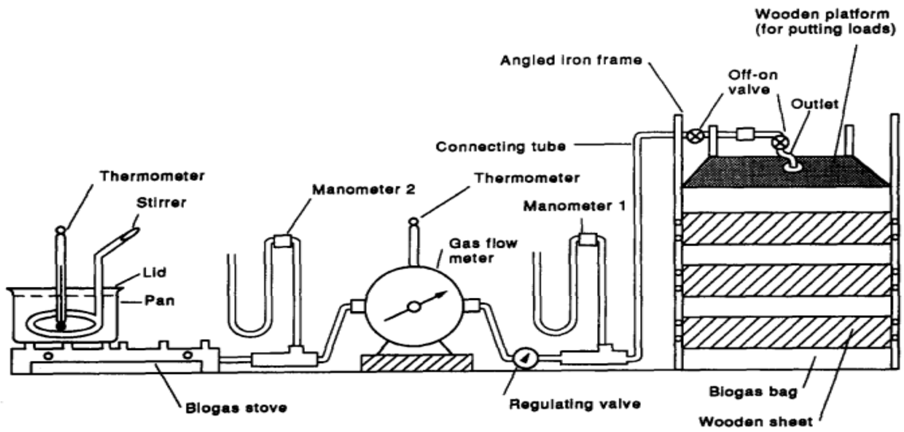

Figure 20. Experimental Set Up for Cooking

At a relatively low gas input rate, the heat transfer coefficient between the combustion gases and the bottom of the pan is relatively small because of the low velocity of the gas flows under the pan bottom. The process of heat transfer is enhanced by raising the gas input rate until optimum conditions are obtained, i.e., when the burner efficiency reaches its highest value. The effect of gas flow pressure on efficiency is shown in Figure 21 below.

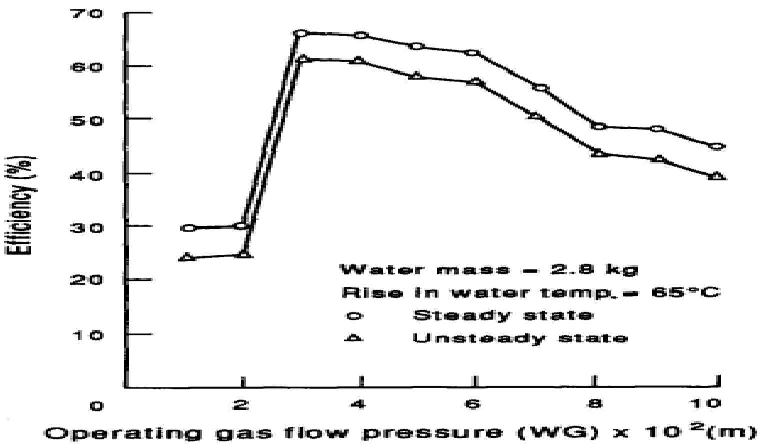

Figure 21. Effect of gas flow Pressure on Efficiency

The study by Awulu J.O.from the Department of Agricultural and Environmental Engineering at the Federal University of Agriculture Makurdi, Benue State (2020) shown in Figure 22 investigates the cooking performance of a newly developed biogas burner (stove) utilizing biogas produced from cattle waste(87). The researchers designed a durable biogas stove featuring key components including a cast iron burner head, mixing tube, and support frame, optimized for efficient biogas combustion. Connected to a 3 m³ continuous-flow biogas plant processing cattle waste, the stove was tested for water boiling and cooking various food items, achieving a boiling rate of 0.2 liters per minute with cooking efficiencies of 63% for rice, 61% for yam, and 30%

for beans (the lower bean efficiency attributed to longer cooking times and biogas quality variations). While demonstrating competitive performance and dual waste-to-energy benefits, the study would benefit from including its publication year for proper contextualization, along with comparative analyses with other models and cost-effectiveness data to better assess its practical applications and advancements in biogas stove technology. Further optimization could enhance its performance across diverse cooking needs in rural communities.

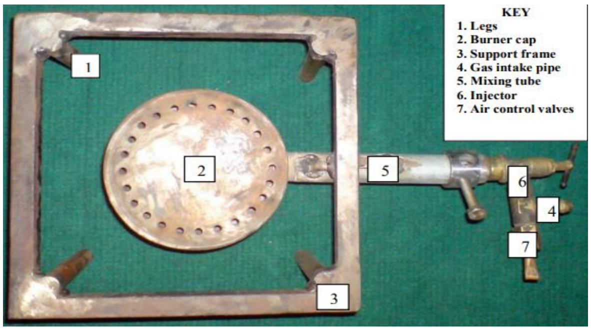

Figure 22.Biogas burner

The other study evaluated the design, construction, and performance of a biogas stove connected to a 3 m³ continuous-flow Indian biogas plant at the University of Agriculture, Makurdi, Nigeria shown in Figure 23. The plant used cattle dung mixed with water (1:2 ratio) and operated on a 30-day retention period with a daily loading of 100 kg slurry. Performance tests involved boiling water and cooking rice and beans, measuring time, biogas consumption, and efficiency. Results showed a boiling rate of 0.14 liters per minute, cooking rates of 5.13 g/min (rice) and 2.55 g/min (beans), and biogas consumption rates of 0.69 m³, 2.81 m³, and 4.87 m³, respectively. Efficiency was highest for cooking (56% for rice, 53% for beans) compared to boiling water (20%). The study highlights biogas technology's potential in addressing energy shortages while supporting rural development (18) .

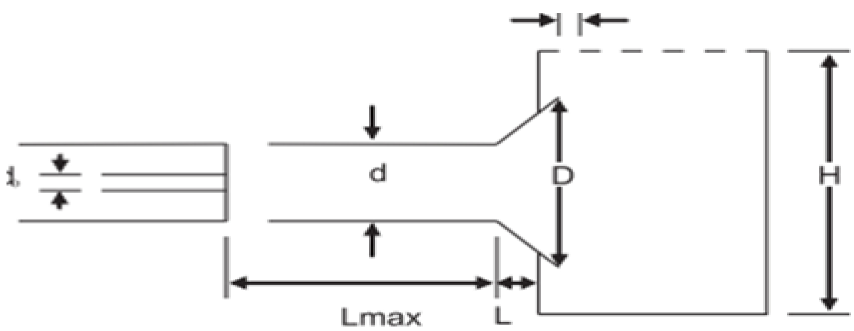

Figure 23.Schematic diagram of the cooking biogas burner

The design and fabrication of a burner system, operating on biogas, for use in remote or rural regions of developing countries such as Nigeria as shown in Figure 24.The stove boiled 0.10 liters of water in one minute while 1.73g of rice was cooked in a minute. The biogas consumption for water boiling and rice cooking were 0.47m^3 /min and 2.87m^3 /min respectively. The efficiencies of the stove in the above processes were 21% and 60% respectively (33).

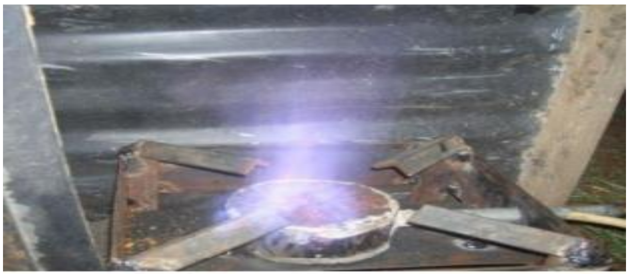

Figure 24. Pictorial view of developed burner

The SNV Netherlands Development Organization, through collaborative test reports in China, India, and the Netherlands, provided comparative data on the thermal efficiency and design of biogas cooking stoves and lamps(49). Their reports highlighted the wide performance variability due to differing test conditions, burner geometries, and gas quality. The findings called for uniform performance testing standards and emphasized that burner design, including port diameter and mixing tube geometry, significantly affects combustion quality and thermal efficiency. SNV recommended investment in user training and local design optimization based on fuel characteristics and cooking practices(49).

2.10.2 Key Parameters influencing efficiency of Biogas Cooking stove

The efficiency of biogas stoves is influenced by several key parameters, including gas flow pressure, pan height, pan size, and burner design. Optimal gas flow pressure typically lies between 3 and 6 cm H_2O, where combustion remains stable and efficient. While higher pressures can increase flame velocity, they may lead to incomplete combustion if the burner is not properly configured. Pan height also plays a critical role, with maximum thermal efficiency observed when the pan is positioned between 2.2 and 4.2 cm above the burner. If the pan is too low, flame quenching can occur, whereas excessive height leads to increased heat loss through convection. The size of the pan affects heat distribution and energy utilization; although smaller pans enhance localized heat transfer, they may not be suitable for bulk cooking and often result in inefficient energy use when mismatched with burner size. Burner design itself is fundamental to stove performance. Parameters such as the number and diameter of burner ports, along with burner head geometry, significantly impact flame stability and combustion quality. Innovations such as conical or swirl-pattern burners have shown promise in enhancing air-gas mixing and promoting stable, efficient flames.

Despite these technological insights, several limitations challenge the widespread adoption of biogas stoves. Chief among these is the absence of standardized testing protocols across regions, making it difficult to compare stove performance objectively. Additionally, biogas quality can vary widely due to inconsistencies in feedstock composition and digester operation, leading to fluctuating combustion characteristics. Many stove designs also fail to incorporate user feedback, which limits usability and long-term adoption. Furthermore, high initial investment costs and ongoing maintenance requirements present economic barriers for many households, particularly in low-income settings(24,39).

2.10.3 Performance of Biogas Cooking Stove

In conclusion, biogas stoves offer considerable potential as clean and efficient cooking solutions, especially in developing regions. Empirical studies from countries such as India and Nigeria demonstrate that these stoves can achieve moderate to high thermal efficiency when optimally designed and operated. However, discrepancies in stove configurations, biogas quality, and evaluation methodologies continue to pose significant obstacles. A harmonized global approach that emphasizes standardized testing, advanced burner design, and context-specific innovations is essential to fully harness the advantages of biogas as a sustainable and scalable cooking fuel alternative.

Table 4. Performance of Biogas Cooking Stove

Study	Year	Key Parameters	Efficiency	Validation Method
Indian Stove	2020	Gas flow pressure: 3–6cmWC	32–49%(unsteady) 37–54% (steady)	ISI standards
Nigeria (Awuluet al.)	2020	Retention: 30 days	Boiling:20%	Controlled Cooking tests
		Fuel 0.69–4.87 m³	Boiling rate:0.14 L/min	Time

2.10.4 Challenges in Biogas Stove Adoption

The widespread adoption of biogas-fueled cooking stoves faces several key challenges. First, the lack of standardized testing protocols across different regions makes it difficult to objectively compare stove performance, leading to inconsistent efficiency claims by manufacturers. Additionally, variable biogas quality, caused by differences in feedstock composition and digester operation, affects combustion stability and stove efficiency. Another major barrier is the high initial cost of biogas systems, including installation and maintenance, which can be prohibitive for low-income households in rural areas. Finally, user resistance often arises due to unfamiliarity with biogas technology or stove designs that do not align with local cooking practices, reducing long-term adoption rates. Addressing these challenges requires a combination of technical improvements, policy interventions, and community engagement to ensure biogas stoves are both efficient and culturally acceptable

2.10.5 Future Research on Biogas Cooking Stove

To overcome these challenges, future research and development should focus on the global adoption of standardized, steady-state testing methods to ensure consistent and comparable performance evaluations. Advanced modeling tools, including Computational Fluid Dynamics (CFD) and Artificial Intelligence (AI), can be employed to optimize burner-port configurations for improved combustion efficiency. It is also essential to integrate user-centered design principles that address cultural cooking practices and usability concerns. Incorporating smart sensor technologies can enable real-time monitoring of gas quality and combustion parameters, thereby enhancing safety and operational efficiency. Moreover, comparative lifecycle analyses of different stove models could offer valuable insights into long-term environmental and economic impacts.

2.11 Review on Biogas Injera Baking Stoves

2.11.1 Introduction

In rural households, the predominant energy source has historically been biomass, particularly firewood, crop residues, and animal dung(88). This reliance has contributed to deforestation, indoor air pollution, and labor burdens, particularly on women and children. Despite the growing urban shift toward electric stoves, rural communities continue to face energy poverty and infrastructure limitations(76).

Biogas as an energy carrier can play an important role in low carbon energy transitions. Biogas, produced from anaerobic digestion of organic waste such as animal manure, emerges as a renewable, locally available, and environmentally sustainable cooking fuel (17,31).

This review critically examines the technological evolution, performance evaluations, and design innovations of biogas-fueled injera baking stoves. It highlights thermal efficiency, burner geometry, manifold configurations, and heat distribution strategies. Special attention is given to how these engineering solutions interact with sociocultural factors such as injera quality, user acceptability, and scalability. In doing so, it identifies research gaps and provides future directions to improve adoption and performance.

The Ethiopian government has undertaken multiple initiatives to disseminate domestic biogas systems through programs such as the National Biogas Program of Ethiopia (NBPE), supported by agencies like SNV Netherlands Development Organization(66). While biogas has found moderate success in heating and lighting applications, its use for injera baking remains at an early stage due to technical and cultural challenges. The high thermal demand, large griddle size, and need for even heating make injera baking a particularly demanding application compared to boiling or frying(89).

Initial biogas stove designs were adopted from general-purpose cooking burners, leading to suboptimal outcomes. Issues such as uneven heat flux, poor injera texture, and long warm-up times limited household acceptance(78,90). Moreover, biogas pressure from small-scale digesters is typically low, which complicates its direct use in high-flame applications like injera baking(66,75). These early limitations highlighted the need for specialized design tailored to the thermodynamic and combustion requirements of injera.

Recent efforts have focused on adapting burner geometries, insulating materials, and griddle configurations to improve thermal efficiency and user satisfaction. Focus on insulation performance, while computational fluid dynamics (CFD) approaches provide insights into burner optimization was studied(20). Nonetheless, a gap persists in transitioning from simulation to field-validated, community-scale designs.

This review synthesizes technical findings across three decades, connecting design evolution with practical deployment outcomes. It emphasizes the critical importance of integrating engineering design with end-user requirements, particularly in rural Ethiopian contexts where injera baking is not merely culinary but also a daily ritual embedded in social life.

This review adopted a systematic and structured approach to gather, evaluate, and synthesize the body of research related to biogas-fueled injera baking stoves, with a focus on technological development, performance enhancement, and future research needs. The methodology integrates both quantitative and qualitative perspectives to provide a comprehensive understanding of the technological evolution and multidisciplinary dimensions of this field.

A comprehensive literature search was conducted using major scientific databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar. Additional searches were carried out through institutional repositories such as the Addis Ababa University Digital Library and technical archives from the Clean Cooking Alliance and the International Energy Agency (IEA) Bioenergy division. The search strategy combined key terms such as biogas injera stove, biogas burner design, clean cooking Ethiopia, thermal efficiency of biogas stoves, mitad material optimization, CFD simulation of biogas burners, and biogas pressure mismatch. The search covered publications to peer-reviewed journal articles, conference papers, theses, and technical reports.

Data extraction from the selected studies emphasized key engineering and operational parameters. Technical attributes such as burner geometry, port size, manifold pressure, insulation type, and mitad material composition were systematically documented. Performance metrics including biogas consumption per injera, thermal efficiency, heat distribution uniformity, and baking time were recorded wherever available. Each study was further classified according to its methodological approach—analytical, computational (CFD-based), experimental, or field-tested—and evaluated for its treatment of socio-economic, environmental, and adoption-related dimensions. This enabled the identification of performance trends and technological milestones over three decades of development, from early concentric ring burners to contemporary conical and CFD-optimized configurations.

The synthesis of findings followed both quantitative and qualitative pathways. Quantitative data were normalized and compared to reveal trends in efficiency improvement, fuel economy, and heat transfer performance. In parallel, qualitative thematic analysis was used to uncover recurring challenges such as biogas pressure mismatch, material durability, heat distribution inconsistencies, and gaps in standardized testing. Together, these complementary analytical approaches provided an integrated perspective on how design evolution has addressed the core engineering and operational challenges of biogas injera stoves.

To ensure scientific reliability, reported data were cross-checked with multiple sources and aligned with established principles of thermodynamics, combustion theory, and heat transfer. When numerical reconciliations were made based on standard engineering assumptions, such as a methane content of 60% and a lower heating value of 20 MJ/m³ for biogas. This methodological framework ensured that the conclusions drawn from the literature are both technically sound and contextually relevant to Ethiopia's clean cooking energy transition.

2.11.2 Biogas Injera Stove Technology: A State-of-the-Art Review

The technological evolution of biogas injera baking stoves in Ethiopia reflects over three decades of iterative experimentation, driven by the urgent need to replace inefficient biomass-based cooking practices (71). Traditional clay-based stoves, such as the widely used Mirt stove, offer low thermal efficiency—often below 20%—and are heavily dependent on fuelwood, contributing to severe deforestation and domestic air pollution (1,2). This section traces the major research milestones, highlighting innovations in combustion geometry, insulation, and modeling of biogas injera baking stove and historical development and design evolution of biogas injera baking stove.

2.11.3 Historical Development and Design Evolution of Biogas injera Baking Stove

The first notable attempt to design a dedicated biogas injera stove dates back to 1996, when Dereje introduced a steel-pipe burner composed of three concentric rings (Figure 1) (71). This pioneering design established the foundational architecture for subsequent biogas stove development, utilizing multiple combustion zones to address the challenge of heating the large surface area of a traditional *mitad*. Operating at a substantial gas flow rate of 41 liters per minute (approximately 2.5 m³/h), the stove delivered a high thermal output of 11 kW, yet achieved a notably low thermal efficiency of only 16%. This significant energy loss was quantified by a consumption of approximately 193 liters of biogas per injera, highlighting the combustion and heat transfer inefficiencies inherent in this early system(71).

The three-ring configuration represented a critical initial approach to solving the problem of uneven heat distribution. By creating concentric circles of flame, the design attempted to provide broader coverage under the baking surface compared to single-ring or compact burners Figure 25. However, the low efficiency underscored fundamental challenges in primary aeration, air-fuel mixing, and insufficient insulation, leading to substantial heat loss to the surroundings. The high gas consumption rate also implied a substantial demand on biogas digester capacity, making the system potentially impractical for typical household use where daily gas production is limited. Dereje's work, while a landmark initiative, primarily served to underscore the need for enhanced combustion control and optimized flame distribution. The design's limitations clearly identified the critical research gaps that future studies would need to address: improving the stoichiometry of the air-biogas mixture, optimizing the port sizing and spacing to prevent flame lift and ensure stability, and integrating thermal insulation to retain heat within the combustion chamber. This early prototype thus established a crucial performance baseline, against which all subsequent improvements in efficiency, fuel economy, and heat distribution uniformity could be measured, setting the stage for the more sophisticated analytical and computational approaches that would follow in subsequent decades.

The Figure *25* illustrates the initial three-ring burner configuration designed to address uneven heat distribution on a mitad baking surface. This prototype represents an early attempt to establish a performance baseline, informing subsequent research on optimized flame distribution, port sizing, and insulation strategies to improve combustion stability and fuel economy.

Figure 25. Early three-ring steel-pipe biogas burner

Nearly two decades later, biogas injera baking development shifted the research focus toward thermal retention and insulation (20). Their analytical study employed Fourier's law of heat conduction to examine the impact of insulation of locally sourced clay ash—on heat loss.

The technical core of the study represents an application of thermodynamic and combustion principles to a well-defined real-world problem. The methodological approach is systematic, beginning with a foundational energy balance to determine the net power requirement (1.414 kW) for baking a single Injera. This calculation is notably robust, as it is predicated on empirical data collected for key variables, including dough mass (581g), composition (60% water, 40% Teff), and specific critical temperatures. However, the subsequent derivation of the required input power (5.656 kW) introduces a significant dependency on an assumed system efficiency of 25%, a value adopted from the performance of the existing "Lakech" stove. While this conservative estimate provides a pragmatic baseline, it also becomes a critical, unvalidated assumption upon which the entire design—including the pivotal biogas flow rate of 0.93 m^3/h—is contingent. The performance of the final design is inherently tied to the accuracy of this efficiency value, which remains a theoretical postulate without experimental verification.

The component-level design further demonstrates a commendable depth of engineering analysis. The sizing of the injector orifice (3.0 mm) using established gas flow equations is standard and well-executed. A particularly insightful demonstration of practical design consideration is the evolution of the throat diameter. The initial calculation suggested a 12 mm diameter, but the authors judiciously selected a larger 21 mm diameter to allow for Stoichiometric aeration, with the intent of using air controls for final adjustment. This reflects an understanding that theoretical models must often be adapted to ensure operational flexibility and robust combustion in practical applications. Similarly, the design of the burner ports shows iterative refinement; the theoretical area calculation mandated 198 ports, but this was rationally refined to 66 ports based on principles of flame stability. This reduction likely enhances operational reliability by mitigating risks of flame blow-off or flashback, while the arrangement of these ports on a 315 mm diameter manifold directly addresses the stated problem of uneven heating on the *mitad*.

Despite the methodological strengths, the research ultimately underscores the study's primary limitation: its confinement to the theoretical domain. Sophisticated analyses, such as the calculation of individual flame height 82mm and the complex heat transfer model for the clay-ash insulation, are presented but lack empirical correlation. The flame height model, for instance, is applied to a single port, yet the collective behavior of multiple flames in close proximity could alter the effective thermal profile. The insulation analysis, while comprehensive in its use of a thermal resistance network, relies on estimated boundary conditions and material properties as shown in Figure 26. Therefore, while the technical design is undeniably a thorough and logically sequenced engineering exercise that successfully translates a defined need into a set of detailed specifications, it remains a well-founded hypothesis. Its considerable merit as a blueprint is ultimately provisional, pending the essential validation that only prototype construction and experimental testing can provide.

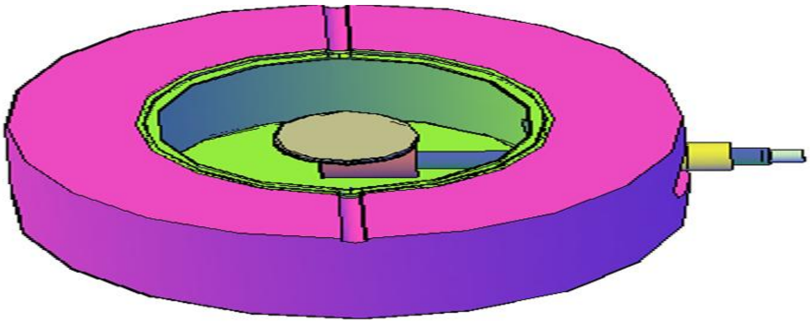

Figure 26. Insulated burner

The application of Computational Fluid Dynamics (CFD) represents a significant methodological leap in the design of specialized biogas stoves for Injera baking(91). Moving beyond the foundational analytical calculations of earlier studies, this research employed ANSYS Fluent software to simulate combustion dynamics and thermal distribution, thereby optimizing the burner design prior to physical fabrication. The study identified a critical flaw in previous models—an undersized 17 cm diameter burner manifold—which led to non-uniform heat distribution and poor baking quality. Through iterative simulations, the authors computationally validated an optimized manifold diameter of 26 cm, configured with 180 flame ports of 2 mm diameter arranged in concentric rings. This design was demonstrated to achieve a more uniform temperature profile across the baking surface, a crucial factor for ensuring the consistent quality of Injera, which requires even heating to develop its characteristic texture and 'eyes'. The CFD analysis further provided detailed visualizations of velocity streamlines and temperature contours, offering deep insights into the mixing efficiency of biogas and air and the subsequent combustion characteristics. This computational approach marks a paradigm shift, enabling precise, cost-effective design optimization that minimizes the trial-and-error typically associated with empirical development. However, this advanced theoretical model underscores a persistent gap in the literature: the transition from digital simulation to tangible product. While the study conclusively proposes an optimized design, it explicitly notes that fabrication and experimental performance testing remain as future work, highlighting a critical juncture where theoretical potential must yet be translated into validated, practical utility. Figure 27 presents a Computational Fluid Dynamics (CFD) simulation of a biogas injera stove burner, illustrating both velocity streamlines and temperature distribution across the baking surface. The simulation was conducted using ANSYS Fluent to optimize burner geometry prior to physical fabrication. The figure highlights the redesigned 26 cm diameter manifold equipped with 180 flame ports of 2 mm diameter arranged in concentric rings. Temperature contours show a more uniform heat profile compared to previous undersized designs, while velocity streamlines visualize the flow patterns of biogas and air, indicating improved mixing efficiency. This computational model provides critical insights into flame stability, heat distribution uniformity, and potential combustion efficiency, demonstrating the role of CFD in guiding precise and cost-effective burner optimization before experimental validation.

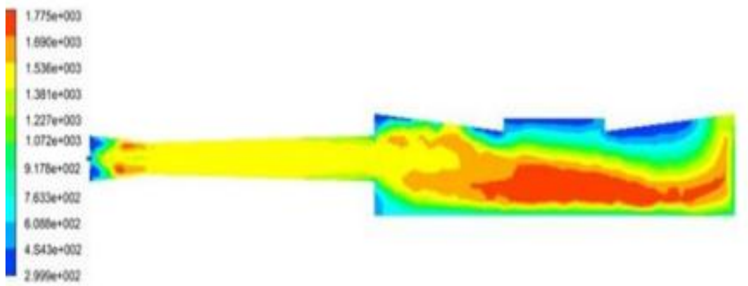

Figure 27. CFD Simulation of Burner

The development of efficient biogas-powered stoves for injera baking has been propelled by a series of experimental prototypes, each building upon the limitations of its predecessors. This experimental trajectory has moved from rudimentary steel-ring designs to analytically informed, field-validated systems, with a consistent focus on improving heat distribution, fuel efficiency, and practical usability.

The prototype featured a 260 mm steel manifold drilled with flame ports tailored to a 540 mm diameter baking surface, closely aligning with hotel-scale injera production. Field trials conducted at Jimma Degitu Hotel confirmed improved baking outcomes, including better browning uniformity and reduced biogas consumption. Figure4 illustrates the experimental biogas stove prototype designed for hotel-scale injera baking(12). It features a 260 mm steel manifold fitted with multiple flame ports, arranged to evenly cover a 540 mm diameter mitad. The concentric ring configuration is intended to enhance heat distribution across the griddle surface, improving browning uniformity and overall baking quality. Figure 28 highlights the integration of analytical design principles with practical field deployment, showing how careful alignment of burner geometry with the baking surface can optimize both thermal efficiency and operational usability.

Figure 28. Composite Mitad with Ring Burner

In a parallel development, Getu Alemayehu (2012) explored the scalability of biogas injera stoves for communal use. His prototype featured a reinforced clay mitad (530 mm in diameter) paired with three concentric burner rings, operating at 0.93 m^3/h of biogas. Deployed across five rural households in the Amhara region, the stove exhibited social acceptability and continuous baking capability. However, technical challenges emerged, including uneven heat distribution and insufficient flame intensity at the griddle's edges. These findings emphasized the importance of aligning burner geometry with the mitad's surface area to avoid cold zones and ensure uniform injera quality Figure 29 shows Getu Alemayehu's communal biogas stove prototype, consisting of a reinforced clay mitad with a 530 mm diameter integrated with three concentric burner rings. Each ring contains multiple flame ports designed to distribute heat over the cooking surface. While the configuration enabled continuous baking and received positive social acceptance among rural households in the Amhara region, the figure highlights areas near the edges of the mitad where flame intensity is lower, indicating uneven heat distribution. This illustration underscores the critical importance of carefully matching burner geometry to the griddle's dimensions to prevent cold zones and ensure uniform injera quality in communal stove applications(92).

Figure 29.Composite mitad with ring burner

Building on these advances, an adjustable conical burner design was introduced that emphasized heat focus and fuel efficiency (93). By reducing the mitad diameter to 400 mm and incorporating an internal flame-guiding cone, the design achieved a significant improvement in combustion efficiency, with a measured thermal efficiency of 25%. The system operated at 605 L/h of biogas, achieving a rapid warm-up time of just three minutes and an average baking time of four minutes per injera. The figure illustrates the adjustable conical burner design developed to enhance heat focus and fuel efficiency in biogas injera stoves. The burner features a 400 mm diameter mitad coupled with an internal flame-guiding cone that directs and centralizes the flame toward the center of the griddle. This geometry increases flame velocity and improves combustion efficiency, achieving a thermal efficiency of 25% and rapid warm-up in just three minutes. Operating at a biogas flow rate of 605 L/h, the design allows an average baking time of four minutes per injera. Figure 30 highlights the conical structure's role in concentrating heat and minimizing fuel wastage, although its limited surface coverage poses scalability challenges for larger households or institutional cooking applications.

Figure 30. Inverted Conical Burner

Table 5 presents a comparative summary of the performance characteristics of three experimental biogas injera baking stove prototypes: the steel manifold, ring burner, and conical burner designs. The steel manifold, featuring a 540 mm mitad, demonstrated good browning uniformity but lacked quantified efficiency data, limiting its evaluative accuracy. The ring burner, composed of three concentric rings and a slightly smaller

530 mm mitad, achieved notable social acceptability but suffered from cold zones at the edges due to uneven heat distribution. In contrast, the conical burner—with an adjustable cone and a 400 mm mitad—recorded the lowest fuel consumption rate of 605 L/h and the highest thermal efficiency of 25%, indicating superior energy utilization. However, despite its technical advantages, the conical burner faces challenges in scalability for larger or community-level baking applications.

Table 5. Experimental Prototype Performance

Prototype Feature	Steel Manifold	Ring Burner	Conical Burner
Pan Diameter	540 mm	530 mm	400 mm
Burner Type	Drilled Port Manifold	Rings	Cone
Fuel Consumption	Not Specified	930 L/h	605 L/h
Key Limitation	Unquantified Efficiency	Cold Zones at Edges	Limited Scalability

2.12 Performance and Comparative Analysis of Biogas Injera Baking Stove

This section presents a comprehensive evaluation of the optimized biogas injera baking stove, analyzing its thermal performance, operational efficiency, economic viability, and environmental impact. The results are systematically compared with traditional and improved biomass stoves to contextualize the achieved advancements.

Thermal efficiency is a critical performance metric for evaluating the effectiveness of a biogas-powered injera baking stove, as it quantifies the proportion of energy extracted from the biogas fuel and converted into useful heat for baking injera (81,94). In this study, thermal efficiency was evaluated based on both the sensible and latent heat involved in the baking process and the input energy derived from biogas consumption.

$$E_{absorbed} = Q_{sensible} + Q_{latent} = m_{batte} C_p (T_{boil} - T_{room}) + (m_{batter} - m_{injera}) h_{fg} \quad (1)$$

Where:

E absorbed = Energy Absorbed

Q = total heat required (J);

m_{batter} = mass of batter (kg);

C_p = specific heat capacity of the batter (J/kg·K);

T_{boil} = boiling temp of water (K);

T_{room} = room temp (K);

h_{fg} = latent heat of evaporation of water (J/kg);

Q_{loss} = heat lost to surroundings due to inefficiency (J);

m_{evap} = mass of water evaporated (kg)

The energy input to the stove is derived from the chemical energy content of the biogas consumed during the injera baking process. This input energy is calculated based on two primary factors: the volumetric flow rate of the biogas and its lower heating value (LHV) or calorific value, which represents the amount of energy released per unit volume of biogas when combusted completely (95).

The total energy consumed represents the total chemical energy supplied to the stove from the biogas during operation. It is calculated by multiplying the total volume of biogas used by its calorific value, which indicates the amount of heat released when one cubic meter of biogas is completely burned. This value provides the total energy input to the system before any losses occur and serves as the basis for evaluating the stove's thermal efficiency and overall performance.

Total energy consumed = total biogas consumed × calorific value of biogas (2)

The thermal efficiency (η) of the biogas stove. It shows how effectively the chemical energy in the consumed biogas is converted into useful heat absorbed by the cooking surface or load.

$$\eta = \frac{Energy\ Absorbed}{Total\ \ amount\ \ of\ Biogas\ Consumed \times Calorific\ value} * 100$$

(3)

The performance of modern biogas injera baking stoves represents a significant leap forward in cooking technology, offering substantial improvements in efficiency, energy consumption, and combustion quality over traditional methods.

Traditional three-stone fires, with a typical thermal efficiency of only 5-10%,are profoundly inefficient, while improved biomass stoves like the Mirt stove achieve around 10-17% efficiency. This latter figure is more than double the efficiency of a three-stone fire and is attributed to key design innovations.

Furthermore, biogas consumption rates have been refined through design iterations. Early stove designs consumed about 0.93 m³/h, whereas later optimized models with improved burner heads and cone systems achieved satisfactory baking with flow rates between 510-605 L/h (0.51-0.605 m³/h), consuming only 22-35 liters of biogas per injera. Critical to this performance is the design of the burner manifold. Research has shown that increasing the manifold diameter from a previous standard of 17 cm to an optimized 26 cm ensures uniform heat distribution across the larger baking surface (mitad), eliminating cold or hot spots that result in poorly baked injera. In summary, the evolution of biogas stove design has successfully addressed the core challenges of heat distribution and fuel efficiency, establishing a new benchmark for clean, economical, and high-performance injera baking Table 6.

Table 6. Comparative Performance of Injera Baking Stove

Feature	Traditional Three-Stone Fire	Improved Biomass (Stove Mirt)	Biogas Stove
Thermal Efficiency	5-10%	10-17%	25%

The operational efficiency of a stove is critical for user adoption, impacting both the time required for cooking and the quality of the food produced. Recent design optimizations in biogas stoves for injera baking have led to significant improvements in heating speed, cycle times, and most importantly, heat distribution uniformity.

2.13 Enhanced Thermal Response and Baking Cycle Efficiency

The core of operational efficiency lies in the stove's thermal response—how quickly it reaches cooking temperature and how well it maintains it between baking cycles. This performance is fundamentally governed by the principles of heat transfer and energy balance.

Equation for Thermal Response (Preheating Time)

The claim of reduced preheating time is governed by the transient heat conduction and the energy balance of the *mitad*. The fundamental equation is the Lumped Capacitance Method (a first-order approximation for a body heating uniformly)(94,96):

$$t_{preheat} = (m_{mitad} * C_p * \Delta T) / (Q_{in} - Q_{loss}) \qquad (4)$$

Where:

$t_{preheat}$= Preheating time (s) - This is what the design aims to minimize.

m_{mitad} = Mass of the *mitad* (kg)

C_p = Specific heat capacity of the *mitad* material (J/kg·K)

ΔT = Temperature change of the *mitad*

Q_{in} = Net heat input rate from the burner (W)

Q_{loss} = Heat loss rate to the surroundings via convection and radiation (W)

Combustion Stoichiometry, Air–Fuel Equivalence Ratio, (λ) and Flame Color

Biogas combustion involves the mixing of air with the fuel gas, followed by ignition of the resulting air–gas mixture. In this study, the biogas used consists of approximately 60% methane (CH_4) and 40% carbon dioxide (CO_2)(45,97). The chemical reaction governing the combustion process primarily reflects the complete oxidation of methane, as CO_2 is inert in combustion.

To optimize combustion performance, a stoichiometric analysis was performed based on the biogas composition. The theoretical air requirement for complete combustion of methane was calculated, resulting in a stoichiometric air-to-biogas ratio of approximately 5.72 m^3 of air per 1 m^3 of biogas. This value ensures sufficient oxygen for complete combustion of methane, minimizing unburned hydrocarbons and carbon monoxide emissions(34,95) .

$$CH4 + 2(O_2 + 3.76\ N_2) \rightarrow CO_2 + 2\ H_2O + 7.52\ N_2 \quad (5)$$

Assuming standard ambient conditions, the required air volume was used to calculate the air–fuel equivalence ratio (λ), defined as follows (95,98): The air–fuel equivalence ratio, λ (lambda), is defined as the ratio of the actual air–fuel ratio to the stoichiometric air–fuel ratio.

$$\text{The equivalence ratio } (\lambda) = \frac{Actual\ Air-Fuel\ Ratio}{Stoichiometric\ Air-Fuel\ Ratio} \quad (6\ )$$

λ provides insight into combustion efficiency and flame characteristics.

Combustion regimes were classified as follows:

λ = 1: stoichiometric (ideal, blue flame);

λ < 1: fuel-rich (incomplete combustion, yellow flame, soot);

λ > 1: fuel-lean (cool flame, lower efficiency).

Targeting λ ≈ 1 allowed for maximized combustion efficiency and thermal output while minimizing pollutant formation.

$$\eta(\lambda)=\eta_0(1-\alpha\ (\lambda-\lambda_{stoich})^2) \quad (7\ )$$

Where

η_0 = maximum efficiency at the optimal equivalence ratio λ (dimensionless);

α = correction coefficient accounting for deviation from stoichiometric combustion (1/Unit^2);

$\lambda_{\mathrm{stoich}}$ = stoichiometric equivalence ratio (dimensionless).

The corresponding useful heat output at a given equivalence ratio is

$$Q_b(\lambda) = Q_{max}.\eta(\lambda) \quad (8)$$

Where:

Q_b = heat output at a specific λ (W or kW);

Q_{max} = maximum possible heat release rate (W or kW);

η(λ) = combustion efficiency as a function of λ (dimensionless);

2.14 Types of Biogas Burner

The performance of an injera baking stove critically depends on the efficiency and uniformity of heat delivery from the burner to the baking pan (mitad). In biogas-fired systems, burner design determines not only the thermal distribution and combustion stability but also directly influences fuel consumption, baking quality, and emission levels. Traditional burner configurations often suffer from uneven heat flux, localized overheating, and incomplete combustion, leading to poor energy utilization and non-uniform injera texture. To overcome these limitations, the optimization of burner geometry and port configuration is essential to enhance both thermal efficiency and combustion performance.

Recent advancements in computational fluid dynamics (CFD) modeling have enabled detailed analysis of flame behavior, flow dynamics, and heat transfer mechanisms within biogas stove burners. The studies reveal that parameters such as manifold diameter, port size, and port density play decisive roles in shaping the flame structure and determining the uniformity of temperature distribution across the mitad surface.(49,98) The optimized burner must therefore achieve a balance between flame stability, air–fuel mixing, and heat flux uniformity.

2.14.1 Ring-Type Biogas Burner Geometry

While electric baking pans have seen advancements in material science, a substantial number of households and commercial enterprises rely on wood-fired systems(82,99). A critical and persistent challenge with the biogas-fired mittads is non-uniform heat distribution, leading to the formation of hot and cold spots on the baking surface

(20,93)and insufficient supply of biogas (100,101). This inconsistency directly compromises injera quality, resulting in unevenly cooked bread, and reduces overall energy efficiency as operators prolong heating times to compensate Figure 31. Addressing this challenge requires a fundamental optimization of the burner head geometry, moving beyond traditional empirical designs toward an engineering solution grounded in fluid dynamics and thermal transport principles.(30)

Figure 31. Ring gas burner with flame port

The optimization of the burner head design, characterized by an enlarged manifold diameter and a high density of small flame ports, is governed by fundamental equations of fluid dynamics and thermal transport. Firstly, the enlargement of the manifold diameter directly improves heat distribution by increasing the radius of influence (R) of the burner, ensuring the flame ports are positioned closer to the edges of the *mitad* (91). This mitigates the formation of cold spots by ensuring the heat flux is applied more uniformly across the entire baking surface. Secondly, the use of a high density of flame ports is critical for creating a continuous "carpet of flame."

The total exit area for gas flow is determined by the sum of the areas of all ports(49):

$$A_{total} = n\pi \, {d^2}/{4}, \tag{9}$$

Maintaining this total area while decreasing the individual port diameter(d) requires a significant increase in the number of ports (n). This high port density is essential for achieving a uniform heat flux profile. Furthermore, the small port size directly influences the port Reynolds number.

$$Re = \frac{\rho v d}{\mu} \tag{10}$$

Where a smaller diameter d can lead to a lower Reynolds number, promoting laminar or transitional flow that results in more stable, quieter flames less prone to lifting. Most importantly, the heat transfer rate is a function of the total flame contact area and temperature. The numerous small flames create a large aggregate flame surface area A_{flame},which significantly enhances the total convective heat transfer to the mitad which is;

$$Q_{conv} = hA_{flame}\left(T_{flame} - T_{mitad}\right), \quad (11)$$

Where h is the convective heat transfer coefficient. This design ensures a broader, more immediate, and uniform application of thermal energy, directly translating to the observed improvements in baking speed and consistency(102,103).

2.14.2 Conical Burner

The conical burner represents a critical advancement in the thermal optimization of biogas injera baking systems, where geometry directly influences combustion stability, heat transfer efficiency, and overall fuel utilization (81,102) as shown in Figure 32. Its design is rooted in the fundamental principles of fluid dynamics and heat transfer, employing a carefully shaped conical passage to control the behavior of the biogas–air mixture as it flows toward the burner exit (98,104).

The primary role of the conical geometry is to function simultaneously as a flow constrictor and flame stabilizer. As the biogas–air mixture passes through the diverging section of the cone, the cross-sectional area increases, and in accordance with the principle of mass conservation (A_1v_1=A_2v_2), the local flow velocity adjusts to maintain a constant mass flow rate(105). This controlled acceleration enhances the momentum of the gas stream, preventing flame flashback and ensuring that the flame remains anchored at the burner exit(105,106). The result is a robust, outwardly projected flame that uniformly directs heat toward the mitad surface.

The elevated jet velocity at the burner also plays a vital role in improving convective heat transfer to the mitad. The impingement of these high-velocity flames promotes intense localized turbulence, which increases the convective heat transfer coefficient (h) and enhances the overall thermal response of the baking surface. Simultaneously, the diverging cone shape facilitates flame spreading and stability, enabling efficient utilization of the available combustion energy while minimizing unburned fuel losses.

In addition to improved convective performance, the conical structure contributes to radiative heat transfer by reflecting and redistributing radiant energy from the combustion zone toward the mitad. This dual-mode heat transfer mechanism—combining forced convection and surface radiation—ensures both rapid heating and uniform temperature distribution across the baking surface. Consequently, the optimized conical burner design significantly enhances thermal efficiency, reduces specific biogas consumption, and maintains the consistent temperature field essential for high-quality product (86,104).

Figure 32.Inverted Conical Burner

The conical shape then acts as a physical guide for this optimized combustion. By focusing and directing the flames inward and upward, the cone creates a concentrated, impinging flame pattern on the center of the *mitad*. This targeted heat delivery minimizes radial heat losses and establishes a powerful high-temperature zone, from which heat is then conducted radially across the baking surface.

The thermal advantage of this design is twofold. First, the impingement of high-velocity flames creates a thin boundary layer on the bottom of the *mitad*, which dramatically enhances the convective heat transfer coefficient (h)(20,107). This is because the convective heat transfer rate is governed by and a higher h directly results in more efficient energy transfer.

$$Q_{conv} = h * A * \Delta T, \quad (12)$$

Where,

Q_{conv} , Convective Heat Transfer

h, Convective heat transfer coefficient

ΔT, Temperature differences between surfaces

Second, the cone itself, heated by the enclosed flames, becomes a radiant body. The heat transferred via radiation, calculated by the Stefan-Boltzmann Law becomes significant. Because radiative heat transfer is proportional to the fourth power of temperature, the high temperature of the cone results in a substantial radiative flux, efficiently heating the *mitad* from the center outward. This synergistic combination of enhanced convection and concentrated radiation is the key to the conical burner's rapid warm-up time. However, this very focus on centralized heat delivery also presents a scalability challenge, as achieving uniform temperature across a larger-diameter *mitad* becomes more difficult, explaining the trade-off with the smaller diameter baking surface(108).

$$q''_{rad} = \varepsilon\sigma(T^4_{cone} - T^4_{mitad}), \quad (13)$$

Where,

q''_{rad} , Radiation heat transfer

T^4_{cone}, Temperature of cone

T^4_{mitad}, Temperature of mitad

ε , emissivity of material

σ, Boltzmann constant

2.15 Product Quality

As demonstrated in Bilhate Chala's experiments, the use of optimized inner cone systems (small, fixed, and adjustable cones) was crucial for achieving even heat distribution on the clay plate (mitad). This uniform heating, a result of design innovations like the conical combustion chamber and strategically arranged burner ports, ensures consistent "eye" formation and browning(78,109). This addresses a key limitation noted by Mulugeta et al., where previous stoves with small manifold diameters (17 cm) led to uneven heat and poor injera quality.

2.16 Stove Insulation

The thermal performance of the injera baking stove is highly influenced by the physical and thermal properties of the baking pan (mitad). Optimizing these parameters enhances heat transfer efficiency, accelerates temperature rise, and reduces overall fuel consumption. A pan with lower thermal mass responds more quickly to heat input, enabling faster attainment of the desired baking temperature and minimizing energy losses to the surroundings. Consequently, less fuel energy is required to achieve the same operational temperature, leading to shorter warm-up periods, improved thermal uniformity, and enhanced overall system efficiency.

The use of materials like gypsum, or mixtures of clay and ash (with thermal conductivity as low as 0.16-0.18 W/m·K), minimizes heat loss to the stove's body and the environment(107). This ensures that a greater proportion of the thermal energy is directed into the mitad, facilitating a faster temperature rise.

The effectiveness of insulation in minimizing heat loss is described by Fourier's Law of Heat Conduction. The rate of conductive heat loss Q_{loss} through the stove's body is directly proportional to the thermal conductivity (k) of the insulating material and the temperature difference (ΔT), and inversely proportional to the insulation thickness (L), as given by the equation.

$$Q_{loss} = k * A * \Delta T / L. \tag{14}$$

The use of materials like gypsum or clay-ash mixtures with a low thermal conductivity—as low as 0.16–0.18 W/m·K—directly reduces the Q_{loss} term. This conservation of thermal energy means a greater proportion of the heat input from combustion (Q_{in}) is available to raise the temperature of the *mitad*(108,110). This net energy available for useful heating is defined by the energy balance

$$Q_{net} = Q_{in} - Q_{loss} . \quad (15)$$

A smaller Q_{loss} results in a larger Q_{net}, which directly translates into a faster temperature rise for the *mitad*. This relationship is captured in the transient heat transfer equation for the *mitad*:

$$m_{mitad} * c_{pmitad} dT/_{dt} = Q_{net} , \quad (16)$$

Where the mass (m) and specific heat (Cp) of the *mitad* are constant. Therefore, by maximizing Q_{net} through superior insulation, the rate of temperature change (dT/dt) is increased, quantitatively explaining the facilitated faster temperature rise and improved fuel efficiency observed in insulated stove designs.

2.17 Material Science in Stove Construction

The thermal performance of the injera baking stove is highly influenced by the physical and thermal properties of the baking pan (80,81). Optimizing these parameters enhances heat transfer efficiency, accelerates temperature rise, and reduces overall fuel consumption. A pan with lower thermal mass responds more quickly to heat input, enabling faster attainment of the desired baking temperature and minimizing energy losses to the surroundings. Consequently, less fuel energy is required to achieve the same operational temperature, leading to shorter warm-up periods, improved thermal uniformity, and enhanced overall system efficiency.

$$\Delta t = \frac{m_{mitad} * C_p}{Q_{net}} \quad (17\ )$$

Where,

m = mass of the baking pan,

C_p = specific heat capacity of the pan material,

$dT/_{dt}$ = rate of temperature change,

Q_{net} = net heat transferred to the pan.

This equation shows that a smaller thermal mass (m × c_p) and higher net heat input (Q_{net}) result in a faster temperature rise, thereby improving thermal responsiveness and fuel efficiency in baking stove systems.

Heat Distribution Uniformity

The achievement of superior heat distribution uniformity, a critical factor for producing injera with its characteristic uniform "eyes," is fundamentally governed by the heat diffusion equation. In a steady-state approximation, the temperature distribution across the *mitad* is described by :

$$\Delta^2 T = {}^{-q(r)'''}\!/_{k} \tag{18}$$

Where

∇²T , Laplacian of the temperature (representing the spatial curvature of the temperature field),

q'''(r), Internal heat generation rate per unit volume (which is zero for the *mitad* itself),

k , thermal conductivity of the *mitad* material.

This simplifies to ∇²T = 0, meaning that for a perfectly uniform heat flux from the burner, the temperature should be constant. In reality, non-uniform burner flux creates a non-zero source term on the *mitad's* bottom surface, leading to significant spatial temperature variations(107). This is mathematically represented by minimizing the variance of the heat flux profile across the radius of the *mitad*. The performance can be summarized by a Temperature Uniformity Index, which can be defined as the standard deviation of the temperature across the baking surface

$$\sigma_T = {}^{\sqrt{(\Sigma(T_i - T_{avg})^2}}\!/_{(n-1)} \tag{19}$$

Where,

σ_T, The non-uniformity of heat flux

T_i, Measured temperature at point i

T_{avg}, Average surface temperature

n, Number of temperature measurement points.

The design innovations—such as the larger manifold diameter and the conical flame guide—effectively flatten the q''(r) profile, thereby reducing both ∇²T and the resulting σ_T which is manifested as the dramatically reduced $to\ \Delta T_{max}$. This ensures the thermal energy is distributed consistently, allowing the injera batter to bake uniformly.

The evolution of biogas injera stove design has been predominantly driven by thermal and combustion efficiency (111). However, the long-term viability and user adoption are equally dependent on the durability and material properties of their construction components. The operational environment subject materials to a demanding combination of high temperatures (800–1100°C flame zone), rapid thermal cycling, oxidizing flames, and potential corrosion from trace compounds in biogas like hydrogen sulfide (H_2S) and water vapor (95,105).

The readily available and easy to fabricate, plain carbon steel undergoes rapid high-temperature oxidation (scaling) above 500°C. The reaction $4Fe + 3O_2 \rightarrow 2Fe_2O_3$ forms a non-protective, flaky scale that continuously exposes fresh metal to oxidation, leading to wall thinning and failure(107). The low thermal efficiency meant excessive heat was conducted into the burner structure itself, accelerating this degradation. Furthermore, the cyclic heating and cooling induced thermal fatigue, causing warping, cracking at welds, and eventual failure of joints(105).

The work of Kebede and Kiflu (2014) marked a critical shift in design philosophy by explicitly addressing debilitating heat loss through the systematic integration of insulation. Their investigation represented helps for material selection, evaluating clay-ash with a thermal conductivity of ~0.18 W/m·K.(94) The exploration of locally sourced clay as an insulator was particularly significant for its affordability and local manufacturability, though its performance is highly variable. Without proper characterization and processing, its unpredictable porosity and thermal shock resistance can lead to cracking, underscoring the persistent gap between theoretical modeling and practical, durable application in the field.

Traditional *mitad* construction relies on clay, a material deeply embedded in Ethiopian baking culture. As evidenced by Bilhate Chala's research, the traditional clay plate remains central to injera baking, even when integrated with modern biogas burners. Clay is prized for its excellent thermal mass, which helps maintain a stable baking temperature, and its ability to distribute heat evenly—a property crucial for achieving the characteristic uniform "eyes" in injera. However, these traditional clay *mitads* possess inherent material limitations. Their low tensile strength and poor fracture toughness make them highly susceptible to thermal shock. The rapid heating and cooling cycles inherent to the baking process create differential expansion stresses that often exceed the material's mechanical strength, leading to cracking and eventual failure.

As biogas injera stove burner designs evolved, the demand for more resilient materials capable of withstanding extreme operational conditions grew significantly. This led to the adoption of advanced alloys and precision manufacturing techniques. Austenitic stainless steels, such as AISI 304 (18% Cr, 8% Ni) and AISI 316 (18% Cr, 10% Ni, 2% Mo), represent a vast improvement over ordinary steel(107). Their key advantage lies in the chromium content, which forms a continuous, adherent layer of chromium oxide (Cr_2O_3) that acts as a protective barrier against oxidation and scaling at temperatures up to ~900°C. The addition of molybdenum in grade 316 provides enhanced resistance to pitting corrosion, a crucial property for combating the moist, sulfidic environment created by biogas impurities. As an alternative, specialized cast irons like ductile iron or high-nickel austenitic cast iron offer excellent high-temperature strength and wear resistance, though their high thermal mass can lead to slower heat-up times and inherent brittleness remains a concern. Beyond material composition, precision manufacturing has become equally critical. The shift from manual drilling to laser-cutting or CNC punching of burner ports is essential for achieving uniform diameter and spacing(105). This precision is fundamental for ensuring a consistent flame pattern, preventing combustion issues like flashback, and minimizing the production of harmful emissions such as carbon monoxide (CO) and nitrogen oxides (NO_x).

The *mitad*, or baking surface, stands as the most complex and critically stressed component in the entire system, where material science directly dictates performance and longevity(82) .Traditional clay *mitads*, while prized for their excellent thermal mass and even heat distribution, are fundamentally limited by low tensile strength and poor fracture toughness(112). Their primary failure mode is thermal shock, where differential expansion between hot and cooler areas creates internal stresses that exceed the material's inherent strength, leading to cracking and eventual failure(107). To address these limitations, modern engineering has shifted towards composite *mitads*, which are sophisticated, multi-layered systems designed to decouple structural and thermal functions.

The performance and longevity of an injera baking pan (mitad) are fundamentally dictated by the material science of its cooking surface. The evolution from traditional clay to modern composites represents a focused effort to optimize thermal properties for efficient cooking and structural integrity for long-term use. The following table provides a comparative overview of three primary material classes investigated for this purpose.

Table 7. Comparative Analysis of pan Material

Feature	Clay	Ceramic	Iron Plate
Primary Material	Aluminum Silicate & Clay	Sintered Aluminum Silicate & Oxide	Iron/Steel
Thermal Conductivity	Low & Variable	Moderate & Stable	Very High
Performance	Inefficient, slow	Even, stable	hard to control
Durability	Porous, brittle	Dense, hard, high-bond	Strong, but rust

As illustrated in Table 7, traditional clay pans, while simple, suffer from low and variable thermal conductivity due to their porous nature and moisture sensitivity, leading to inefficient energy use and uneven baking. Their brittle structure further limits durability. Conversely, metal plates, despite excellent conductivity, fail because their low heat capacity causes aggressive, uncontrollable heat transfer that is unsuitable for the delicate injera baking process.

The engineered ceramic pan addresses many of these flaws. Through high-temperature sintering (>1000°C), a dense, vitrified structure is formed, resulting in stable thermal performance, even heat distribution, and superior durability.

This optimized thermal "effectivity" ensures rapid heat transfer for faster baking cycles while retaining sufficient thermal energy to maintain a stable cooking temperature. The fired composite structure is denser and more robust than traditional clay, offering improved mechanical strength and resistance to thermal shock, thereby enhancing its operational lifespan and efficiency beyond traditional options.

The trajectory of mitad material science moves decisively from naturally occurring but inefficient clay towards engineered solutions. For electric baking, the clay-steel composite and high-fired ceramic represent the current peak of performance, successfully balancing thermal responsiveness with heat retention. Future research should focus on further optimizing these composites and exploring their integration with sustainable energy systems, such as biogas burners, to create solutions that are not only high-performing and durable but also accessible and environmentally sustainable.

2.18 Health and Environmental Impacts

The adoption of biogas stoves offers significant potential health and environmental co-benefits, though quantitative assessments specific to injera applications are limited(101,111).

Replacing biomass with biogas fundamentally improves indoor air quality by eliminating the emission of harmful particulate matter (PM2.5) and carbon monoxide (CO) during combustion(8,35). This reduction directly mitigates the risk of acute respiratory infections, chronic obstructive pulmonary disease, and other health issues associated with household air pollution, particularly benefiting women and children(22).

2.18.1 Environmental Impacts and Sustainability of Biogas Injera Stoves

The adoption of biogas technology for injera baking presents a compelling case for sustainable development, offering multifaceted environmental advantages that extend from the global atmosphere to the rural household kitchen(10). Its primary benefit lies in climate change mitigation, functioning on a nearly carbon-neutral cycle. Unlike fossil fuels that release ancient carbon, biogas is derived from recently grown organic matter, meaning the CO_2 emitted during combustion is part of the active atmospheric carbon cycle, resulting in no net addition. An even more significant climate benefit is the reduction of methane emissions(56,113). By capturing organic waste that would otherwise decompose anaerobically in open pits—releasing methane, a potent greenhouse gas with 84-87 times the warming power of CO_2 over 20 years—and combusting it, the technology transforms high-impact methane into low-impact CO_2, slashing the global warming potential of the emissions by over 95%(4,14). Furthermore, the shift to biogas dramatically improves public health through superior combustion emissions and indoor air quality. Traditional wood-fired *mogogos* are a major source of harmful pollutants, including particulate matter (PM2.5), carbon monoxide (CO), and black carbon, due to incomplete combustion. In stark contrast, a well-designed biogas burner undergoes near-complete combustion, emitting primarily CO_2 and water vapor, with negligible PM2.5 and CO(71). This leads to a dramatic improvement in indoor air quality, providing a critical health benefit for women and children by directly reducing the incidence of acute respiratory infections and other related diseases(8).

2.18.2 Deforestation and Biomass Resource Conservation

The displacement of firewood for injera baking, a major driver of biomass consumption in Ethiopia, represents one of the most significant environmental benefits of biogas technology. The adoption of a single household biogas system can save an estimated 1.5 to 2.5 tons of firewood annually(2,114). When scaled to a community or national level, this drastic reduction in demand directly alleviates immense pressure on forest ecosystems. By providing a reliable and clean alternative, biogas stoves serve as a powerful tool in combating deforestation and forest degradation. This conservation effort has cascading positive effects: it preserves biodiversity, protects vital watersheds, reduces soil erosion, and maintains crucial natural carbon sinks. This creates a positive feedback loop for enhanced climate resilience, as healthier forests sequester more atmospheric carbon. The tangible impact of this shift has been quantitatively demonstrated in studies from southern Ethiopia, which have directly linked biogas adoption to reduced fuelwood consumption and associated decreases in carbon emissions (101,115).

2.18.3 Sustainable Waste Management and Sanitation

The anaerobic digester, as the cornerstone of the system, fundamentally transforms a waste management problem into a comprehensive energy and agricultural solution, thereby closing the sanitation loop. Operating within a sealed, heated environment, the digestion process significantly reduces pathogen levels compared to raw manure, producing a sanitized digestate (effluent) that is a much safer organic fertilizer. This systematic collection of manure and organic waste is crucial for preventing the leaching of nutrients and contaminants into groundwater and surface water, a common environmental hazard associated with open manure piles. Furthermore, the technology establishes a circular nutrient economy; the resulting digestate is a stabilized, nutrient-rich (NPK) bio-fertilizer that, when returned to agricultural fields, closes the nutrient loop. This practice reduces dependence on energy-intensive synthetic fertilizers and concurrently improves soil health and structure, creating a sustainable cycle that benefits both the farm and the environment. Biogas injera stoves represent a transformative technology with profound environmental benefits, including climate change mitigation through a closed carbon cycle and methane capture, dramatic improvements to indoor and outdoor air quality, and the conservation of forest resources. Furthermore, they promote a circular economy by converting waste into energy and fertilizer (46,111). To fully validate their sustainability credentials and guide policy, a standardized LCA specific to the Ethiopian context is a critical and urgent research priority. This will ensure that the upstream and downstream impacts do not inadvertently offset the substantial operational gains.

2.19 Technical and Socioeconomic Constraints in Biogas Stove

The pathway to widespread adoption of efficient biogas injera stoves is fraught with multifaceted technical and socioeconomic challenges that extend beyond mere stove design(68,77). According to Sime's comprehensive study in southern Ethiopia, these constraints permeate the entire biogas ecosystem, from production to end-use application. The technical limitations begin at the fundamental level of biogas production and supply chain management. Feedstock availability remains problematic due to seasonal variations in livestock feed quality, which directly affects manure composition and biogas yield. Many digesters suffer from poor maintenance, leading to inconsistent gas production and quality. Furthermore, the absence of a centralized biogas purification and distribution system severely limits scalability beyond individual household units, preventing the technology from achieving broader community impact. At the stove performance level, several critical technical barriers persist. The pressure mismatch between household digesters and stove requirements presents a fundamental operational challenge. Most stoves are designed for large mitads receive insufficient pressure, resulting in weak flames and uneven heating(20,69). This problem is compounded by the persistent challenge of heat distribution across the large, circular mitad surface. Even with improved burner designs, achieving uniform temperature distribution remains elusive due to inadequate flame geometry and insufficient insulation in current stove configurations. These technical shortcomings contribute to the consistently low thermal efficiency rates, which often remain below 25%, coupled with high specific gas consumption that undermines the technology's cost-effectiveness(69).

The socioeconomic dimensions of these challenges are equally constraining. Sime's research reveals that inadequate technical skills among masons and users significantly hamper system functionality. The absence of local manufacturing capacity for biogas appliances creates dependency on imported components, with lengthy procurement periods of 4-10 months and weak quality control mechanisms. Maintenance services are largely unavailable, with nearly all surveyed users reporting the absence of standby technicians, leading to 25% of bio-digesters being completely non-functional or abandoned(10,65).

Financial barriers present another significant hurdle. The high initial investment, despite 40% subsidy coverage, remains prohibitive for many rural households. Microfinance institutions show decreasing interest in providing loans due to challenges in monitoring and managing credit repayments, with 45% of households failing to meet interest payment schedules(25). Additionally, critical compatibility issues between bio-digester size and household resources are frequently overlooked. The study found that bio-digesters were underfed due to incompatibility between installed digester size and available livestock holding size, while some of them were completely abandoned due to water shortages, particularly during extended drought periods(10,25).

The integration challenges extend to institutional coordination, with weak organizational alignment among key stakeholders undermining technology dissemination. The underestimation of bio-slurry benefits and inadequate attention to cultural barriers regarding toilet connections to bio-digesters further limit technology acceptance. These interconnected technical and socioeconomic constraints create a complex implementation landscape that requires comprehensive, system-level solutions rather than isolated technical fixes to achieve sustainable adoption of biogas technology for injera baking applications.

The success of any technology is measured not only by its technical performance but also by its adoption and sustained use within the target community. For biogas injera stoves, this transition from the laboratory to the kitchen is fraught with significant socio-economic and cultural hurdles. While engineering advances have solved many technical problems, the intertwined challenges of cost, usability, and cultural acceptance remain the final frontier for widespread implementation.

The most formidable barrier to the widespread adoption of biogas injera stoves is the prohibitive initial cost, which represents a significant financial shock for low-income households. A functional system is an integrated unit, and its substantial upfront investment encompasses not only the specialized injera stove—which is more complex and costly than a standard cooktop due to its large size, and precision burner ports—but also the anaerobic digester itself, including construction materials like cement, bricks, and piping, along with essential gas system components such as the gas holder, regulator, and valves. The total expense can amount to several times the monthly income of a typical rural household, making the technology inaccessible without external support. As studies indicate, the economic calculus often leads families to prioritize the immediate, albeit labor-intensive, "free" cost of collecting firewood over a large capital investment, despite the long-term health and time savings. Therefore, scaling adoption necessitates innovative financial mechanisms, including targeted government or NGO subsidies, accessible microfinance loans, and community-shared digester models that distribute costs across multiple households.

2.20 Research Gaps on Biogas Injera Stove and Future Directions

The evolution of the biogas injera stove has reached a critical juncture, where future progress depends on addressing well-defined research gaps that span technical, socio-economic, and systemic domains. Bridging these gaps is essential for transforming advanced prototypes into universally accessible, reliable, and culturally embraced household appliances.

High-Priority Technical Research must focus on overcoming the practical challenges that hinder performance and durability. A primary objective is the development of pressure-adaptive burner designs that can maintain stable combustion and consistent heat output under the variable, and often low-pressure, conditions typical of small-scale rural digesters. Furthermore, while Computational Fluid Dynamics (CFD) has proven invaluable for optimization, there is an urgent need for the experimental validation of these models through rigorous laboratory and field testing, utilizing techniques like infrared thermography to correlate simulated temperature distributions with real-world performance. Concurrently, research should systematically explore advanced insulation materials for the *mitad*, such as aerated ceramics or nano-composites, to develop standardized, lightweight, and highly durable solutions that minimize heat loss and extend service life.

Beyond technical performance, the standardization and socio-technical integration of these stoves require dedicated effort. The field is currently hampered by the lack of context-specific performance standards. Developing and implementing ISO/IWA-aligned testing protocols is crucial for enabling reliable benchmarking, consumer protection, and quality certification. This must be coupled with a deeper commitment to User-Centered Design (UCD), employing participatory approaches to ensure stove ergonomics, safety, and maintenance align with user capabilities and cultural practices, including a specific focus on gender roles in stove operation. Finally, long-term durability studies and detailed techno-economic analyses are needed to provide robust data on real-world lifespan and to inform viable business and subsidy models that can overcome the barrier of initial cost.

At a system level, future innovations should look beyond the stove as a standalone device. Research into hybrid energy systems, which integrate biogas with solar thermal or electric heating elements, could guarantee reliable injera production during periods of low biogas yield, thereby enhancing user confidence. Additionally, given Ethiopia's diverse topography, there is a need to study the adaptation of burner configurations to environmental variability, ensuring that combustion dynamics are optimized for consistent performance across the country's different altitudes and climates.

CHAPTER THREE
METHODOLOGY

3.1 Introduction

Domestic biogas systems represent a promising solution for clean cooking in livestock-rich rural and peri-urban communities. By converting animal manure and organic wastes into methane-rich biogas and bio-slurry via anaerobic digestion, household digesters can supply a clean, controllable fuel for cooking while simultaneously producing a nutrient-rich fertilizer co-product. However, simply replacing the fuel source does not guarantee improvements in cooking performance: burner design and stove–load interactions determine how effectively chemical energy in biogas is converted to useful thermal energy at the mitad. For injera baking — which requires rapid heating to create a uniform porous surface and precise control of surface temperature — burner geometry and flame characteristics critically influence heat flux, uniformity, and fuel-use efficiency.

This study focuses on the experimental investigation of a biogas injera baking stove equipped with a conical burner. Conical burner of conical geometries and related conical nozzle arrangements alter the flame shape, jet coherence, and mixing characteristics between fuel and ambient air, and they can promote more uniform radial heat distribution compared with conventional ring or planar burners. While conical burners have shown promise in other small-combustion applications, their application and optimization for injera baking — given the large-area heat transfer demands of a 40–50 cm diameter mitad and the sensitivity of injera quality to surface temperature and moisture dynamics — require focused experimental evaluation.

The primary aims of this chapter are to design and characterize a conical burner suitable for household biogas injera stoves, quantify the thermal performance and fuel consumption of the stove under realistic injera-baking conditions, and evaluate the effect of burner geometry and operating parameters on baking quality and heat-use efficiency. To achieve these aims, the study conducts controlled laboratory experiments using an instrumented mitad and an adjustable conical burner prototype. Key performance metrics include thermal efficiency, specific fuel consumption (SFC) per unit mass of injera, surface temperature uniformity, transient heating response, and qualitative/quantitative indicators of injera quality (rollability, pore structure, browning).

The experimental methodology comprises burner fabrication and calibration, steady-state and transient thermal measurements on the Pan (using thermocouples and infrared thermography where appropriate), controlled injera baking trials with standardized batter and operator procedures, and post-bake quality assessment using established sensory and instrumental measures. The study also estimates economic implications by calculating fuel consumption savings and projecting payback times under representative household usage scenarios.

This chapter is organized as details of the experimental setup, instrumentation, and test protocols and presents results on thermal efficiency, surface temperature uniformity, and baking quality, followed by a discussion that interprets findings, identifies optimal operating windows, and compares the conical burner's performance with conventional burners. It concludes with recommendations for design refinement, scale-up considerations, and directions for future research, including field trials and long-term durability studies.

3.2 Description of The Stove

The biogas injera baking stove represents an innovative cooking solution designed specifically for Ethiopia's traditional flatbread preparation. Featuring a 45 cm diameter clay baking pan (mitad) with 1.5 cm thickness, the stove ensures uniform heat distribution critical for proper injera baking (as demonstrated in Figure 33). The burner system consists of two integrated components: a base section containing the biogas injector and air inlet box, and an upper conical-shaped combustion chamber that optimizes air-fuel mixing. Fuel delivery is managed through a ½-inch diameter gas pipe with a control valve, while the rectangular air inlet connects to the combustion chamber via welding. The chamber's innovative cylindrical-to-conical transition accommodates the clay mitad perfectly, with complete combustion ensured by an exhaust outlet pipe. For thermal efficiency, the unit incorporates 30mm gypsum insulation protected by steel sheet casing, along with a standard aluminum baking cover featuring a wooden edge grip for safe handling.

Developed through mathematical modeling, geometric design, and experimental testing, this system utilizes biogas produced from underground anaerobic digesters. The sustainable solution not only provides clean cooking fuel but also yields nutrient-rich slurry as a valuable fertilizer byproduct. Operation begins when biogas flows through the control valve , mixes with air in the pressurized combustion chamber, and ignites to produce a stable cooking flame. This thoughtful design successfully bridges modern renewable energy technology with traditional culinary practices, offering an efficient, culturally appropriate solution for injera preparation.

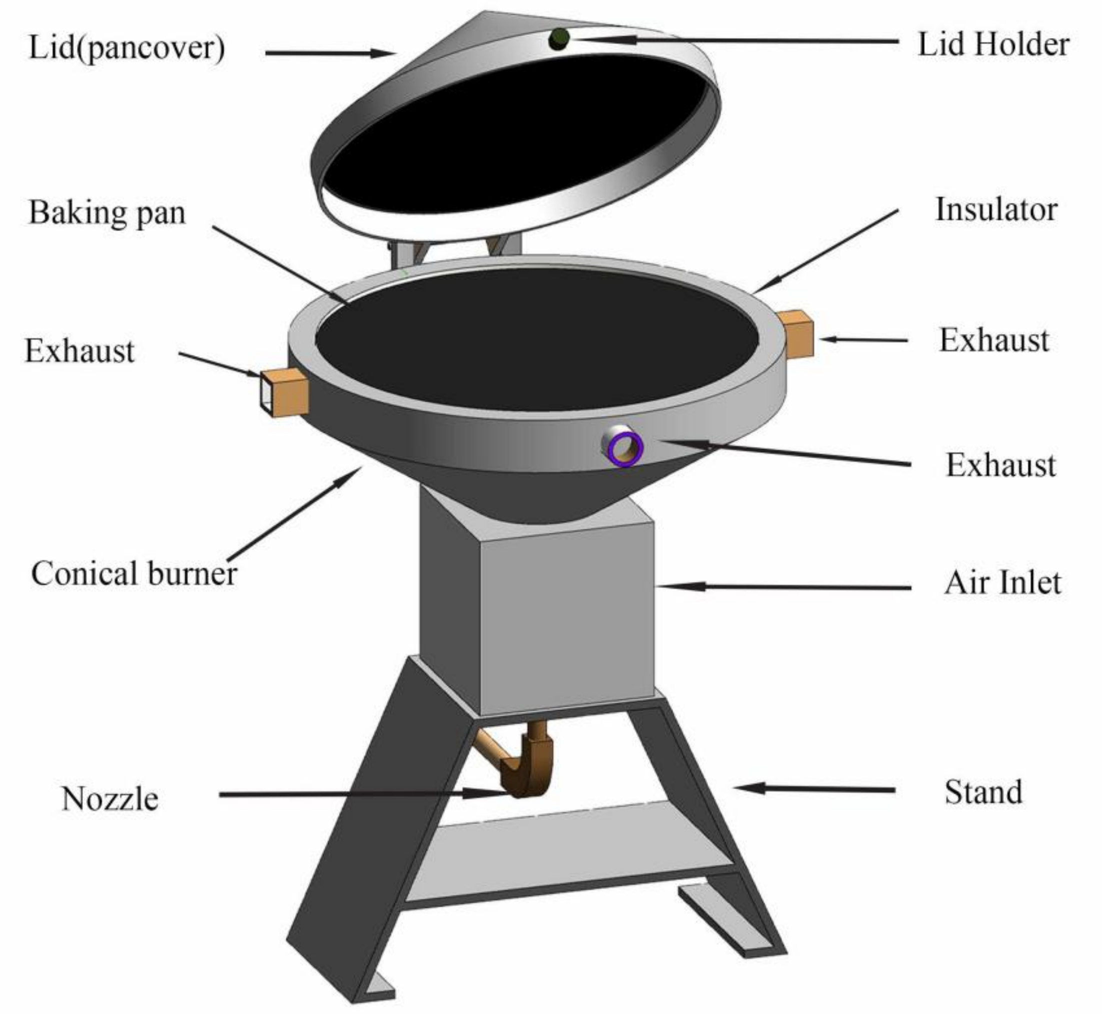

Figure 33. Conical Burner Biogas Injera Baking Stove

3.3 Materials and Instruments

The following materials and instruments were used for the experiments are as follows and depicted in Figure 34.

Digital Weighing Scale: Used to measure the mass of the batter and injera

Thermal Imaging Camera: Used for measuring heat distribution across the baking pan.

Biogas Plant: Provides biogas as the energy source for the stove.

Baking Pan: The surface on which the injera is baked.

Plastic Tank: Used for holding the batter during the baking process.

Sefied: A tool used for removing the injera from the baking pan once it is cooked.

Mild Steel: Material used to construct the stove.

Infrared Thermometer: Used to measure temperature at specific points, typically the surface of the baking pan.

Digital Watch: Used to track the time during the baking process.

Caliper: Used to measure thickness of injera

The instruments used for measuring the temperature were an infrared thermometer for measuring temperature. The sensitive balance was used for measuring the weight of water and fuel and mentioned as follows.

Figure 34.Instrument and material

In this experiment, a fixed dome biogas plant with an 8m³ capacity was utilized as shown in Figure 35. The plant consists of PVC pipes for biogas input and output. The feedstock, cow dung, was collected from a local household and mixed with water to form slurry. The anaerobic digester, an airtight container where bacteria decompose the organic waste, generates biogas and produces liquid slurry as a by-product(18).

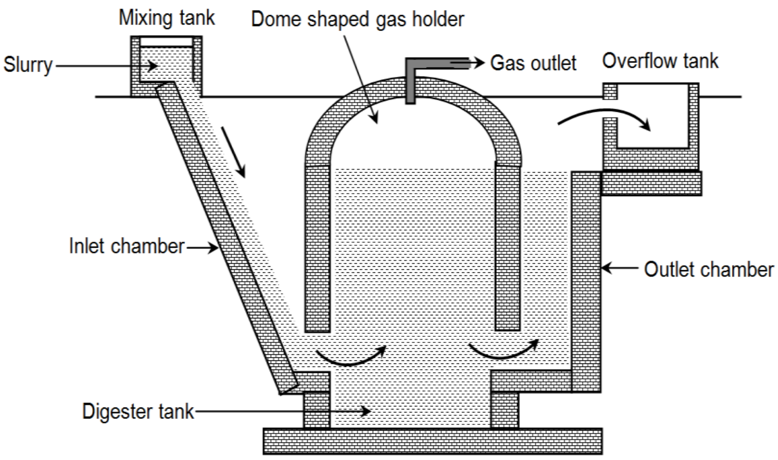

Figure 35. Fixed Dome Biogas Plant

3.4 Design of Biogas Injera Baking Stove

The combustion of gas involves mixing air with fuel gas, igniting the biogas resulting in air-gas mixture. The chemical reaction of combustion of biogas containing 60 % methane and 40 % carbon dioxide and air mixture is shown below(27).

$0.6CH_4+0.4CO_2+1.2O_2+4.5N_2 \rightarrow 0.4CO_2+1.2H_2O+4.5N_2+\text{Energy}$ (20)

Thus, one volume of biogas requires 5.7 volumes of air or the stoichiometric requirement is 1/ (1+5.7) which is 14.9 percent biogas in air.

The force which drives the gas and air into the burner is the pressure of gas in the pipeline. Bernoulli equation is applied in order to determine the fluid velocity from the observed differential pressure ΔPthe knowm density of the fluid. The key equation that relates gas pressure to flow is Bernoulli's theorem (assuming incompressible flow) is as follows(107):

$$P_1 + \frac{1}{2}\rho {v_1}^2 = P_2 + \frac{1}{2}\rho {v_2}^2 \quad (21)$$

Bernoulli's theorem essentially states that for an ideal gas flow, the potential energy due to the pressure, plus the kinetic energy due to the velocity of the flow is constant. In practice, with gas flowing through a pipe, Bernoulli's theorem must be modified. An extra term must be added to allow for energy loss due to friction in the pipe: Using compressible flow theory, an empirical version of Bernoulli's theorem is used to define the flow rate.

$$Q = 0.0467 C_d A_0 \sqrt{\frac{p}{s}}, (116). \quad (22)$$

The size and shape of the injector orifice control the gas flow rate and hence heat input for a given gas composition and supply pressure. d_o is an injector orifice diameter, Q is the flow of biogas through the orifice, s is the specific gravity of biogas which is 0.985, Cd is the coefficient of discharge for the orifice takes into account the vena contractor and friction losses through the orifice. It usually has a value between 0.985 and 0.95 and P is the biogas pressure supply (20).

The amount of power output from a burner, referred to as burner heat release, depends on how much fuel the burner consumes and how much chemical energy the fuel has (heating value), which is referred to as the heating value of the biogas and can be written as follows:

Energy Consumed = $\text{Total amount of Biogas Consumed} * \text{Calorific value}$

To maintain the 14.9% biogas-to-air ratio, the required air flow rate is calculated as follows (117).

$$V_{air} = V_{Biogas} * 5.72 \quad (23)$$

The air inlet size depends on the velocity of air entering the stove. For natural draft systems, a typical air velocity is around 2m/s (107).The cross-sectional area (A) of the air inlet can be calculated using the formula: Assuming a natural draft system with air velocity of 2 m/s, the air inlet cross-sectional area becomes.

$$A = \frac{Q_{air}}{V_{air}} \quad (24)$$

Q_{air}, air flow rate in m³/s,

Vair, Air velocity in m/s

This area is adjusted based on stove design constraints, shaped as a rectangular slot.

The conical burner shape helps in directing heat uniformly toward the baking surface. The relationship is given by

$$tan\,\theta = \frac{R}{H}, \quad (25)$$

R, Radius of the base of the cone.

H,Height of the cone.

Θ, Half-angle of the cone

The pressure drop (ΔP) across the burner to ensure proper biogas flow;

$$\Delta P = {}^{1}\!/_{2}\,\rho v^2 \frac{A_{Pipe}}{A_{nozzle}} \quad (26)$$

ΔP, Pressure drop (in Pa).

ρ, Density of biogas (typically 1.15 kg/m³).

V, Velocity of biogas through the burner (in m/s).

A_{pipe}, Cross-sectional area of the biogas supply pipe (in m²).

A_{burner}, Cross-sectional area of the nozzle (in m²)

3.5 Manufacturing of Biogas Injera Baking Stove

Mild steel is used for manufacturing of stove as it can withstand high-temperature applications, is readily available, and also ensures the robustness of the system, and galvanized mild steel for gas pipe because it has a fair resistance to corrosion(118). This Biogas Injera baking stove is designed and manufactured in Addis Ababa SAM Mechanical Engineering metal workshop using rolling, cutting, drilling, and welding machines, mild steel sheet was used for the construction of the stove as gypsum having thermal conductivity of was used as the insulating material. The upper part of the stove is a conical-shaped combustion chamber where combustion takes place and allows distribution of heat throughout the baking pan. The part of stove such as combustion chamber, inlet air, and stand are assembled by bolt and welding(115).

Injector

The injector orifice is made up of mild brass. The Injector is machined with 2mm diameter hole and length 20mm with angle approach of 45^0 in Figure 36. The amount of gas used by a burner is controlled by the size of the gas "jet" or "injector orifice". This is a brass with a hole drilled in the end, screwed onto the end of the gas line fitting, so that it can be easily replaced. As well as controlling the gas flow rate, the injector an important role of separating the burner from the gas supply.

Figure 36. Injector

Insulation

To minimize heat loss and enhance thermal efficiency, gypsum insulation was applied between the cylindrical wall of the stove body and the side part of the baking pan. A 3 cm thick layer of gypsum was used due to its excellent insulating properties, affordability, and local availability Figure 37. Gypsum acts as a thermal barrier, reducing heat transfer from the combustion chamber to the outer environment and ensuring that more heat is retained and directed toward the baking surface (mitad).

This insulation layer plays a crucial role in maintaining the uniform temperature distribution necessary for producing high-quality injera with consistent texture and appearance. It also prevents excessive surface heat that could lead to safety issues or material degradation of the stove's outer shell. Moreover, using gypsum helps reduce fuel consumption by improving combustion efficiency and decreasing the required input energy to reach and sustain baking temperatures. Proper packing and drying of the gypsum layer are essential to avoid cracking or disintegration over time

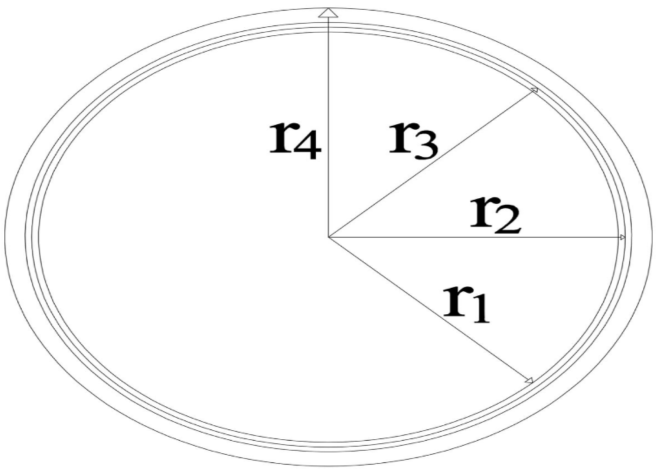

Figure 37. Insulator

Primary Air Inlet

To ensure adequate oxygen supply for efficient biogas combustion, a rectangular primary air inlet was designed with dimensions of 218 mm × 218 mm mild steel sheet metal box. This inlet facilitates the entry of atmospheric air into the combustion chamber, enabling the required air-to-biogas ratio for clean and complete combustion.

A perforated cap is welded to the air inlet opening, serving two essential functions: it acts as an airflow regulator and a protective barrier against excessive high-velocity winds that could disturb the flame direction and stability. This design helps maintain a steady and well-directed flame toward the baking pan (mitad), which is critical for uniform heat distribution and high-quality injera production.

The use of mild steel provides the necessary durability and heat resistance, while the perforated cap ensures a controlled primary air supply, optimizing combustion efficiency and minimizing thermal losses as shown in Figure 38. The inlet's placement and structure also help reduce turbulence around the flame, enhancing the overall performance of the biogas injera baking stove.

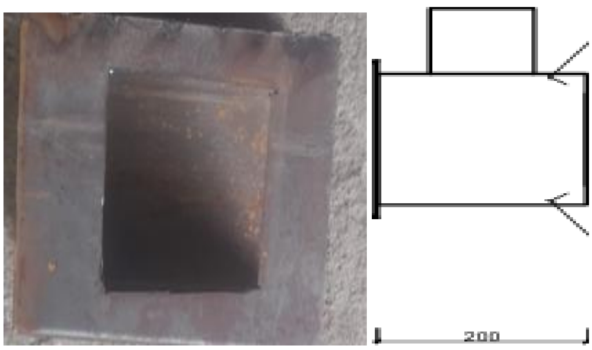

Figure 38. Air Inlet

Combustion Chamber

The combustion chamber is a conical unit specifically designed to ensure optimal mixing and combustion of biogas with the incoming air. This is the core section of the stove where biogas ignition and flame generation occur, providing the primary source of thermal energy for injera baking.

The conical geometry is engineered to concentrate and direct the flame uniformly toward the base of the baking pan (mitad), enhancing heat transfer and promoting even temperature distribution across the surface. The shape also minimizes flame turbulence and improves thermal efficiency.

To facilitate efficient heat circulation and prevent localized overheating, the chamber is equipped with three strategically placed exhaust outlets along the circumference of the baking plate. These outlets allow for the controlled release of combustion gases, ensuring a cleaner burn and helping to stabilize the internal pressure within the chamber.

The design of the combustion chamber—its angle, size, and outlet arrangement—plays a critical role in achieving a consistent baking temperature, reducing fuel consumption, and improving the quality of the injera produced (Figure *39*).

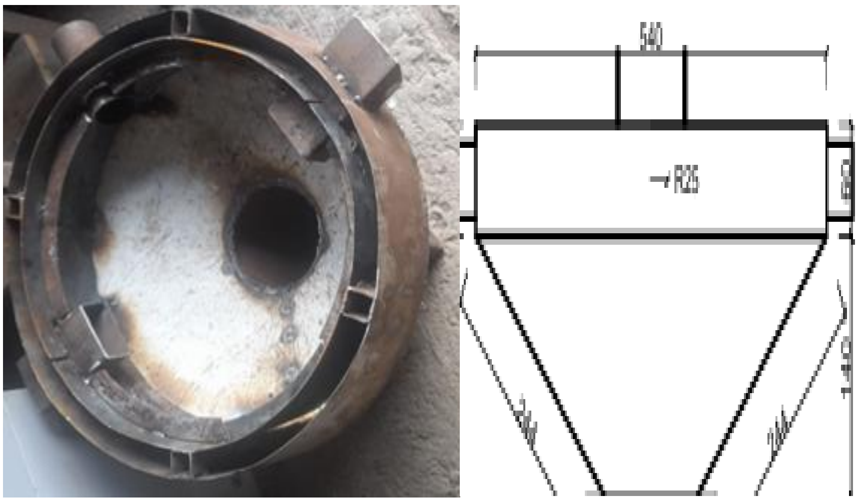

Figure 39.Combusition Chamber

Supply Pipe

The supply pipe serves as the conduit through which biogas travels from the biogas digester to the injera baking stove Figure 40. It plays a critical role in maintaining an adequate and consistent flow of biogas for combustion made of ½-inch (12.7 mm) diameter polyethylene tubing.

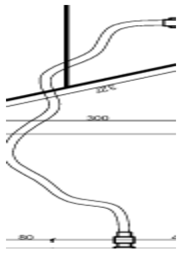

Figure 40. Biogas Supply Pipe

Lid

The lid of the biogas injera baking stove plays a crucial role in heat retention, thermal efficiency, and baking uniformity Figure 41. It is designed to enclose the baking chamber during operation, minimizing heat loss to the surrounding environment and promoting even temperature distribution over the mitad (baking pan).

The lid is typically cylindrical in shape, matching the diameter of the baking pan—45 cm in diameter and 20 cm in height—allowing it to fully cover the cooking surface without obstructing gas flow or flame spread. The vertical height is optimized to trap hot air above the injera surface, thereby improving convective heat transfer and assisting in the even cooking of the top surface of the injera, which is crucial for developing its characteristic texture and "eyes" (gas bubbles).

Constructed from lightweight, heat-resistant sheet metal, the lid ensures durability and portability while reflecting radiant heat downward.

In addition to improving baking efficiency, the lid also serves as a safety and hygiene feature, protecting the injera from dust and airborne contaminants during the cooking process.

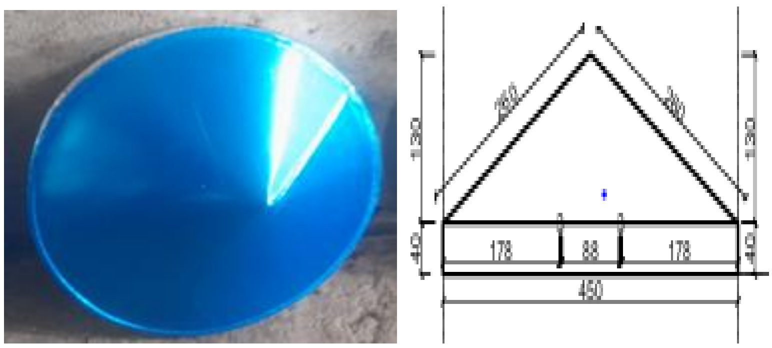

Figure 41. Lid

3.6 Geometry and Thermo-Physical Property of Pan

In developing the improved biogas injera baking stove, special attention was given to the diameter and thickness of the clay baking pan (Mitad), as these dimensions critically influence heat transfer, temperature distribution, and ultimately the quality of the injera. For this study, a clay pan with a diameter of 450 mm and thickness of 15 mm was selected. This size was specifically designed to bake injera with a final diameter of approximately 400 mm, matching typical with biogas pressure Figure 42.

The thermo-physical properties of the clay material used for the baking pan were sourced from literature and are as follows: thermal conductivity (k) = 0.5 W/m·K, specific heat capacity (Cp) = 830 J/kg·K, and density (ρ) = 1900 kg/m³(94,119). These properties play a crucial role in determining the heat retention and transfer efficiency of the baking surface. A well-designed pan with appropriate thickness and Diameter ensures uniform temperature distribution, reduces baking time, and maintains the texture and consistency of the injera.

Figure 42. Clay Baking Pan

3.7 Experimental Setup for Injera Baking Biogas Stove

The experimental setup for evaluating the performance of the biogas injera baking stove was designed using a clay baking pan with 450 mm diameter and 15 mm thickness, integrated with a conical biogas burner. The biogas used was sourced from cow dung-based biogas digesters, including both household-scale and institutional-scale systems. The primary objective of this experimental study was to identify the optimal operating parameters—namely gas pressure, flow rate, temperature distribution, and air-fuel ratio—to ensure high-quality injera baking with improved energy efficiency.

The stove was preheated for 20 minutes to allow the baking pan to reach a stable operating temperature. The performance of the stove was then evaluated under real-world conditions, and the following measurements and instruments were employed in the experimental setup:

- ✓ Gas Pressure Monitoring

  A U-tube manometer were installed at the inlet to measure and control the biogas supply pressure, maintaining a consistent flame.

- ✓ Flow Rate Measurement

  A biogas flow meter was used to measure the volumetric flow rate of biogas in m^3/hr, directly impacting the burner's heat input and efficiency.
- ✓ Temperature Distribution Testing. This arrangement helped in analyzing temperature uniformity, which is critical to ensure evenly cooked injera without overcooked or undercooked spots.
- ✓ Injera Quality Evaluation

The quality of injera baked during the experiment was assessed based on traditional standards such as uniformity and number of "eyes", texture, color, baking time, fermentation aroma, and ease of removal from the pan. This qualitative analysis was vital in correlating heat distribution and stove efficiency with actual food quality.

This experimental setup provided a comprehensive framework for assessing and optimizing the biogas injera baking stove, allowing for improvements in thermal performance, combustion efficiency, and injera quality. The insights gained support the development of biogas-based cooking technologies tailored to local needs in Ethiopia and other developing regions.

3.8 Biogas Injera Baking Stove Functionality and Pressure Test

The Biogas Injera Baking Stove Functionality Test was conducted to determine the optimal operating parameters for the stove, such as pressure, temperature, and gas velocity. This is essential for ensuring uniform heating, fuel efficiency, and high-quality injera production. Several key instruments are used to carry out these tests and measure the necessary parameters.

One of the main instruments used in the test is the water manometer pressure gauge, which is a U-tube partially filled with water. This instrument allows us to measure the pressure difference in the biogas flow to the stove as in Figure 43. The U-tube manometer functions based on the principle that the difference in water levels on both sides of the U-tube is proportional to the pressure difference between the biogas supply pipe and the stove's combustion chamber(107). The difference in water levels in the U-tube represents the pressure difference, and this is used to measure the biogas pressure supplied to the stove. The equation for calculating the pressure difference is as follows.

Figure 43. Testing setup to measure pressure/Calibration

The difference in water height in a liquid-column manometer is proportional to the pressure difference. Supplied biogas Pressure was determined from manometers placed between the digester and the stove. The gas flows from the biogas plant into manometer, which then conducts the gas through a valve regulated pipe to stove. The other end of this manometer is opened to atmospheric air. When the valve is turned-on, there will be a rise in the right and drop in the left of manometers to a certain height in the manometer. P_{Biogas} and P_{atm} represents biogas plant supply pressure and atmospheric pressure respectively.

3.9 Optimization of Biogas Injera Baking Stove

The aim is to minimize biogas consumption while maintaining sufficient thermal energy for injera baking by optimizing: Nozzle diameter (mm), Injection pressure (kPa or mbar) and Biogas flow rate (L/hr).

To optimize the biogas injera baking stove, it is essential to understand how biogas flow rate (Q) depends on nozzle size (d) and supply pressure (p).

$$Q = 0.0467 C_d A_0 \sqrt{\frac{p}{s}}, \qquad (27)$$

The governing formula highlights this interdependence. Increasing the diameter significantly increases the flow rate due to the quadratic relationship. Likewise, higher pressure increases flow rate, but with a square root dependency, meaning the effect is less dramatic than that of diameter. Thus, to achieve efficient combustion and optimal fuel usage, a balance must be struck. Too large a nozzle may waste gas, while too small may result in insufficient heat. The optimization involves selecting a nozzle size and pressure that provide sufficient heat for baking without excessive gas consumption, ideally supported by experimental or simulated data to determine the best combination for minimal consumption and optimal baking performance

3.10 Injera Baking Testing Procedure: Cold Start and Hot Start Phases

To comprehensively evaluate the thermal performance, fuel efficiency, and baking consistency of the biogas injera stove, standardized injera baking tests were conducted under both cold start and hot start conditions. These two distinct phases were designed to simulate realistic cooking scenarios, reflecting the stove's behavior during initial startup as well as continuous, multi-injera baking sessions.

Cold Start Phase

In the cold start phase, both the stove and the baking pan (mitad) were initially at ambient temperature, approximately 23 ± 2°C. The biogas burner was then ignited, and the stove was allowed to heat up until the mitad reached the optimal surface temperature of around 230°C, suitable for injera baking. The time required to reach this target temperature was carefully recorded using a surface thermocouple sensor positioned at the center of the mitad.

Once the baking temperature was attained, the injera batter, mixed with ersho, was poured onto the preheated mitad using a standard ladle of approximately 450 ml, and the injera was baked without a lid. During this phase, key parameters such as preheating time, individual baking time per injera, number and quality of "eyes" (bubbles), uniformity of color and texture, and fuel consumption measured via a biogas flow meter were systematically recorded. The cold start phase primarily evaluates the stove's startup efficiency, the fuel required to reach baking temperature, and the quality of the first injera baked under initial, unheated conditions. This provides a baseline for comparing stove performance during continuous operation, as observed in the subsequent hot start phase.

Hot Start Phase

The hot start phase follows immediately after the cold start phase and simulates a typical multi-injera cooking session, where the stove is already preheated and in continuous use. During this phase, a series of injeras were baked consecutively on the same stove without allowing the system to cool down between batches. The mitad surface temperature was maintained within a range of 206–230°C, ensuring that the heat was sufficient for consistent baking. Injeras were prepared at regular intervals, typically every three minutes, allowing for a steady cooking rhythm that mirrors real household practices.

This phase was critical for evaluating the stove under steady-state conditions, as it provided insights into thermal stability and the consistency of injera quality over multiple baking cycles. By maintaining the stove in continuous operation, it was possible to assess how efficiently the fuel was being utilized and whether the stove could sustain its performance over time. Measurements of standard quality parameters, identical to those used in the cold start phase, were recorded for each injera, providing a comparative basis for evaluating changes in baking uniformity, texture, and browning. Overall, the hot start phase offered a realistic assessment of stove performance during prolonged use, highlighting both the thermal reliability of the system and its potential for fuel-efficient continuous cooking.

Temperature Data Recording and Replication

To ensure the reliability and reproducibility of the injera baking tests, each phase—both cold start and hot start—was repeated three times on separate days under similar environmental and operational conditions. This replication allowed for the assessment of consistency in stove performance and minimized the influence of day-to-day variations in ambient temperature, humidity, or biogas quality.

A stopwatch was employed to accurately record key temporal parameters, including the preheating time, individual baking time per injera, and intervals between successive batches during the hot start phase. Fuel consumption was monitored concurrently using a biogas flow meter, providing precise measurements of biogas utilization during each baking cycle.

Injera quality was evaluated based on visual and structural characteristics, including eye density (the number and distribution of bubbles on the surface), diameter, and overall surface uniformity. These attributes were documented photographically to allow detailed comparison between repetitions and across the cold and hot start phases. Photographic records also facilitated post-experiment analysis and ensured an objective assessment of product quality over multiple baking sessions.

Through systematic replication and careful data recording, the methodology provided robust and reliable information on both the thermal performance of the stove and the quality of injera produced, forming a solid basis for evaluating the stove's efficiency, consistency, and practical applicability in real cooking scenarios.

Table 8 presents the recorded variation of the mitad (baking pan) surface temperature over time during a typical injera baking session, illustrating the different operational phases of the biogas stove. At the start, the pan temperature was at ambient conditions

(21°C), representing the initial cold state of the stove. During the preheating phase, the stove was ignited and the pan temperature rose steadily, reaching 84°C at 5 minutes, 152°C at 10 minutes, and 180°C at 15 minutes.

The baking phase began once the pan reached approximately 230°C, recorded at 20 minutes. During this phase, the temperature remained stable, allowing for consistent injera baking. The table also shows intermittent drops in temperature to around 120°C, representing idle periods when the stove was not actively baking. Subsequent baking cycles resumed at 230°C, demonstrating the stove's ability to recover and maintain high temperatures for repeated injera preparation.

The data provides a clear basis for analyzing both the thermal efficiency and operational consistency of the biogas stove across multiple baking cycles, essential for evaluating its performance in realistic cooking scenarios.

Table 8. Heating Temperature Vs Time

Time (min)	Pan Temperature (°C)	Operational Phase
0	21	Start (ambient)
5	84	Preheating
10	152	Preheating
15	180	Preheating
20	230	Baking Begins
23	230	Baking
26	120	Idle
29	230	Baking
32	230	Baking
35	120	Idle
38	230	Baking
41	230	Baking
44	120	Idle

3.11 Moisture Content Analysis

Moisture content is a critical parameter in evaluating the quality and texture of injera, as it directly affects the batter consistency, baking behavior, and final product characteristics. In this study, the moisture content of the injera batter and the baked product was systematically analyzed to assess water retention during the cooking process and to ensure consistent injera quality across different baking conditions.

The initial moisture content (M_0) of the batter was determined based on the weight of water (W_w) and the weight of flour (W_f) used in the preparation of the dough. These weights were measured precisely using a digital balance. The batter was mixed thoroughly with ersho to achieve a homogeneous consistency before baking. During baking, the weight of the injera was recorded after it was fully cooked, allowing for the determination of water loss and final moisture content.

Table 9 presents the measured weights of the injera batter before baking and the corresponding weight of the baked injera after moisture loss. As shown, the initial batter weight was 580 g, while the final weight of the baked injera was 230g. This substantial reduction in weight indicates significant moisture evaporation during the baking process, which is expected due to the high surface temperature of the pan and the short exposure time. The difference between the two weights reflects the amount of water lost as steam, which plays a vital role in developing the characteristic texture and softness of injera. This observation confirms that a large portion of the batter's water content is removed during baking, leaving behind a spongy, porous structure essential for good-quality injera.

Table 9. Weight of batter and Injera

No.	Weight of batter	Weight of injera
1.	580g	230g

By comparing the initial and final moisture content, the study was able to assess the effectiveness of the stove in maintaining adequate hydration in the injera, which is essential for achieving the desired texture, softness, and "eye" formation. Proper moisture control also influences fuel efficiency, as excessive water evaporation increases energy consumption, while insufficient water content can lead to uneven baking or structural defects.

Overall, moisture content analysis provides a quantitative measure to link stove performance, baking efficiency, and product quality, forming an integral part of the comprehensive evaluation of the biogas injera stove.

M_0 = Initial moisture content and It was calculated as follows(81).

$$M0 = \frac{W_w}{W_w + W_f} \times 100 \quad (28)$$

w_w = Weight of water

W_f= Weight of flour

As the batter bakes, the moisture content M(t) changes as water evaporates. The rate of moisture loss can be modeled using the evaporation equation(120):

$$M(t) = M_o e^{-\alpha(T_{inj}-T_{amb})t} \quad (29)$$

Where:

α = Evaporation constant (depends on batter, airflow, and altitude).

Tinj = Injera surface temperature (°C)

$T_{ambient}$ = Ambient temperature (which varies with altitude)

M_o= Initial Moisture Content

The baking time for injera was calculated using an evaporation-based model incorporating environmental parameters and a crust correction factor Table 10.The fundamental equation for baking time determination is:

$$t = \left(\frac{ln\left(M_o/M_{(t)}\right)}{\alpha(T_{inj}-T_{amb})}\right) \times C \quad (30)$$

t, represents the total baking time (seconds)

M_0, is the initial moisture content of the batter (dimensionless)

M(t), is the target moisture content after baking (dimensionless)

α, denotes the evaporation constant ($s^{-1}°C^{-1}$), adjusted for local conditions

Tinj, is the injera surface temperature during baking (°C)

Tamb, is the ambient temperature (°C)

C,the crust correction factor (dimensionless)

Table 10. Evaporation Constant (α) Adjustment Formulas

Factor	**Formula**
Baseline (Sea Level)	αsea≈0.001 s−1°C (for injera batter)
Altitude (h)	$\alpha_{Alt}=\alpha_{sea}\sqrt{\frac{P_{sea}}{P_{local}}}$, $P_{loc} = P_{sea}e^{-h/1800}$
Humidity (RH)	$\alpha RH = \alpha_{alt}.(1 - RH)$
Airflow	$\alpha_{airflow} = \alpha RH. C$,No fan, C=0.000575
Batter Thickness	$C_{thick} = \frac{1}{1+\frac{k\delta}{D}}$
Porosity (C_{batter})	(dense) to 1.3 (porous)

CHAPTER FOUR

RESULT AND DISCUSION

4.1 Energy Analysis

The performance of baking stove is fundamentally determined by how effectively it converts the chemical energy of fuel into useful heat for cooking. In the case of injera baking, this requirement is particularly demanding, as the process involves heating a large circular pan (mitad) to working temperatures within a short time, while ensuring uniform heat distribution to achieve the desired texture and quality of the product. Traditional biomass stoves often fail to meet these requirements efficiently, resulting in high fuel consumption, low thermal efficiency, and significant heat losses to the surrounding environment.

Biogas offers a cleaner alternative fuel, but its effectiveness depends strongly on the design of the burner and the overall energy balance of the stove. A well-designed biogas injera stove must maximize the proportion of input energy transferred to the pan while minimizing losses through conduction, convection, and radiation. In addition, factors such as insulation, flame characteristics, and combustion air–fuel ratios play crucial roles in determining both efficiency and product quality.

The energy analysis of the biogas injera baking stove with a conical burner is therefore essential for evaluating its thermal performance and identifying pathways for design improvement. By quantifying the heat transferred to the pan, the heat absorbed by the injera batter, and the losses to the stove body, insulation, and surroundings, it becomes possible to establish the stove's overall thermal efficiency. Furthermore, analyzing the relative contributions of conduction, convection, and radiation provides insight into the dominant heat transfer mechanisms and their implications for stove optimization.

This chapter presents a detailed energy analysis of the developed stove. It begins by describing the theoretical background of heat transfer processes relevant to stove operation, followed by the experimental measurements of gas and surface temperatures at different points of the system. Heat loss pathways are quantified, and energy balance equations are applied to determine useful energy, losses, and overall efficiency. The analysis also considers the effect of burner geometry and air–fuel equivalence ratio on flame stability and combustion quality. The outcomes of this chapter provide a foundation for assessing the performance of the conical burner design and guiding future improvements in biogas stove development for efficient and sustainable injera baking.

The baking of injera involves the transfer of energy from the stove to the batter, primarily in the form of thermal energy, which raises the temperature of the dough, initiates water evaporation, and triggers the chemical and physical changes required to form the characteristic texture and “eyes” of injera. Understanding energy transfer is essential for evaluating stove efficiency, optimizing fuel consumption, and ensuring consistent product quality.

4.2 Mechanisms of Heat Transfer in the Injera Baking Pan

According to the second law of thermodynamics, heat naturally flows from regions of higher temperature to those of lower temperature. In the biogas-powered injera baking stove, heat is transferred primarily through three fundamental mechanisms: conduction, convection, and radiation. These mechanisms operate simultaneously to transport thermal energy from the combustion zone to the baking pan and ultimately to the injera batter. Each plays a distinct role in determining the stove's overall thermal efficiency and performance.

4.2.1 Conductive Heat Transfer

Conduction heat transfer is defined as the process of energy transfer from one point in a medium to another due to a temperature difference, without any noticeable movement of the material. This form of heat transfer occurs either within the same medium or across the boundary of a medium into another medium that is in direct contact with the first. It is a key mechanism in cooking applications, such as stove-top cooking, where heat from the gas flame is directly transferred to the bottom of the pan. This heat then propagates through the pan, ultimately reaching the food placed in the pan.

In the context of the biogas injera baking stove, the heat conduction process plays a vital role in transferring thermal energy from the combustion zone to the baking pan, which is used to cook the injera. The equation for heat conduction can be expressed using the following formula, which calculates the rate of heat transfer to the baking pan, also known as heat flux .

$$\dot{Q} = \mathrm{k}\, A \Delta \mathrm{T}/x, \tag{31}$$

Where:

$\dot{Q}$= Rate of heat input to baking pan (W), Heat transfer due to conduction

k= Thermal conductivity of baking pan (W/m.K) ,

x = Pan thickness parallel to heat flow (m),

ΔT= Temperature difference between baking pan upper and lower surface (K),

A= Contact area normal to the direction of heat flow (m^2).

4.2.3 Convective Heat Transfer

Convection aids heat transfer through liquids and gases, which otherwise conduct heat slowly. It involves the constant movement of cold currents of air or liquid toward warmer currents. Because warmer liquids and gases are less dense and rise up while colder liquids and gases are denser and they sink. Heat and mass transfer in fluids occur, almost always, simultaneously with bulk movement of the medium. This system is called convection heat transfer. Convection heat transfer is considered as heat loss (gain) of the system even if in such cases it uses for heat balance of the product.

$$Q_{cov}=Ah\Delta T \qquad (32)$$

Where;

Q_{cov} = Heat transferred by convection, kJ;

h = Convective heat transfer coefficient, W/m^2 K;

A = Surface area of the Material, m^2

ΔT = Temperature differences between material in °C

The movement is caused by heat or mass transfer itself, usually by virtue of density differences is known as natural (free) convention heat transfer. Air in contact with the stove surface is heated, expands, becomes less dense, moves upwards and is replaced by colder, heavier air. Empirical correlations for convection heat and mass transfer for natural (free) convection, which is essentially based on differences in density, hence on thermal expansion of the fluid, the correlations contain the Grashof number (Gr). This dimensionless group contains the term Δρ, the difference in the density of the fluid, which in turn is related to the differences in temperature (ΔT) and the coefficient of thermal expansion, β. The following correlation is often recommended for the calculation of natural convection heat transfer from vertical surface. These temperature measurements were conducted for each of the components such as Injera Baking Pan, Injera Baking Cover and Combustion Chamber Cone. In order to estimate the heat losses from the Injera Baking Biogas Stove the measured surface temperatures and measured/assumed inside gas temperatures were used in the computation (Table 16).

Table 13 presents the measured gas temperatures at critical components of the biogas injera stove during operation. The data highlight the thermal conditions experienced in the stove, which are essential for understanding energy distribution, combustion efficiency, and baking performance.

The injera baking pan exhibited the highest gas temperature, recorded at 400°C, reflecting the direct transfer of heat to the batter and the pan's central role in the baking process. This high temperature ensures rapid and uniform cooking of the injera, facilitating proper "eye" formation and consistent texture.

The injera baking cover recorded a significantly lower temperature of 93°C, indicating that the cover primarily serves as a protective layer, reducing heat loss to the environment rather than directly contributing to energy transfer. Maintaining moderate temperatures at the cover also minimizes the risk of burns during handling and improves safety during operation.

The combustion chamber cone had a temperature of 390°C, which reflects the efficiency of biogas combustion and the energy available for transfer to the baking surface. This temperature demonstrates that a substantial portion of the thermal energy generated by the stove is effectively directed towards the pan, while also highlighting the potential for heat losses through the combustion chamber walls.

Overall, these measurements provide valuable insights into the temperature distribution within the stove, the efficiency of energy transfer from fuel to the cooking surface, and the thermal behavior of stove components during injera baking. Understanding these temperatures is critical for optimizing stove design, improving fuel utilization, and ensuring consistent baking quality.

The surface temperature of different stove components was measured during stable operation to evaluate heat distribution and insulation effectiveness. The results, presented in Table 11, indicate significant variation across components, reflecting both heat transfer characteristics and thermal management efficiency of the stove design.

The highest surface temperature was recorded at the injera baking pan (230 °C), consistent with the requirements for proper injera baking. The combustion chamber also reached a high temperature (225 °C), while the stove cover remained relatively cool (72 °C), demonstrating effective heat containment. The insulation temperature (102 °C) suggests partial heat loss, highlighting areas for potential improvement in thermal management.

Table 11. Measured Out Side Surface Temperature

Component Type	Surface Temperature, ^0C	
Injera Baking Pan	230	
Stove Cover	72	
Insulation	102	
Combustion Chamber	225	

The temperature measurements were conducted for each of the components such as Injera Baking Pan, Injera Baking Cover and Combustion Chamber Cone. The measured surface temperatures and measured/assumed inside gas temperatures were used in the computation . The results in Table 12 show that the highest inside gas temperature was observed at the injera baking pan (400 °C), which corresponds to the required heat flux for proper baking. The combustion chamber cone also exhibited a similarly high gas temperature (390 °C), indicating efficient combustion and heat transfer within the chamber. In contrast, the injera baking cover maintained relatively low gas and surface temperatures (92 °C and 72 °C, respectively), reflecting its limited exposure to direct flames and effective thermal shielding. The insulation surface temperature (102 °C) was considerably lower than the core combustion zones, demonstrating its role in minimizing heat loss and improving overall stove efficiency.

Table 12. Measured Inside Surface Temperature

Component type	Inside Temp,^{0} c	Surface Temperature, ^{0} c
Injera Baking Pan	400	230
Injera Baking Cover	92	72
Combustion Chamber Cone	390	225
Insulation	200	102

4.3 Heat Loss Calculation

For energy consumption analysis additional positions are required, these are from the center tip of the Aluminum lid cover, At the bottom of the baking stove and at the sides of the baking stove. Heat flows from the baking plate to the different stove components and the product injera. Analysis of energy consumption in the biogas injera stove requires a comprehensive understanding of heat losses to various components and the surrounding environment. Heat is transferred not only to the injera during baking but also to the stove structure itself, including the lid, sides, and bottom of the stove. To quantify these losses, temperature measurements were taken at several critical positions: the center tip of the aluminum lid cover, the bottom of the stove, and the sides of the stove. These measurements allow for the calculation of heat flow from the cooking surface to both the product and the stove components.

Heat naturally flows from the baking plate, which is the primary energy source, to the surrounding environment and stove components through conduction, convection, and radiation. Conduction occurs through direct contact between the baking plate and the stove structure, while convection transfers heat to the air around the stove and the inner surfaces of the lid and walls. Radiation from the hot baking plate and stove surfaces contributes further to energy losses to the environment.

Figure 44 illustrates the primary heat flow pathways in the stove. During baking, a portion of the thermal energy generated by the biogas combustion is absorbed by the injera, enabling cooking, while the remaining energy is lost to the stove structure and the surrounding environment. Heat loss at the lid primarily occurs through radiation and convection from the hot aluminum surface, whereas losses at the bottom and sides are mostly due to conduction through the stove walls and convective transfer to the ambient air.

By quantifying these heat losses, it is possible to evaluate the thermal efficiency of the stove, determine where energy is being wasted, and identify opportunities for design improvements. For example, insulating the stove walls or optimizing the lid design could reduce unwanted heat losses, improve energy utilization, and enhance overall fuel efficiency. Such analysis is essential for optimizing stove performance, minimizing fuel consumption, and ensuring consistent and high-quality injera baking under practical operating conditions.

An overall energy balance of the stove can be expressed in terms of the various heat loss mechanisms. Heat losses occur through conduction, convection, and radiation from the stove surfaces, and can be quantified as follows.

Quantifying these losses is essential for evaluating stove performance and identifying areas where improvements can be made. For instance, insulation of the lid or stove walls can reduce both convective and radiative losses, thereby increasing the fraction of energy effectively used in cooking.

4.3.1 Heat loss from baking surface of the baking pan to the lid

During the baking process heat is transferred from the baking surface to the lid and surrounding through convection and radiation, respectively. The transferred heat through convection and radiation is lost heat. To determine the lost energy, it required to know their heat transfer coefficients. Heat transfer across the baking lid cover by free convection to the environment. The heat transfer coefficient from the baking pan surface to the lid cover can be determined by equation below.

For free convection heat transfer the Nusselt number relates the Rayleigh number and other parameters. In addition to that, the Nusselt number is defined as function of Rayleigh number, Prandtl number, geometric shape and boundary condition. The air properties are used at film temperature in order to determine the convective heat transfer coefficient between baking surfaces of the baking pan to the lid .The Nusselt number for horizontal plate and uniform surface temperature for the calculated interval, the recommended correlation for the heated top surface is given as follows(106).The surface heat transfer coefficient is influenced by the composition of the fluid, the nature and geometry of particle surface, and the hydrodynamics of the fluid moving past the surface.

$$h_c = Nu\frac{k}{l} \quad (33)$$

hc – Heat transfer coefficient b/n baking pan and lid

k= thermal conductivity of evaporated water ($W/_{m.K}$)

L – distance from pan to lid cover

N_u= Nusselt number,

For horizontal plate and uniform surface temperature of the baking pan, Nusselt Number is given as follows,

$$N_u = 2+0.6{P_r}^{0.33}{G_r}^{0.25} \quad (34)$$

The recommended correlation for the heated upper surface of baking pan

$$10^5 < R_a < 2\times10^7 N_u=0.54(Ra)^{0.25} \quad (35)$$

$$2\times 10^7 < Ra < 3\times10^7 N_u = 0.14Ra^{1/3} \quad (36)$$

$$Ra = GrPr \quad (37)$$

4.3.2 Heat Transfer Between the Pan and the Stove's Side Wall

Steady heat transfer through multilayered cylindrical is handled as follows. This insulator has a thermal conductivity of 0.3w/m^{2}k. The overall heat transfer coefficient could be simply calculated by using thermal resistance concept: The convective heat transfer (h_D) coefficient and convective heat loss (q_D) for cylindrical shape were calculated.

$$h_D = \frac{Nu_D k}{D} \quad (38)$$

$$Gr = \frac{gB\Delta T(L)^3}{v^2} \quad (39)$$

$$Ra_L = GrPr \quad (40)$$

For vertical plate& heat flows in horizontal direction. Empirical correlation for the average Nusselt number for natural convection over side enclosure was given by eqn.

$$Nu = 0.59\, {Ra_L}^{1/4}\ (10^4 \le Ra_L \le 10^9), \quad (41)$$

$$Nu = 0.1{Ra_L}^{1/3}(10^9 \le Ra_L \le 10^{13}) \quad (42)$$

In the upper section of the stove, heat transfer plays a critical role in determining the overall thermal performance. This region consists of a cylindrical mild steel pan, which is surrounded by layers of insulating gypsum. The radial heat transfer from the combustion chamber to the external environment occurs through a combination of convection, conduction, and insulation resistance mechanisms, as illustrated in Figure 44.

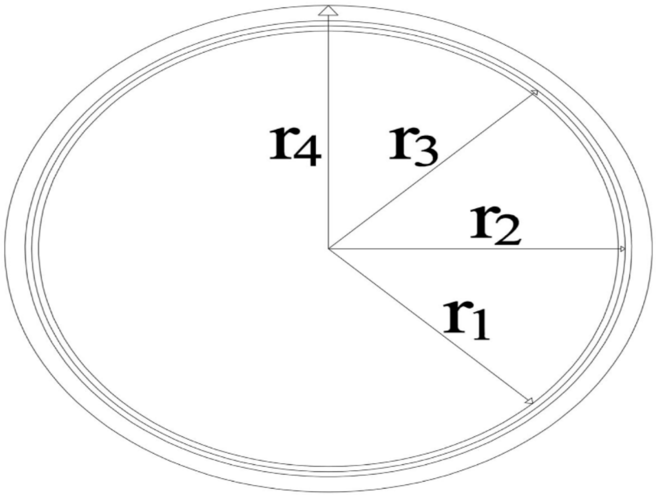

Figure 44. Heat transfer through insulator

Specifically, hot combustion gases transfer heat convectively to the inner surface of the steel wall. This is followed by radial conductive heat transfer through the steel and gypsum insulation layers, and finally, convective heat loss from the outer steel surface to the ambient air. This layered structure leads to a composite heat transfer process, which is critical for minimizing thermal losses and maintaining efficient stove operation.

The radial heat transfer rate through the cylindrical multilayer system can be mathematically expressed as [19,29]:

$$Q_{cyl} = \frac{(T_{hot} - T_{cold})}{\frac{1}{2\pi r_1 L h_i} + \frac{ln\,(\frac{r_2}{r_1})}{2\pi k_s L} + \frac{ln\,(\frac{r_3}{r_2})}{2\pi k_g L} + \frac{ln\,(\frac{r_4}{r_3})}{2\pi k_s L} + \frac{1}{2\pi r_4 L h_o}} \qquad (43)$$

Where

T_{hot} and T_{cold} are the temperatures on the hot and cold sides (°C), respectively;

r_1, r_2, r_3, r_4 are the radial positions corresponding to the interfaces of the different concentric layers;

k_s *and* k_g are the thermal conductivities of steel and gypsum (W/m·K);

h_i *and* h_o are the convective heat transfer coefficients on the inner and outer surfaces (W/m^2·K);

L is the axial length of the cylindrical section (m).This formulation accounts for both conductive and convective resistances across the multilayer wall, offering an accurate representation of radial thermal resistance through the stove body.

4.4 Empirical Correlations for Heat Transfer Coefficients

To accurately estimate the convective heat transfer coefficients in various parts of the biogas injera stove, empirical correlations based on Nusselt number (Nu) were employed (Table 3). These correlations relate the Nusselt number to the Rayleigh number (Ra) and are applicable for natural convection regimes, as observed in the stove system. Following the guidelines in Reference (32). This correlation is suitable for horizontal flat plates subjected to natural convection. By integrating measured temperatures, convective correlations, and heat loss calculations, the study provides a comprehensive understanding of how energy is transferred and lost within the stove system. This analysis supports optimization of stove design, enhances fuel efficiency, and ensures consistent injera quality by maximizing the energy delivered to the baking surface while minimizing losses to the surroundings.

Table 13 summarizes the empirical correlations used to estimate convective heat transfer coefficients for key components of the biogas injera stove. Convective heat transfer plays a significant role in energy losses from the stove, and accurate estimation is essential for evaluating stove efficiency and optimizing design.

The table lists four critical stove components: the combustion cone (bottom), the horizontal baking pan, the pan cover (top cone), and the side insulator or wall. For each component, the characteristic length (Lc) is specified, which is a geometric parameter used in calculating the Rayleigh number (Ra) and, subsequently, the Nusselt number (Nu).

Table 13. Empirical correlation applied to heat transfer

Component	Characteristic Length Lc (m)	Nu Correlation	Ra, Range	Ref.
Combustion Cone (Bottom)	0.20	$Nu=0.59Ra^{1/4}$	$10^5<Ra<10^7$	(118)
Baking Pan (Horizontal)	0.225	$Nu=0.54Ra^{1/4}$	$10^4<Ra<10^9$	(106)
Pan Cover (Top Cone)	0.225	$Nu=0.27Ra^{1/4}$	$10^5<Ra<10^7$	(106)
Side Insulator (Wall)	0.20	$Nu=0.59Ra^{1/4}$	$10^5<Ra<10^7$	(118)

Grashof number (Gr) = $\frac{g\beta(T_s - T_\infty)L^3}{\upsilon^2}$, (44)

$\beta = \frac{1}{T_f}$, $T_f = \frac{T_s + T_\infty}{2}$, (45)

Rayleigh number (Ra) = Gr×Pr, (46)

$h_{conv} = \frac{Nu \times k_m}{L}$, Convective Heat Transfer Coefficient (47)

$h_{rad} = \epsilon\sigma\,(T_s + T_{surr})(T_s{}^2 + T_{surr}{}^2)$, Radiation heat transfer Coefficient (48)

The net radiative heat transfer between two gray, diffuse surfaces with different temperatures and emissivity is described by the generalized Stefan–Boltzmann law (28):

$$Q_{rad} = \frac{\sigma A_{Sur}(T_{s1}{}^4 - T_{s2}{}^4)}{(\frac{1}{\epsilon_{s1}} + \frac{1}{\epsilon_{s2}} - 1)} \quad (49)$$

Where:

Q_{rad}: bet radiative heat transfer (W);

σ: Stefan–Boltzmann constant (5.67 × 10−8 W/m^2K^4);

A_{sur}: surface area through which radiation occurs (m^2);

T_{s1}, T_{s2}: surface temperatures (K);

ε_{s1}, ε_{s2}: Emissivity of surface 1 and surface 2.

Convective Heat Transfer between the Pan, Bottom, Upper, and Side Parts of the Stove.

Convection is the transfer of heat between a stove surface, combustion gases within the stove enclosures, and ambient air.

The convective heat transfer is given by Newton's law of cooling (18):

$$Q_{conv} = h_i A_{sur}.(T_{s1} - T_{s2}) \quad (50)$$

Where:

Q_{conv}: convective heat transfer rate (W);

h_i: convective heat transfer coefficient ($W/m^2 \cdot K$);

A_{sur}: surface area through which convection occurs (m^2);

T_{s1}: temperature of the stove or pan surface (K);

T_{s2}: temperature of the surrounding fluid (K).

4.5 Thermal Efficiency

This section presents a comprehensive evaluation of the optimized biogas injera baking stove, analyzing its thermal performance, operational efficiency, economic viability, and environmental impact. The results are systematically compared with traditional and improved biomass stoves to contextualize the achieved advancements. The experimental evaluation of the biogas-powered injera baking stove demonstrated substantial thermal performance improvements compared to conventional biomass-based stoves. The system achieved a measured thermal efficiency of 33.7%, representing more than a two-fold increase over traditional three-stone stoves, which typically operate at 10–15% (1,43).

This notable improvement was primarily the result of several targeted technical innovations, including conical combustion chamber, 3 cm thick gypsum-based insulation, and optimized air–fuel mixing (44), where the excess air coefficient was maintained, ensuring efficient combustion with minimal heat loss (32,45).

In particular, the conical combustion chamber geometry promoted uniform flame distribution and stable blue flame characteristics, indicative of complete combustion, while the insulation minimized conductive losses to the stove body (46). The integration of these design features enabled the system to reach a thermal efficiency comparable to or exceeding modern improved cookstoves used in other biomass- or gas-based applications (47).

The stove's energy requirement per injera was also significantly reduced. On average, the biogas system required only 700 kJ per injera, compared to 800–1200 kJ typically consumed by firewood-based baking systems such as the Mirt stove or traditional three-stone arrangements (39). This represents an energy reduction of approximately 12% to 40%, further emphasizing the stove's efficiency and sustainability advantages.

In addition to improved fuel utilization, the biogas stove contributes faster baking cycles and enhanced user comfort, making it a compelling clean cooking solution aligned with national clean energy strategies and international climate mitigation frameworks (21).

Thermal efficiency is a critical performance metric for evaluating the effectiveness of a biogas-powered injera baking stove, as it quantifies the proportion of energy extracted from the biogas fuel and converted into useful heat for baking injera(121). In this study, thermal efficiency was evaluated based on both the sensible and latent heat involved in the baking process and the input energy derived from biogas consumption using parameters (Table 4).

$$E_{absorbed} = Q_{sensible} + Q_{latent} = m_{batte} C_p (T_{boil} - T_{room}) + (m_{batter} - m_{injera}) h_{fg} \qquad (51)$$

The energy input to the stove is derived from the chemical energy content of the biogas consumed during the injera baking process. This input energy is calculated based on two primary factors: the volumetric flow rate of the biogas and its lower heating value (LHV) or calorific value, which represents the amount of energy released per unit volume of biogas when combusted completely (34).

Total energy consumed = total biogas consumed × calorific value of biogas.

$$\eta = \frac{\text{Energy Absorbed}}{\text{Total amount of Biogas Consumed} \times \text{Calorific value}} * 100 \quad (52)$$

4.6 Combustion Stoichiometry and Air–Fuel Equivalence Ratio, (λ)

Biogas combustion involves the mixing of air with the fuel gas, followed by ignition of the resulting air–gas mixture. In this study, the biogas used consists of approximately 60% methane (CH_4) and 40% carbon dioxide (CO_2). The chemical reaction governing the combustion process primarily reflects the complete oxidation of methane, as CO_2 is inert in combustion.

To optimize combustion performance, a stoichiometric analysis was performed based on the biogas composition. The theoretical air requirement for complete combustion of methane was calculated, resulting in a stoichiometric air-to-biogas ratio of approximately 5.72 m^3 of air per 1 m^3 of biogas. This value ensures sufficient oxygen for complete combustion of methane, minimizing unburned hydrocarbons and carbon monoxide emissions (10).

Assuming standard ambient conditions, the required air volume was used to calculate the air–fuel equivalence ratio (λ), defined as follows (19):

The air–fuel equivalence ratio, λ (lambda), is defined as the ratio of the actual air–fuel ratio to the stoichiometric air–fuel ratio.

$$\lambda = \frac{\text{Actual Air}-\text{Fuel Ratio}}{\text{Stoichiometric Air}-\text{Fuel Ratio}} \quad (53)$$

The equivalence ratio λ provides insight into combustion efficiency and flame characteristics.

Combustion regimes were classified as follows:

$\lambda = 1$: stoichiometric (ideal, blue flame);

$\lambda < 1$: fuel-rich (incomplete combustion, yellow flame, soot);

$\lambda > 1$: fuel-lean (cool flame, lower efficiency).

Targeting $\lambda \approx 1$ allowed for maximized combustion efficiency and thermal output while minimizing pollutant formation.

$\eta(\lambda) = \eta_0(1-\alpha\ (\lambda - \lambda_{stoich})^2)$ (54)

Where:

η_0 = maximum efficiency at the optimal equivalence ratio λ (dimensionless);

α = correction coefficient accounting for deviation from stoichiometric combustion ($1/\mathrm{Unit}^2$);

λ_{stoich} = stoichiometric equivalence ratio (dimensionless).

The corresponding useful heat output at a given equivalence ratio is

$Q_b(\lambda) = Q_{max}.\eta(\lambda)$ (55)

Where:

Q_b = heat output at a specific λ (kW);

Q_{max} = maximum possible heat release rate (W or kW);

η(λ) = combustion efficiency as a function of λ (dimensionless);

Table 14 presents the key experimental inputs and reference values used for analyzing the thermal performance and energy consumption of the biogas injera stove. These parameters serve as the foundation for calculations related to heat transfer, fuel efficiency, and moisture loss during baking. The biogas pressure and volume flow rate were measured experimentally at 6 kPa and 0.84 m^3/hr, respectively, providing the basis for calculating energy input to the stove. The mass of batter (0.58 kg) and the corresponding mass of baked injera (0.232 kg) were recorded to determine moisture loss during baking, which was found to be 0.348 kg. The specific heat capacity of the batter (3.6 kJ/kg·K) was obtained from literature (19), and it was used to calculate the energy required to heat the batter to baking temperature.

Environmental and physical parameters, including room temperature (21 °C) and boiling temperature of water (93 °C), were considered for accurate energy balance calculations. The latent heat of vaporization of water (2260 kJ/kg) was used to quantify energy consumed in moisture evaporation, while the calorific value of biogas (22,000 kJ/kg) provided a reference for total energy available from fuel (45, 51). Operational parameters were also included: the heat-up time of the stove (20 minutes), the baking time per injera (3 minutes), and the idle time between successive injeras (3 minutes). A total of 15 injeras were baked during the experimental session. These operational data were essential for analyzing the thermal stability of the stove during both cold start and hot start phases, as well as for estimating overall fuel consumption and energy efficiency.

Furthermore, these parameters enable detailed assessment of energy utilization and losses in the stove system. By combining the measured fuel input, stove operational times, and the thermal properties of the batter, it is possible to calculate the energy required to heat and cook each injera as well as the energy lost through heat dissipation to the stove components and ambient environment. This analysis provides insight into how effectively the biogas stove converts fuel energy into useful thermal energy for baking, which is crucial for identifying potential design improvements.

Finally, the experimental and reference values also support the evaluation of injera quality in relation to thermal performance. Parameters such as moisture loss, baking time, and batter mass directly influence the texture, eye formation, and uniformity of the injera. By integrating these inputs into the thermal and energy analysis, the study establishes a clear link between stove operating conditions, energy efficiency, and final product quality, offering a comprehensive understanding of stove performance under practical household cooking scenarios.

The quantification of these energy components relies directly on the experimental inputs and reference values recorded during the study, as summarized in Table 14 Parameters such as the mass of batter (0.58 kg), mass of baked injera (0.232 kg), and moisture mass loss (0.348 kg) provide the physical basis for calculating the heat absorbed by the injera, while the specific heat capacity of the batter (3.6 kJ/kg·K) and the latent heat of vaporization of water (2260 kJ/kg) enable precise determination of the energy required for heating and moisture evaporation.

Environmental and operational measurements, including room temperature (21 °C), boiling temperature of water (93 °C), heat-up time (20 min), baking time per injera (3 min), and idle time between injeras (3 min), were also incorporated into the analysis. These inputs allow for a realistic assessment of how energy is absorbed during both the cold start and hot start phases, reflecting practical cooking conditions. Furthermore, the volumetric flow rate of biogas (0.6m^3/hr) and its calorific value (22,000 kJ/kg) provide the necessary data to determine the total energy input to the stove, forming the basis for calculating thermal efficiency and potential energy savings.

Table 14. Experimental Inputs and Reference Values

Item	Parameters	Reference
Biogas pressure gauge reading (kPa)	6	Experimental
Volume flow rate (m^3/hr)	0.84	Experimental
Mass of Batter (kg)	0.58	Experimental
Mass of Injera (kg)	0.23	Experimental
Moisture mass loss	0.34	Experimental
Specific heat capacity of batter (kJ/kg·K)	3.60	(19)
Room temperature (°C)	21	Experimental
Boiling temperature of water (°C)	93	(45)
Latent heat of vaporization of water (kJ/kg)	2260	(51)
Calorific value of biogas (kJ/kg)	22,000	(45)
Heat-up time	20 min	Experimental
Baking time to bake 1 injera	3 min	Experimental
Idle time between injeras	3 min	Experimental
Total number of injera baked	15	Experimental

The heat transfer processes within the biogas injera stove were analyzed by considering the combined effects of conduction, convection, and radiation. To estimate the total thermal energy required for injera baking, a comprehensive energy balance was developed. This model accounts for the sensible heat needed to raise the batter temperature, the latent heat required to evaporate moisture, and heat losses due to system inefficiencies. The total energy demand Q can be expressed as

$$Q = m_{batter}\ C_p\ (T_{boil} - T_{room}) + (m_{evap} h_{fg}) + Q_{loss} \tag{56}$$

Where:

Q = total heat energy required (J);

m_{batter} = mass of batter (kg);

C_p = specific heat capacity of the batter (J/kg·K);

T_{boil} = boiling temp of water (K);

T_{room} = room temp (K);

h_{fg} = latent heat of evaporation of water (J/kg);

Q_{loss} = heat lost to surroundings due to inefficiency (J);

m_{evap} = mass of water evaporated (kg)

The primary structural components contributing to heat loss in the biogas injera stove include the aluminum pan cover, bottom surface, and side walls of the stove body. Heat is transferred away from the main baking surface (the pan) to both the surrounding environment and the baked product (injera), resulting in energy losses that reduce overall system efficiency.

As illustrated in Figure 45, heat transfer occurs predominantly through radiation and convection, which are the dominant mechanisms influencing thermal losses in this setup. The total heat loss Q_{loss} from the stove system was estimated by summing radiative and convective heat fluxes from the stove's external surfaces—specifically the top, bottom, and lateral areas. The overall heat loss can be expressed using the following equation derived from classical heat transfer theory (27):

Total heat loss (Q_{loss}) was calculated as the sum of radiative (Q_{rad}) and convective (Q_{conv}) losses from each region:

$$Q_{loss} = \sum(Q_{rad,top} + Q_{conv,top}) + (Q_{rad,bottom} + Q_{conv,bottom}) + (Q_{rad,side} + Q_{Conv,side} \quad (57)$$

Thermal energy losses were evaluated via radiation and convection from three critical regions as shown in Figure 45.

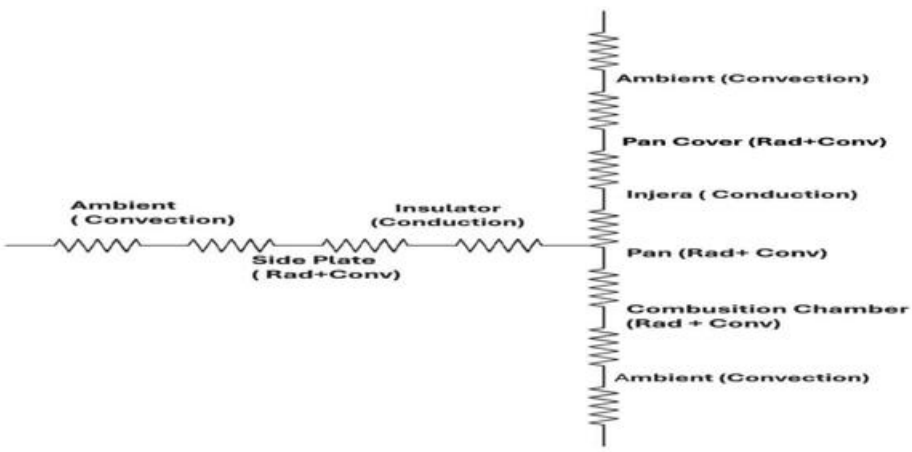

Figure 45. Heat Transfer Flow

Top: Baking pan → aluminum cover → ambient

Bottom: Baking pan → combustion cone → ambient.

Side: Pan/cone → gypsum insulation → ambient.

The energy input to the stove is derived from the chemical energy content of the biogas consumed during the injera baking process. This input energy is calculated based on two primary factors: the volumetric flow rate of the biogas and its lower heating value (LHV) or calorific value, which represents the amount of energy released per unit volume of biogas when combusted completely (34).

Total energy consumed = total biogas consumed × calorific value of biogas.

$$\eta = \frac{\text{Energy Absorbed}}{\text{Total amount of Biogas Consumed} \times \text{Calorific value}} * 100 \qquad (58)$$

4.7 Energy Savings Analysis: Input Parameters

The energy savings achieved by transitioning from a traditional wood-burning stove to a biogas stove for injera baking were quantified by comparing the energy consumption of both systems under standardized testing conditions, as presented in Table 15. Energy Saving Calculation input parameter (35,36). Energy recovery from organic waste can be significantly increased through process optimization, including controlled operating conditions (37). To estimate this, the energy savings (ESs) were calculated as the difference between the energy required for wood combustion and that required for biogas, using the following relationship:

Table 15 presents the parameters used for calculating energy savings achieved by replacing traditional biomass stoves with the optimized biogas stove. The comparison includes thermal efficiency, fuel consumption, energy content, and annual injera consumption at both household and national levels. It summarizes the parameters used in the energy savings calculations for both traditional biomass and biogas stoves. The table includes key inputs such as thermal efficiency, annual injera consumption, specific fuel consumption, energy content, and fuel unit costs. It also presents per capita and per household injera consumption, as well as national biogas adoption targets. References for each parameter are provided to indicate the source of the data or the basis for calculations, including experimental measurements, literature values, and calculated estimates.

Table 15. Energy Saving Calculation input parameter

Parameter	Biomass Stove	Biogas Stove	Ref.
Thermal efficiency	15%	33.7%	(38)
Annual injera consumption	7.375 bil.kg	7.375 bil.kg	(21)
Specific fuel consumption	0.535 kg/kg injera	0.244 m^3/kg injera	(39)
Energy content	15 MJ/kg	22MJ/m^3	(38)
Injera consumption /person/year	295 kg	295 kg	(21)
Injera consumption per/year	1475 kg	-	-
National biogas adoption	–	5,000,000 households	
Fuel unit cost	0.25 USD/kg	0.05 USD/m^3	(36)

$$Energy_{Saving} = Energy_{Biogas} - Energy_{Wood} \quad (59)$$

$Energy_{saving}$: energy saving from using Biogas Stove (MJ);

$Energy_{Wood}$: energy required using traditional biomass (wood);

$Energy_{Biogas}$: energy required using biogas Fuel.

4.8 Flame Color and Combustion Quality

The color of the flame serves as a visual diagnostic for combustion efficiency and completeness(104). As illustrated in Figure 46, the optimized biogas stove was designed to maintain a stable blue flame, signifying high combustion efficiency and effective thermal transfer to the baking surface. This feature not only improves overall energy utilization but also reduces indoor air pollution and enhances the quality of the injera. Visual flame assessment therefore serves as a practical and immediate indicator of combustion quality in household energy systems. A blue flame typically indicates complete combustion, characterized by optimal air-fuel mixing and a high-temperature, clean-burning reaction that results in the efficient conversion of fuel to heat energy. This combustion state also ensures lower emissions of unburned hydrocarbons. In contrast, a yellow or orange flame is a sign of incomplete combustion, often caused by a deficiency in oxygen supply or poor mixing, which results in the formation of soot and other pollutants.

Figure 46.Flame Color

4.9 **Heat Loss Characteristics**

Accurate evaluation of heat loss pathways in biogas-powered injera baking stoves is essential for improving overall system efficiency. Based on analytical calculations, the heat losses during each baking cycle were estimated from various stove surfaces: 4.2 MJ from the sides, 5 MJ from the bottom, 6.3 MJ from the pan surface, and 3 MJ from the top, as illustrated in Figure 47. These values correspond to 17.4% heat loss through the bottom, 17% through the sides, 14.48% through the pan, and 10.34% through the top, relative to a total input energy of 29 MJ required to bake 15 injera.

These findings align with earlier studies indicating that uninsulated or poorly shielded stove components can result in substantial thermal losses, especially from the bottom and lateral walls, which are in continuous contact with ambient air or poorly conductive materials (9). Moreover, radiative and convective heat loss from the pan and top surfaces contributes to overall inefficiency if not properly mitigated through insulation or heat recirculation designs. Hence, addressing these thermal loss points is critical for improving the energy performance and fuel economy of the stove.

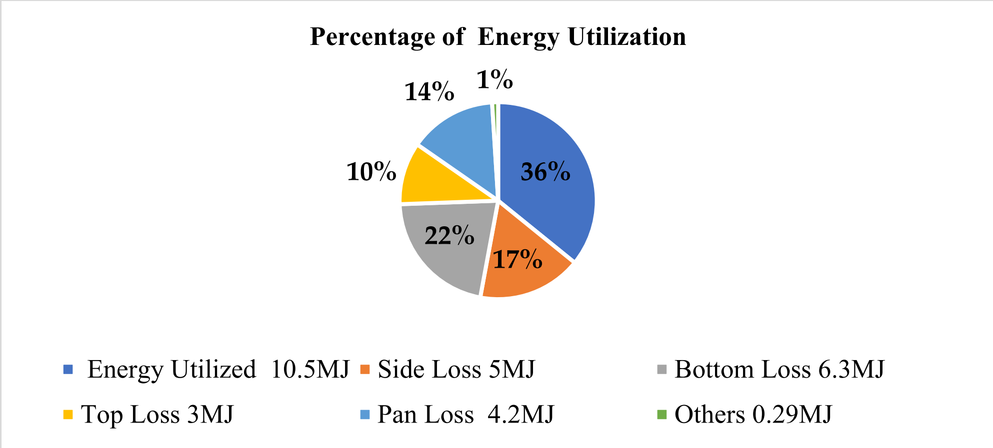

Figure 47. Percentage of Heat Loss

4.10 Temperature Profile During Stove Operation

This improved uniformity, attributed to the conical combustion flame geometry of the optimized burner as shown in Figure 48, ensures even thermal exposure a critical factor for achieving high-quality injera structure and texture. The enhanced heat transfer and minimized temperature gradients not only improve injera consistency but also reduce the risk of undercooked or scorched sections, commonly seen in traditional stoves (47).

Figure 48. Conical Combustion Flame pattern

The temperature profile observed during the operation of the biogas injera baking stove reveals three distinct thermal phases: preheating, active baking, and idle. As shown in Figure 8a, the preheating phase is characterized by a gradual increase in surface temperature from ambient conditions (21°C) to the target baking temperature of 230 °C within 20 min. This rapid thermal response highlights efficient biogas combustion and effective heat transfer between the burner and the pan surface (44). Achieving baking temperature quickly is a key indicator of low energy loss and strong thermal coupling (29).

In the active baking phase, the pan temperature stabilizes around 230 °C with minimal fluctuation. Such thermal stability indicates a consistent combustion process and uniform heat output, both of which are crucial for producing injera with even texture and well-distributed eyelets (2). Maintaining this steady temperature minimizes batch-to-batch variations, which is essential for household acceptability.

During the idle phase, a gradual temperature decline is observed. However, the pan surface remains above 120 °C for an extended period, enabling subsequent baking without the need for complete reheating—thereby reducing biogas consumption (40). This heat retention reflects the stove's high thermal inertia and efficient insulation, both of which enhance energy efficiency and user convenience (49).

Overall, the thermal behavior across the three phases—rapid preheating, stable baking, and extended heat retention—demonstrates the stove's strong energy performance and its practical suitability for continuous injera baking in domestic settings (50). Thermal imaging further confirmed uniform heat distribution across the entire 45 cm clay pan surface, with temperature variations consistently kept within 25 °C—a notable improvement compared to the 55 °C differentials observed in earlier stove models (11). The temperature variation of only 25 °C across the pan surface is significantly lower than the 55 °C variation observed in previous biogas injera baking stoves (11), reflecting the benefits of improved burner design and pan contact efficiency. Such thermal consistency enhances not only product quality—resulting in uniformly browned, evenly cooked injera—but also contributes to energy savings, as less heat is wasted or unevenly distributed (51).

Moreover, the stable thermal profile reduces the likelihood of undercooked or burnt sections, which often occur with irregular heat zones in traditional setups. These improvements confirm that targeted burner geometry and improved heat transfer mechanisms can significantly elevate both the efficiency and performance of injera baking stove (47).

When compared with prior investigations on biogas-fueled injera stoves, the system developed in this study exhibits marked improvements in thermal and operational performance. Chala (93)reported an initial heating time of 25 min, a baking duration of 4 min per injera, and a reheating interval of 4 min. In contrast, the optimized stove presented in this study achieved a reduced initial heating time of 20 min, a baking time of 3 min, and a reheating duration of 3 min. These enhancements underscore the improved thermal responsiveness and efficiency of the system, primarily resulting from

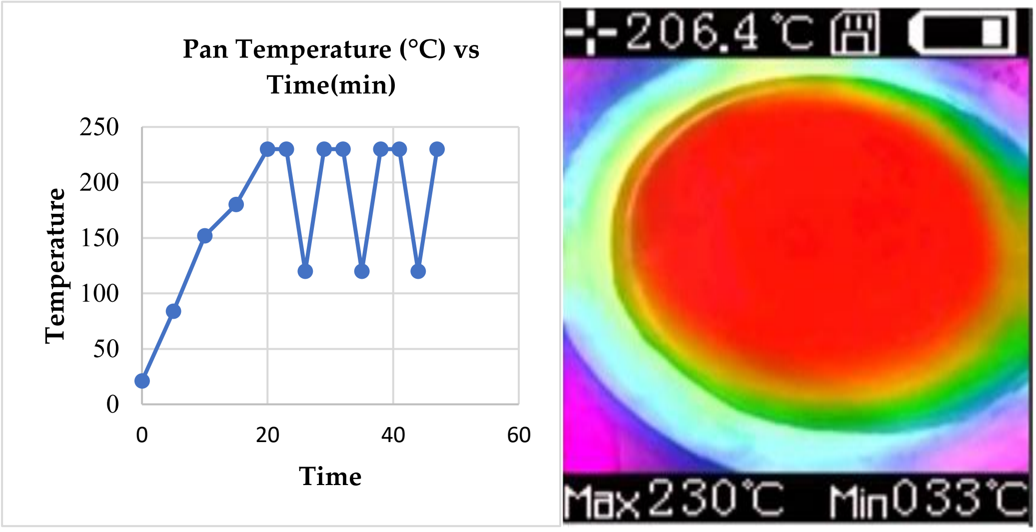

Figure 49. a) Surface temperature profile over time b) Thermal imaging

advancements in burner geometry, combustion control, and heat retention capabilities. When comparing the current biogas stove's performance with that of previous studies, several notable improvements were observed. The initial heating time in this study was reduced to 20 minutes, compared to 25 minutes. Additionally, the baking time for each injera was reduced to 3 minutes, compared to 4 minutes in the earlier study. The reheat time was also shorter, dropping from 4 minutes to 3minutes, thus improving the stove's overall efficiency(93).

These findings suggest that improvements in stove design, such as better heat distribution and faster heating, have contributed to the enhanced performance observed in this study. Furthermore, the lower energy consumption and faster baking times are likely to lead to higher productivity and lower operating costs, making biogas stoves a more viable option for household injera baking.

4.11 Energy Saving Benefits

The analysis reveals a substantial energy saving when transitioning from traditional biomass (wood-fired) stoves to biogas-powered stoves for injera baking in rural Ethiopia. For a population of 5 million households consuming a total of 7.375 billion kilograms of injera annually, the traditional wood-fired stoves require approximately 3.944 billion kilograms of wood, equating to a total energy consumption of 59,160 (TJ). In contrast, the same demand can be met using 1.800 billion cubic meters of biogas, which corresponds to only 33.7 billion MJ of energy. This translates to a net energy saving of 23,160 TJ per year, or roughly 6.43 TWh. These savings stem from the higher combustion efficiency and better heat transfer characteristics of biogas stoves, as well as the absence of energy losses associated with moisture content in firewood. The 39% reduction in energy use not only underscores the superior thermal performance of biogas stoves but also indicates their potential to significantly lower the national energy burden associated with household cooking. Furthermore, this improvement in energy efficiency directly supports climate goals, resource conservation, and household energy resilience in off-grid rural areas.

4.12 Injera Baking Process and Product Quality

Environmental conditions—particularly ambient temperature, relative humidity, and altitude—significantly affect moisture loss during injera baking and influence final product quality (24,33). As ambient temperature rises, air holds more water vapor, accelerating moisture evaporation from the batter (40,51). Moderate heat improves drying efficiency, but excessive temperatures can lead to over-drying, surface cracking, and a loss of the desired soft and spongy texture. Careful thermal management is therefore essential to retain moisture without underbaking (24). Relative humidity influences the evaporation gradient. Low humidity accelerates moisture loss, potentially producing injera that is dry and brittle. In contrast, high humidity slows moisture removal, yielding a softer texture but increasing the risk of stickiness or underbaking unless heat input or baking duration is adjusted. Combined, high temperature and low humidity maximize moisture loss but often degrade softness and structural integrity. Conversely, lower temperatures with high humidity retain moisture but can result in incomplete baking. These findings emphasize the importance of environmentally adaptive baking strategies.

The optimized biogas injera stove consistently delivered high-quality baking outcomes, producing injera with uniform thickness (2.0 ± 0.2 mm), porosity of 15–17 pores/in^2, and excellent flexibility, allowing the bread to be folded 180° without cracking (Figure 9). This quality attributes conform to established cultural and culinary standards across Ethiopia and the Horn of Africa (53).

The symmetrical conical burner design enabled uniform heat distribution, which enhanced the formation of the distinctive “eyes” (fermentation pores) and produced even surface browning. Shelf-life assessments indicated that injera baked on the biogas stove remained fresh and palatable for up to 72 h, matching or exceeding the quality of injera made on traditional biomass stoves (54).

(a) (b) (c)

Figure 50. Sequential stages of the injera baking process

(a) cleaning the pan surface to maintain hygiene and prepare for batter application preheating the baking pan (mitad) to ensure uniform heat distribution and preheating the pan , (b) pouring the batter on the pan (c) the final baked injera showing uniform texture and well-developed fermentation "eyes," indicating high-quality baking performance.

4.13 Effect of Baking Pan size on Performance of Stove

The other parameters that were considered in developing the improved Biogas Injera backing stove was the effect of pan size (diameter and thickness of baking pan/Mitad). The Clay baking pan was manufactured with 450mm diameter for this specific work. The 'Mitad' with 15 mm thickness was selected in this particular work. Clay has the properties of retaining heat for a long time.

One important factor contributing to the overall thermal efficiency of the biogas Injera baking stove is the optimization of the baking pan thickness. During the experiment, different thicknesses of the baking pan were tested to determine how the material's thickness affects heat retention and distribution. Optimization of baking pan thickness leads to several key improvements in stove efficiency:

A thinner baking pan improves the heat transfer rate from the burner to the pan. As the pan absorbs heat faster, it allows for a more even distribution of heat across the baking surface, which directly improves the quality of Injera by preventing undercooking or overcooking of parts of the Injera (122).

With an optimized thickness, the pan can heat up more quickly, thus reducing baking time. The shorter cooking time reduces the overall energy consumption, making the process more energy-efficient. This study found that thinner baking pans (15 mm) and smaller diameters (450 mm) reduced cooking time by 20%. The researchers attributed these improvements to the enhanced heat transfer and reduced heat loss associated with thinner and smaller pans (119). By reducing biogas consumption, the optimized baking pan contributes to the sustainability of the cooking process. Lower fuel usage not only reduces costs but also minimizes the environmental impact of biogas production and use, supporting broader sustainability goals.

This study investigated the impact of baking pan thickness and diameter on the performance of biogas injera stoves. The results showed that thinner pan 15 mm thickness and smaller diameters (450 mm) achieved faster heating and more uniform heat distribution compared to thicker or larger pans. The study concluded that optimizing pan thickness and diameter is essential for improving stove efficiency and reducing energy consumption (110). The optimization of baking pan thickness from 20 mm to 15 mm and diameter to 450 mm directly correlates with a reduction in fuel consumption(123). A thinner and smaller pan requires less energy to heat up and maintain the desired temperature, leading to significant energy savings. This is particularly important in resource-constrained settings, where fuel costs and availability are critical concerns (75).

The time required to heat baking pan to its working temperature and temperature measured by infrared thermometer was indicated in (Table3). The results of this study demonstrate that the optimal baking time for injera to achieve the desired texture and quality is 3min, with an idle time of 3min between successive baking cycles with initial heating time of 20 min. This finding aligns with the hypothesis that shorter baking times and adequate reheat intervals are critical for maintaining injera quality.

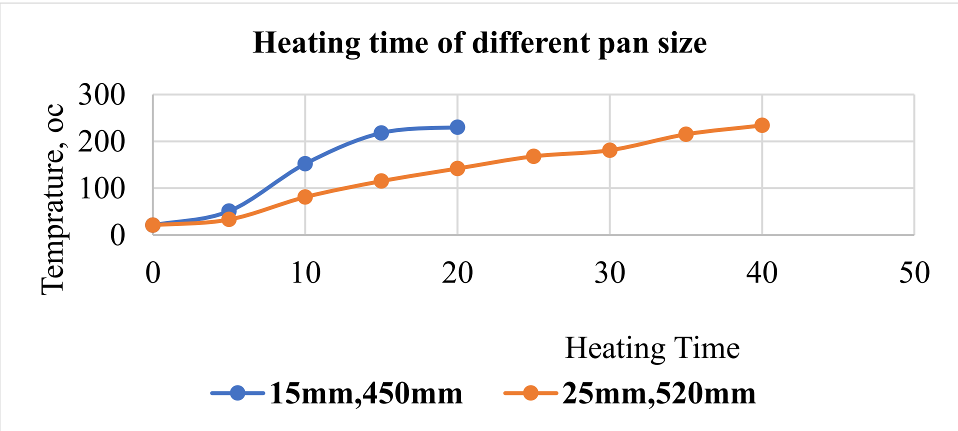

Figure 51. Heating time Vs Baking pan thickness

The thermal performance of the injera baking pan plays a pivotal role in determining the efficiency and overall productivity of the biogas stove system. This study highlights the significant influence of pan thickness (x) on heat conduction, which directly affects both the rate of heat input (Q) and the baking time.

From the theoretical model based on Fourier's law of heat conduction, it is evident that heat transfer rate is inversely proportional to the pan thickness. As the pan becomes thicker, thermal resistance increases, which limits the amount of heat transferred to the upper surface in a given time. This reduction in heat input delays the attainment of the optimum surface temperature required for baking injera, leading to longer baking durations as shown in Figure 51.

The plotted results show a steep decline with even modest increases in pan thickness. For instance, doubling the pan thickness from 2 mm to 4 mm results in a 50% reduction in the heat transfer rate, and this effect continues nonlinearly. This inverse relationship between thermal response and pan thickness suggests that thinner pans can substantially enhance thermal performance by facilitating faster and more consistent heating of the batter.

4.14 Comparative Performance

This study analyzed the effects of reducing baking pan dimensions—thickness from 25 mm to 15 mm and diameter from 520 mm to 450 mm—on heat consumption, baking time, and idle time. Experimental data confirms that the reduced pan heats 50% faster, and decreases idle time between batches Table 16. Recommendations for material improvements are provided to balance efficiency and heat retention. Reducing pan thickness and diameter significantly improves thermal efficiency, baking speed, and energy savings, making it ideal for commercial bakeries. Further refinements in material science can enhance heat retention, making this optimization a cost-effective upgrade for traditional and industrial baking applications.

Table 16. Performance metrics

Metric	Optimized Pan	Original Pan	Improvement
Heating time (min)	20	25	50% faster
Energy Consumption	Lower	Higher	Significant savings
Idle Time	Reduced	Longer	More efficient workflow

Table 17 summarizes the key results of the improved biogas-powered injera baking stove. It highlights that the overall achievement of the study was the development of a high-performance stove with a thermal efficiency of 33.7%, which is significantly higher than traditional and earlier biogas stove models. The design innovation includes a 45° conical burner and an optimized 45 cm, 15 mm thick clay pan, improving air–biogas mixing and ensuring uniform heat distribution for better combustion.

In the heat transfer and baking performance category, the optimized pan thickness enhanced heat transfer and minimized temperature variation across the pan surface to within 25°C, ensuring uniform baking. The baking time and energy use section shows that the stove required 706 kJ per injera and could bake 15 injeras in 110 minutes, including preheating, with a 25% reduction in total baking time. Finally, the combustion quality result indicates that a stable blue flame was achieved, demonstrating efficient and clean combustion with near-complete methane oxidation.

Table 17. Summary of Key Result

Category	Key Result Summary
Overall Achievement	Developed and optimized an improved biogas-powered injera baking stove with a thermal efficiency of 33.7%,
Design Innovation	Integration of a 45° conical burner and optimized 45 cm, 15 mm thick clay baking pan, ensuring better air–biogas mixing, uniform heat distribution, and complete combustion.
Baking Performance	15 mm pan thickness improved reduced baking time; uniform heat distribution (≤25°C variation) achieved across the pan surface.
Baking Time	Total baking time 110 min for 15 injeras (20 min preheating).
Combustion Quality	Stable blue flame with near-complete methane combustion observed, indicating efficient and clean operation

4.15 Survey Outcomes and User Feedback

The stakeholders/users confirmed their satisfaction with baking injera using biogas. Previously, biogas had only been used for cooking sauces and boiling water. However, after the implementation of this research and the application of biogas for injera baking, users expressed confidence in the quality of the produced injera. They reported that the texture, appearance, and overall acceptability met their expectations. Furthermore, they recommended increasing the size of the injera in future applications to enhance productivity and meet higher demand.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The biogas injera baking stove developed in this study demonstrates significant improvements in thermal efficiency, heat distribution, and combustion performance compared to traditional and improved biomass stoves. With a thermal efficiency of 33.7%, the stove outperforms the traditional three-stone fire, which has an efficiency of only 14%, and previous biogas stoves, which typically achieve efficiencies between 15% and 20%. This improvement is attributed to the optimized design of the conical burner, which ensures better air-biogas mixing, uniform heat distribution, and complete combustion, as evidenced by the stable blue flame observed during operation. The study also highlights the importance of optimizing baking pan thickness and diameter. A 15 mm thick baking pan with a 450 mm diameter improves heat transfer, reduces baking time, and enhances energy efficiency. These design improvements, combined with the conical burner, contribute to the stove's overall performance and sustainability.

The designed stove resolves the heat distribution problem of the baking pan and a full-size injera of 40cm in diameter was baked successfully. The baked injera is good in texture and removed from the baking pan surface easily (without sticking on the/ baking pan). However, the study identifies areas for further improvement, particularly in reducing heat losses. The breakdown of heat losses across stove components reveals that the bottom part of the stove (7.7%) and the cover side enclosure (15%) are the primary sources of energy loss due to inadequate insulation. Addressing these inefficiencies through better insulation and design optimization could further enhance the stove's thermal efficiency and reduce fuel consumption.

The biogas stove was designed, manufactured and its performance evaluated using a institutional and household fixed dome type biogas plant.The study showed the improvement in design of burner and selection of efficient baking pan enabled biogas application for Injera baking applications. Thus, Biogas technology can improve the lives of millions of people living in rural societies and meet efforts to combat climate change and meet sustainable development goal (SDG7). The designed stove enables uniform heat distribution to the baking pan. The biogas injera stove offers a cleaner alternative to traditional firewood, requiring 706 kJ per injera with a total baking time of 110 minutes for 15 injeras, including a 20-minute preheating period. While more efficient than firewood (~33.7% vs. 5–17%), it still suffers from heat loss during idle periods. In contrast, the traditional firewood mitad is slower (21–25 min preheating) and less energy-efficient (800–1,200 kJ per injera).

This dissertation presents a comprehensive investigation into the development, optimization, and evaluation of an improved biogas-powered injera baking stove system using conical burner. Through systematic experimentation and analysis, this research has yielded improved injera baking for Ethiopia's culturally essential injera preparation. The study's multifaceted approach encompassed thermal performance assessment, combustion optimization and culminating in a holistic understanding of biogas stove technology for injera baking applications.

Technical Innovations and Performance Enhancements

The core achievement of this research lies in the development of an optimized stove system that integrates several key technical innovations. The 45 cm diameter clay baking pan with 15 mm thickness represents a new design. This configuration was determined through extensive heat transfer modeling and empirical testing, demonstrating optimal balance between thermal conductivity and heat retention capacity. The reduced thermal mass of the thinner pan decreased the energy required for initial heating while maintaining sufficient thermal inertia for consistent baking performance.

The conical burner geometry was specifically designed to complement the pan dimensions, creating a synergistic system that maximizes flame contact area while minimizing heat loss. The stable blue flame combustion observed in experimental trials. This combustion quality, achieving near-complete methane conversion(104).

Operational Performance and User Benefits

The optimized system demonstrated substantial improvements in practical baking metrics that directly benefit end-users. The baking cycle time reduction to 3 minutes per injera, coupled with the 20-minute preheating period, represents a 25% decrease in total baking time compared to previous study(93). These time savings translate directly to improved quality of life for users, particularly women who bear the primary responsibility for food preparation in Ethiopian households.

Temperature uniformity across the baking surface (25°C) was achieved, a significant improvement over the 55°C variations observed in previous designs(12). This enhanced temperature control produced injera with consistent quality parameters: uniform thickness (2.0 ± 0.2 mm), optimal porosity (15-17 pores/in^2), and excellent flexibility (180° foldability without cracking) - all critical attributes for cultural acceptability.

Energy Implications

The system's energy efficiency gains are particularly noteworthy. When scaled to Ethiopia's national level, with approximately 5 million households adopting this technology, the potential energy savings amount to 23,160 TJ annually - equivalent to 6.43 TWh of energy.

Material Science and Heat Transfer Optimization

The research provides important insights into material selection and geometry optimization for baking applications. The clay baking pan's performance was systematically evaluated across multiple thicknesses and diameters, with the 15mm/45cm configuration emerging as optimal. Fourier's law-based heat transfer analysis confirmed that this thickness provides the ideal compromise between rapid heat transfer (for energy efficiency) and sufficient thermal mass (for baking consistency).

Experimental data demonstrated that reducing pan thickness from 20mm to 15mm decreased heating time by 20% while maintaining adequate heat retention. The smaller diameter (450mm vs traditional 520mm) contributed to reduced heat loss and better fuel utilization. These findings have important implications for future stove designs, suggesting that careful dimensioning of baking pan surfaces can yield substantial performance benefits(123,124).

Sociocultural Acceptance and Health

Beyond technical and economic metrics, the research confirms strong sociocultural compatibility of the biogas stove. The quality of injera produced meets traditional standards, a critical factor for user acceptance. The significant reduction in smoke and particulate emissions (characteristic of blue flame combustion) addresses major public health concerns associated with traditional biomass cooking, particularly respiratory illnesses in women and children.

The system's faster cooking times and reduced fuel-gathering requirements (compared to firewood) also contribute to improved gender equity by reducing the domestic workload typically borne by women and girls in rural households.

5.2 Recommendations

The biogas Injera baking stove developed in this study shows a 33.7% thermal efficiency. When compared to previous biogas Injera stoves, this stove offers improved thermal efficiency but still presents areas for further improvement, particularly in reducing heat losses through better insulation.

By reducing heat losses and further optimizing combustion efficiency, the stove has the potential to further increase its energy savings contributing to deforestation mitigation and a more sustainable cooking process. Additionally, ensuring the blue flame remains stable across various operating conditions will continue to enhance the performance of the stove in baking Injera.

The prototype developed in this study was tested for performance of heat distribution, baking time, and quality of Injera.

To fully realize the benefits of the improved biogas injera baking stove and ensure its widespread adoption, it is essential to strengthen the national biogas infrastructure, particularly in rural areas where access to electricity remains limited. This requires coordinated intervention from government agencies, development partners, and local institutions. Establishing reliable and well-managed biogas systems will not only support clean energy access but also enhance the performance and sustainability of the biogas injera stove introduced in this study.

A key component of this expansion involves training and capacity-building for technicians responsible for the installation, operation, and maintenance of biogas plants. Skilled technical support is crucial for ensuring consistent biogas production, minimizing system downtime, and maintaining user confidence. Therefore, establishing regional training centers, integrating biogas technology into vocational education programs, and providing continuous professional development for biogas technicians are strongly recommended.

Furthermore, the economic capacity of rural households must be strengthened so they can invest in biogas technologies, either through the construction of household biogas plants or by purchasing biogas from community-based or institutional systems. To achieve this, it is important to expand and empower financial institutions and microfinance organizations that can offer affordable loans, credit schemes, or energy-specific financing products tailored to biogas projects. Subsidies, low-interest loans, and result-based financing models can further encourage household adoption.

Government intervention is also needed to create an enabling environment by developing supportive policies, incentives, and regulatory frameworks that prioritize renewable energy technologies. This may include tax incentives, subsidies for biogas plant construction materials, integration of biogas into rural electrification programs, and partnerships with NGOs that specialize in clean energy development.

Overall, expanding biogas infrastructure, strengthening technical capacity, and improving household financial access will significantly accelerate the adoption of biogas technology. These measures are essential for ensuring reliable biogas availability, enhancing the performance of the injera baking stove, reducing dependence on biomass fuels, and contributing to national goals related to climate change mitigation and sustainable development (SDG 7).

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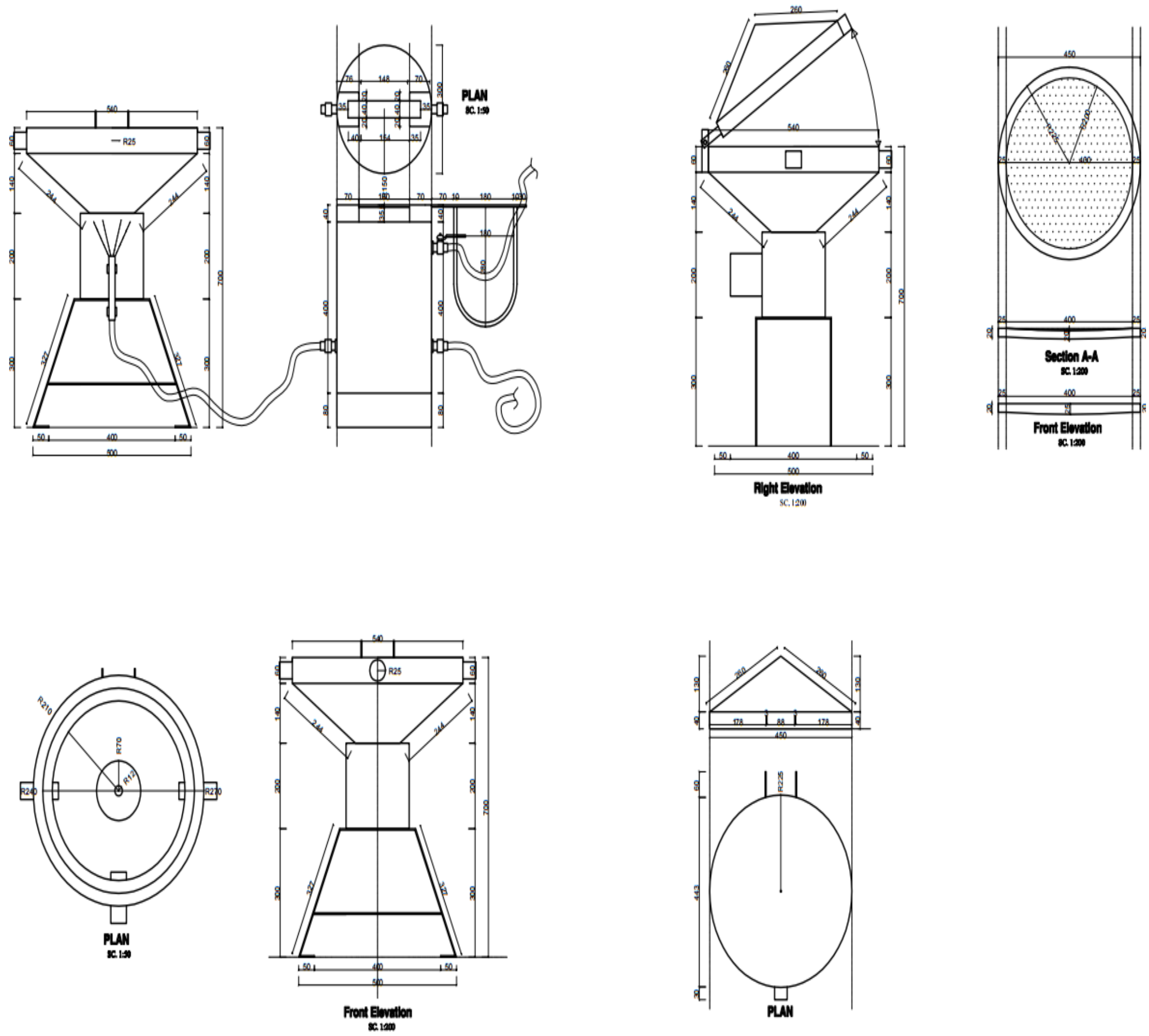
APPENDICES

APPENDIX A- DRAWING OF BIOGAS INJERA BAKING STOVE



APPENDIX B: THERMAL PROPERTY OF SELECTED MATERIALS(107)

Material	Density (kg/m³)	Specific Heat (J/kg·K)	Thermal Conductivity (W/m·K)
Metals			
Aluminum (pure)	2,700	900	237
Copper (pure)	8,950	385	401
Iron (pure)	7,870	450	80.2
Steel (mild)	7,850	502	50.2
Stainless Steel (304)	8,030	502	16.2
Lead	11,340	129	35.3
Gold	19,300	129	317
Silver	10,500	235	429
Building Materials			
Concrete	2,300	880	1.4
Brick	1,800	840	0.72
Glass (window)	2,500	840	1.05
Wood (oak)	700	2,000	0.17
Plywood	540	1,300	0.12
Insulation			
Fiberglass	25–100	840	0.04–0.045
Polystyrene (foam)	30–50	1,300	0.033–0.035
Polyurethane (foam)	30–50	1,800	0.02–0.03
Liquids			
Water (20°C)	1,000	4,182	0.60
Ethanol	789	2,440	0.17
Engine Oil	888	1,880	0.15
Gases (at 1 atm, 20°C)			
Air	1.205	1,005	0.0257
Argon	1.661	520	0.0177
Helium	0.166	5,193	0.152

APPENDIX C- EMISSIVITY VALUE OF COMMON MATERIALS (107,116)

Materials	Emissivity
Aluminum	0.30
Copper	0.95
Glass	0.85
Iron	0.70
Lead	0.50
Steel	0.80
Iron	0.70
Sand	0.90
Lime stone	0.98
Water	0.93
Wood	0.94

APPENDIX D- THERMO PHYSICAL PROPERTIES OF AIR AT ATMOSPHERIC PRESSURE (107)

T (K)	ρ,kg/m3	C_p, J/kg.k	μ.10^7 N.s/m^2	ν. 10^6 m/s^2	κ, 10 ^{7} W/m.k	α, 10^6 m/s^2	Pr
100	3.5562	1.032	71.1	2	9.34	2.54	0.788
150	2.333.74	1.012	1034	4.426	13.8	5.84	0.758
200	1.7458	1.007	132.5	7.590	18.1	10.3	0.737
250	1.3947	1.007	159.6	11.44	22.3	15.9	0.720
300	1.1614	1.006	184.6	15.89	26.3	22.5	0.707
350	0.9950	1.007	208.2	20.92	30	29.9	0.700
400	0.8711	1.009	230.1	26.41	33.8	38.3	0.690
450	0.7740	1.014	250.7	32.39	37.3	47.2	0.686
500	0.6964	1.021	270.1	38.79	40.7	56.7	0.684
600	0.5804	1.030	305.8	52.69	46.9	76.9	0.689
650	0.5356	1.051	322.5	60.21	49.7	87.3	0.690
700	0.4975	1.063	338.8	68.10	52.3	98.0	0.695

APPENDIX E: BIOGAS FLOW RATE

Dia (mm)	30 mbar	40 mbar	50 mbar	60 mbar	70 mbar	80 mbar
1.5	0.15	0.173	0.194	0.213	0.23	0.247
1.6	0.171	0.198	0.222	0.244	0.264	0.283
1.7	0.193	0.223	0.251	0.276	0.299	0.321
1.8	0.217	0.251	0.282	0.311	0.337	0.33.72
1.9	0.243	0.281	0.316	0.348	0.378	0.406
2	0.27	0.313	0.352	0.388	0.421	0.452
2.1	0.299	0.347	0.39	0.429	0.466	0.501
2.2	0.33	0.383	0.43	0.472	0.513	0.552
2.3	0.33.73	0.421	0.472	0.518	0.563	0.606
2.4	0.397	0.461	0.517	0.566	0.615	0.662
2.5	0.433	0.502	0.563	0.617	0.67	0.721
2.6	0.471	0.546	0.611	0.67	0.727	0.782
2.7	0.51	0.591	0.661	0.725	0.786	0.846
2.8	0.551	0.637	0.713	0.782	0.847	0.911
2.9	0.593	0.686	0.767	0.841	0.911	0.978
3	0.637	0.733.7	0.823	0.902	0.976	1.048

APPENDIX F: HEATING TIME PAN

Heating Time, min	Pan Temp, ^{0}C (15mm,450mm)	Pan Temp, ^{0}C (25mm,520mm)
0	21	21
5	104	33
10	152	81
15	218	115
20	230	142
25	257	168
30	271	181
35	280	215
40		234

APPENDIX E. HEATING TEMPERATURE VS TIME

Time (min)	Operational Phase	Pan Temperature (°C)		
		Test 1	Test 2	Test 3
0	Start (ambient)	21	24	23
5	Preheating	84	87	85
10	Preheating	152	154	152
15	Preheating	180	183	181
20	Baking Begins	230	234	231
23	Baking	230	234	231
26	Idle	120	121	121
29	Baking	230	234	231
32	Baking	230	234	231
35	Idle	120	121	121
38	Baking	230	234	231
41	Baking	230	234	231
44	Idle	120	121	121

APPENDIX -F PERFORMANCE ANALYSIS

The thermal energy required to bake a single injera (E_{injera}) is calculated as follows

$E_{injera} = (m_{batter}Cp(T_{boil}-T_{room})+(m_{batter}-m_{injera})h_{fg})$

Where:

n = Total Injera baked per cycle

E_{injera}, Heat Energy utilized (kJ) .

Mass of batter (*m*batter): 0.58 kg

Mass of water evaporated (*m*evap): 0.235 kg

Mass of injera baked (*m*injera): mbatter−mevap=0.58−0.235=0.345 kg*m,* batter −*m*evap=0.58−0.235=0.345 kg

Specific heat capacity of water (*Cp*): 4.184 kJ/kg°C

Boiling temperature of water (*T*boil): 93 °C

Room temperature (*T*room): 21 °C

Latent heat of vaporization (*h*fg): 2260 kJ/kg

The energy required to heat the batter from room temperature to boiling temperature (sensilbe heat):

$Q_{sensible} = m_{batter}Cp(T_{boil}-T_{room})$,

Substitute the values:

Qsensible=0.58kg·4,184kJ/kg°C·(93−21)

Qsensible=0.58·4,184·72

Qsensible=174.6 kJ

The energy required to evaporate the water (latent heat):

$Q_{latent}=m evap \cdot h fg$

Substitute the values:

Qlatent=0.235kg·2260kJ/kg

Qlatent=531.1kJ

Total Energy Utilized

Add the sensible and latent heat energies:

Einjera=Qsensible+Qlatent

Einjera=174.6+531.1

Einjera=705.7kJ

The energy consumption of the stove was determined by measuring the amount of biogas used per unit time. It was calculated as:

where:

(Q_{Input})= is the total energy consumed (MJ),

Q= is the biogas volumetric flow rate (m^3/s), and

t= is the duration of the experiment (s),

CV= is the calorific value of biogas (MJ/m^3).

Assuming total injera baked of 15 for per for Ethiopian house hold, preheating time baking pan 20 min, baking time 3min, idle time 3min, the heat energy consumed during heating time, baking time and idle time .

The Latent heat and sensible heat and the total energy utilized was calculated as follows

Heat Energy Consumed During Preheating of pan

The heat energy required for initial heating or to reach the temperature of baking is given by the following equation :

Epreheat = $m_{bm}cp_{bm}(T_{bs} - T_{\infty})$

Where: Epreheat= heat energy required for initial heating (kJ)

mbm = Mass of Injera baking Mitad plate (kg), 4kg

bs = Baking surface temperature (K) ,

$T\infty$ = Surrounding temperature (K) ,

cpbm= Specific heat capacity of Injera baking Mitad (kJ/kg.K),

Assume the preheating energy is equal to the sensible heat energy (Qsensible):

Epreheat=550.08kJ

Heat Energy Consumed During Baking

The total heat energy utilized during baking is the sum of sensible and latent heat for all 15 injera:

Ebaking=n·Einjera =15·705.7=10,585.5kJ

Heat Energy Consumed During Idle Time

During idle time, the baking pan is heated for 3 minutes per cycle. Assume the energy consumed during idle time is proportional to the sensible heat energy (Qsensible):

$E_{idle}=(\frac{idle\ time}{preheating\ time}.Energy$ preheating)

Substitute the values:

The total heat energy utilized during idle heating of baking pan for all 15 injera:

Eidle=n. ($\frac{20min}{45min}$·550.08kJ)

Eidle=15·0.44.550.08 =33,767.2kJ

Total Heat Energy Consumed

The total heat energy consumed during the entire baking process is the sum of preheating, baking, and idle time energy:

Etotal=Epreheat+Ebaking+Eidle

Etotal=550.08+10,585.5+33.767.2

Etotal=14,802.78kJ

Efficiency of the Baking Pans

Baking energy efficiency is controlled by two parameters. Those are how heat is imparted to the food and how heat loss is controlled.

$$\eta = {}^{nqbaking}/_{Totalenergyinput}$$

$qbaking$, total energy input to the clay mitad and

Total energy input, energy absorbed by injera

$$= 100 \times \frac{10{,}585.5\text{kJ}}{14{,}802.78\text{kJ}}$$

η =71%

Total Time Taken

The total time taken is the sum of preheating time, total baking time, and total idle time:

Total time=Preheating time+Total baking time+Total idle time

Total time=20min+45min+42min=107minutes

Convert the total time to hours:

Total time in hours=$\frac{107min}{60min}$=1.8 hours

The total biogas consumed is the product of the flow rate and the total time:

V_{biogas}=Flow rate·Total time

V_{biogas}=0.84 m^3/hr·1.8 hr

V_{biogas}=1.5m^3

The total energy consumed is the product of the total biogas consumed and the calorific value of biogas:

*E*total=*V*biogas·Calorific value of biogas

Total energy consumed= Total biogas consumed. Calorific value of biogas

Substitute the values *E*total=1.5m^3·22,000kJ/m^3

Total energy consumed=39,833.31 kJ

Efficiency of the Baking biogas stove,

$$\eta = \left(\frac{\text{Energy Utilized}}{\text{Input Energy}}\right) \times 100$$

$$\eta = \frac{\text{Energy Absorbed By Injera}}{\text{Total amount of Biogas Consumed} * \text{Calorific value}} * 100$$

$$= 100 \times \frac{10{,}585.5\text{kJ}}{39{,}833.31\text{kJ}} = 33.77\%$$

APPENDIX G: PRESSURE AND FLOW RATE CALCULATION

To calculate the flow rate of biogas using Bernoulli's equation, we considered the principles of fluid dynamics. Bernoulli's equation relates the pressure, velocity, and height of a fluid in a steady, incompressible flow. For biogas, which is compressible, we can still use a simplified form of Bernoulli's equation.

$Q = 0.0467 C_d A_0 \sqrt{\frac{p}{s}}$,

Q ,gas flow rate

A_0,area of orifice

P, gas pressure before orifice

s ,specific gravity of biogas gas

Cd ,coefficient of discharge for the orifice

Q, Biogas flow rate

.