

PERFORMANCE EVALUATION OF A RETROFITTED COOK STOVE BY CO-
FIRING BIOMASS WITH STEAM, SPIRIT AND BIO-DIESEL

By

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DECLARATION

Student Declaration

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DEDICATION

I dedicate this thesis to my Wife Mrs. Josphine Jepchirchir Koech, My children Keziah Chemutai Koech and Kerren Jepngetich Koech for their sacrifice and support this far.

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Great appreciation to the Lord Almighty for the knowledge, wisdom and understanding that he enabled me to successfully complete this project.

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ABSTRACT

The continued use of biomass cookstoves in households and the traditional open fires for cooking is not only a major health hazard but also an environmental hazard. Although biomass offers a sustainable and carbon neutral source of energy, its inefficient use in household cooking has led to the indoor air pollution due to smoke emission resulting to respiratory and other health problems. The main objective of this study was to determine the performance of a retrofitted cook stove co-firing biomass with steam, spirit and bio-diesel. The specific objectives were to design and fabricate a retrofitted cookstove, determine the thermal efficiency of biomass when steam, biodiesel and spirit are used as gasification agent and to carry out the techno-economic analysis of the retrofitted cookstove. Mild steel, copper and aluminium were selected as the construction material. The computer aided drawing (CAD) was used to design the cook stove based on cook stove energy requirements, reactor diameter, height of the reactor and the heat exchange area for the gasification agent (steam). The fabrication was guided by technical 2D and 3D CAD drawings. The empirical relations for the design were borrowed from closely related literature, such as energy requirements, fuel consumption rate, reactor diameter, height of the reactor and heat exchanger for steam. The performance was based on already established standard methods which includes efficiency, fire power and burning rate. The analysis revealed an efficiency of retrofitted stove when biodiesel, spirit and water were used was 53.83%, 37.65% and 14.75% respectively. The fire power for retrofitted stove for water, spirit and biodiesel were 76.66 J/s, 80.93J/s and 83.93J/s respectively. The burning rate for retrofitted stove for water, spirit and biodiesel were 0.25g/sec, 0.27g/sec and 0.28g/sec respectively. The boiling cost in KES for 1 liter of water in Retrofitted stove, Envirofit, Jiko Koa, Clay stove, and Kenya ceramic jiko were 2.0,20.0,23.9,31.1 and 31.6 respectively. The initial cost in KES for acquiring Retrofitted stove, Envirofit, Jiko koa, Kenya ceramic jiko and Clay stove were 4,895, 5,470, 5,499, 500 and 2,500 respectively. The Power for Envirofit, Jiko koa, Kenya ceramic jiko, Clay stove and Traditional stove were 0.95J/s,0.71J/s,0.37J/s,0.36J/s and 0.35J/s respectively. In conclusion retrofitted cook stove was more efficient and emits limited smoke when cooking hence friendly to the environment and improve rate of cooking. Further studies be done on rate and amount of gas produced as syngas from retrofitted cook stove

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LIST OF ABBREVIATIONS

ALRI –	Acute lower respiratory infections
CCT –	Control cooking test
CDM –	Clean development agency
CO-	Carbon monoxide
COPD –	Chronic obstructive pulmonary disease
CV –	Calorific value
EPA –	Environmental protection agency
FCR-	Fuel combustion rate
GDP –	Gross domestic product
HAP –	House hold air pollution
HTP –	Heterogeneous testing protocol
ICS –	Improved cook stove
ISO –	International standards organizations
KCJ –	Kenya ceramic jiko
KPT –	Kitchen performance test
LPG –	Liquefied petroleum gas
NISP –	National retrofitted stove programs
NPIC-	National retrofitted stove programs
PPM –	Parts per million
SGR –	Standard gasification rate
TBC –	Traditional bio-mass cook stove
TLUD –	Top lit up draft
TSF –	Three stone fires
UFT-	Uncontrolled field test
WBT –	Water boiling test
WHO –	World health organization

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The increasing reliance on non-renewable energy sources such as crude oil, coal, and natural gas has accelerated global environmental challenges, including global warming, air pollution, and resource depletion. While these sources have historically powered industrial development, they have also contributed significantly to ecological degradation and public health crises (Juan Camilo, Yessica, & Carlos, 2018).

Kole, Zeru, Bekele and Ramayya (2022) designed, developed, and evaluated a continuous feed husk biomass cook stove suitable for high-altitude conditions in Ethiopia. The study was motivated by the fact that most improved cook stoves in developing countries, including those in Sub-Saharan Africa, are primarily designed for wood fuel and are therefore unsuitable for husk-type biomass such as coffee husk, rice husk, and sawdust, which are abundantly available. Using the Water Boiling Test (WBT) version 4.2.3 and emission measurements, the researchers conducted detailed experiments with two different pot sizes and husk biomass fuels. The findings indicated that for a 3.5-liter pot, the stove achieved an average thermal efficiency of 29 percent with coffee husk and 28 percent with rice husk, with the corresponding boiling times being 7.7 and 8.4 minutes, respectively (Kole, Zeru, Bekele and Ramayya 2022). The maximum CO emissions measured were 262 ppm for coffee husk and 235 ppm for rice husk during the simmer phase, while the average indoor CO emissions were 0.274 g/min and 0.186 g/min for coffee husk and rice husk, respectively, both falling within the acceptable International Workshop Agreement (IWA) limits. The study further showed that the stove consumed an average of 98 g/l of fuel, which was lower than the 115 g/l recorded for improved biomass stoves, making it more fuel-efficient. In

addition, the affordability of the stove was emphasized, with a production cost of only 6.72 USD. The researchers concluded that the developed husk biomass stove was not only efficient and clean-burning but also offered a low-cost solution for households at high altitudes.

Suresh, Singh, Malik, Datta and Pal (2016) conducted a study to evaluate the performance of improved biomass cooking stoves using different solid biomass fuel types. The study employed an experimental research design in which various fuels such as wood, crop residues, and pellets were tested in improved cook stoves under controlled conditions. Performance parameters measured included thermal efficiency, burning rate, specific fuel consumption, and emission levels. The findings revealed that stove efficiency and emission outcomes varied significantly with the type of biomass fuel used, with wood pellets generally producing higher efficiency and lower emissions compared to raw wood and crop residues. The study concluded that the choice of feedstock is a critical determinant of stove performance and sustainability. However, the research was limited in scope as it mainly focused on laboratory testing and did not extensively consider field-level adoption factors such as user behavior and maintenance. This study is relevant to the current project as it underscores the importance of testing different fuel combinations in retrofitted cook stoves to optimize efficiency and environmental performance

In many developing regions, particularly in Eastern Africa, cooking remains a fundamental daily activity carried out primarily using biomass-based fuels such as firewood, charcoal, and agricultural residues. In Kenya, over 68% of households rely on firewood, while charcoal use accounts for approximately 13.3% figures that underscore a persistent dependence on solid biomass fuels. These fuels are often burned

using traditional stoves or open fires that are inefficient and emit high levels of pollutants.

This study presents the design, fabrication, and performance evaluation of a retrofitted cook stove that integrates steam, spirit, and biodiesel with biomass as gasification agents. By assessing thermal efficiency, emissions levels, and techno-economic viability, this research aims to contribute to the development of cleaner, more sustainable household cooking technologies suitable for rural and peri-urban communities in Kenya and beyond.

1.2 Problem Statement

Biomass remains the dominant source of household energy in developing countries, with the International Energy Agency (IEA, 2021) estimating that nearly 2.6 billion people globally rely on it for cooking and heating. However, its use in traditional cook stoves is inefficient and contributes significantly to indoor air pollution, deforestation, and health risks. The World Health Organization (WHO, 2020) reports that household air pollution from biomass smoke causes approximately 3.8 million premature deaths annually, primarily from respiratory infections, chronic obstructive pulmonary disease, and lung cancer. In Sub-Saharan Africa, over 80 percent of households depend on biomass as their primary cooking fuel (Kammen & Sunter, 2016), yet most use rudimentary stoves with thermal efficiencies as low as 10–15 percent. This inefficiency not only increases cooking duration but also exerts pressure on forest resources, contributing to a deforestation rate of about 0.5 percent annually in East Africa (FAO, 2020). These statistics underscore the urgent need for efficient and cleaner stove technologies that could reduce fuel consumption, minimize smoke emissions, and improve household health and environmental sustainability.

Although various improved cook stove programs have been introduced across Africa and Asia, their adoption remains low due to technical, cultural, and economic barriers. Studies in India by Prakash et al. (2019) and in Ethiopia by Alemayehu and Asfaw (2021) reveal that improved stoves reduce fuel consumption by up to 40 percent and significantly lower indoor particulate matter. However, such technologies often require high upfront costs or are incompatible with local cooking practices, leading to low sustained use. In Kenya, more than 70 percent of rural households continue to rely on firewood despite the availability of alternative stoves, citing affordability and durability challenges (Mutai, 2022). At the same time, vast amounts of agricultural residues such as maize cobs, sugarcane bagasse, and sawdust remain underutilized, largely because traditional stoves are unsuitable for their combustion. The lack of affordable, adaptable, and efficient technologies for co-firing biomass with other agents such as steam, spirit, and biodiesel creates a gap in the sustainable energy sector. This highlights the pressing need to design, fabricate, and evaluate retrofitted stoves capable of improving efficiency, utilizing diverse residues, and reducing health and environmental burdens.

1.3 Objectives of the study

1.3.1 Main objective

The main objective of this study was to carry out a comparative study of co-firing biomass with steam, methylated spirit and biodiesel in a retrofitted steam stove.

1.3.2 Specific objectives

The specific objectives were:

- i. To design, fabricate and validate a retrofitted stove
- ii. To determine the thermal efficiency of biomass with steam, biodiesel and spirit as gasification agent using retrofitted stove.

- iii. To carry out the techno-economic analysis of the retrofitted stove

1.4 Scope of Work

This project mainly focused on the co-firing of firewood with steam, methylated spirit, and biodiesel in a retrofitted cook stove. The aim was to achieve improved performance and efficiency through the use of a modified retrofitted design that could accommodate multiple fuel types. In order to meet this goal, attention was given to the distinguishing features of biomass gasifiers, which play a central role in determining the overall functionality of the system.

Biomass gasifiers exist in various designs, which differ based on several factors. These include the location of the combusting gas burner, whether it is closely coupled or separate from the gas generation unit, as well as the direction of gas flow, which may be cross-draft, down-draft (co-flow), or up-draft (counter-flow). Other important considerations are the operating gas pressure, which can be suction-based, atmospheric, or pressurized, and the choice of gasifying agent, which may include steam, oxygen, or natural air. Similarly, the vapor flow speed of the gasifying agent and the draft creation technique—whether natural draft, fan-assisted, or draft-induced—affect performance outcomes.

The type of feedstock also influences the gasification process, with options such as sawdust pellets, wood chips, and maize cobs requiring suitable levels of dryness and size preparation. Additional factors include the ash form produced (dry ash, melting ash, or clinker formation), the heat characteristics of the gasification process, the size of the gasification device (ranging from micro to large-scale industrial systems), and the extent of gas cooling and cleaning, which is especially vital for industrial applications where gases are stored or transported. The ultimate objective of such

systems is to generate heat or electricity from producer gas while also providing solutions for energy needs and municipal management.

In this project, emphasis was placed on steam gasification as an endothermic process. From a kinetics perspective, steam gasification is slower than air gasification but faster than carbon dioxide gasification. Its efficiency depends on factors such as gasification temperature, particle size, steam flow rate, steam-to-biomass ratio, and steam-to-carbon ratio. The process involves two major phases: pyrolysis as the initial stage, followed by steam gasification reactions. These include the water-gas shift reaction, hydrogasification, water-gas reaction, and steam reforming. Studies indicate that increasing the operating temperature from 600°C to 850°C significantly improves gas yield and carbon conversion efficiency, while maintaining steam flow in the range of 0.054 to 0.357 g/min/g enhances the overall reaction kinetics (Sataar, Leeke & Hornung, 2014).

Therefore, this project's scope extended beyond testing the retrofitted cook stove into examining the fundamental principles of steam gasification in relation to co-firing. This approach ensured not only the development of an improved cooking system but also the exploration of gasification dynamics that influence energy conversion, efficiency, and environmental sustainability.

1.5 Justification of Study

Household energy demand continues to rise in developing countries, where reliance on traditional biomass such as firewood and charcoal remains widespread. This dependence has been linked to high levels of indoor air pollution, deforestation, and low thermal efficiency of conventional cook stoves (IEA, 2022). Retrofitting cook

stoves with improved combustion technologies offers a sustainable pathway to enhance energy efficiency while reducing harmful emissions.

Co-firing biomass with alternative fuels such as steam, spirit, and biodiesel provides a viable strategy to optimize fuel use and improve heat transfer efficiency. Studies have shown that hybrid fuel approaches significantly reduce particulate matter and carbon monoxide emissions compared to the sole use of raw biomass (Okello et al., 2021). In addition, integrating renewable liquid fuels such as biodiesel ensures cleaner combustion and contributes to reducing reliance on fossil fuels in domestic energy use (Singh & Kumar, 2020).

Furthermore, in many rural and peri-urban communities, retrofitted cook stoves have the potential to alleviate health risks associated with prolonged exposure to smoke, which is estimated to cause over 3.2 million premature deaths annually worldwide (WHO, 2021). Evaluating the performance of a retrofitted cook stove using co-firing will therefore provide critical insights into its efficiency, emission profile, and adaptability to household cooking practices. The findings from this study will inform policy, guide stove design improvements, and promote the adoption of sustainable cooking technologies.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The purpose of this chapter was to provide a comprehensive review of the theoretical and empirical literature relevant to the performance evaluation of retrofitted cookstoves through co-firing biomass with steam, spirit, and biodiesel. The literature review positioned the current study within the broader body of knowledge on household energy, biomass combustion, and clean cooking technologies. It drew on theories that guided stove design and fuel utilization, empirical studies that demonstrated the effectiveness and limitations of different cookstove models, and regional energy contexts that shaped adoption.

Cookstove research had evolved over the decades, with increasing attention to improving efficiency, reducing emissions, and ensuring affordability for users in developing countries (World Health Organization [WHO], 2018). The theoretical underpinnings of combustion, gasification, and energy transfer guided much of the technological advancement in this area (Bhattacharya & Abdul Salam, 2016). Empirical studies conducted across Asia, Africa, and Latin America revealed both the successes and challenges of improved cookstove adoption, highlighting critical issues such as durability, user behavior, cultural acceptance, and policy support (Pope et al., 2017).

In the African context, particularly Sub-Saharan Africa, reliance on traditional biomass had remained high, with an estimated 80% of households depending on firewood, charcoal, and other solid fuels for daily cooking (International Energy Agency [IEA], 2021). In Kenya, this figure stood at approximately 70%, underscoring the urgent need for scalable and sustainable cooking solutions (Kenya National Bureau of Statistics

[KNBS], 2020). Against this background, the study of retrofitted stoves that integrated co-firing with alternative fuels such as biodiesel, spirit, and steam was both timely and relevant.

This chapter was organized into six main sections. The first section presented the theoretical literature that guided cookstove design and combustion processes. The second section reviewed empirical studies on cookstove performance and adoption. The third section explored the historical development of cookstoves, from early models to recent innovations. The fourth section examined the energy and fuel context in Sub-Saharan Africa and Kenya. The fifth section introduced the conceptual framework that underpinned the present study. The final section provided a summary of key insights and identified research gaps that this study sought to address.

2.2 Theoretical Literature

The theoretical literature guided the understanding of cookstove technologies, energy conversion, and combustion efficiency. Several theories had been widely cited in the field, each offering a framework for evaluating stove performance and adoption.

2.2.1 Combustion Theory

Combustion theory explained the chemical and physical processes that occurred when biomass and alternative fuels were burned to release energy. According to Turns (2012), combustion involved the rapid oxidation of fuel, producing heat, light, and reaction by-products such as carbon dioxide and water vapor. The fundamental principle of combustion rested on the chemical reaction between fuel molecules and oxygen, which required three essential elements: fuel, oxygen, and an ignition source, commonly referred to as the fire triangle. The theory encompassed various combustion modes including premixed, diffusion, and partially premixed flames, each with distinct

characteristics affecting heat release rates, flame stability, and emission formation. Complete combustion occurred when sufficient oxygen was available, resulting in maximum energy release and minimal harmful emissions, while incomplete combustion led to the formation of carbon monoxide, particulate matter, and other pollutants.

The theory provided a foundation for understanding stove efficiency, heat transfer mechanisms, and emission reduction strategies. Its strength lay in its ability to quantify energy output relative to fuel input through stoichiometric calculations and thermodynamic analysis, enabling precise evaluation of fuel conversion efficiency and heat transfer rates. However, the theory was limited by its focus on idealized conditions, which often differed significantly from real-world household settings where factors such as variable fuel moisture content, irregular airflow patterns, inconsistent fuel feeding rates, and ambient temperature fluctuations influenced combustion performance. For this study, combustion theory informed the evaluation of how co-firing biomass with steam, spirit, and biodiesel influenced thermal performance and emission profiles in retrofitted cookstoves, providing the scientific basis for understanding fuel interaction mechanisms and optimizing combustion parameters.

2.2.2 Gasification Theory

Gasification theory described the partial oxidation of solid fuels at high temperatures to produce combustible gases, which could then be ignited to generate heat (Kaliyan & Morey, 2009). The theory emphasized four distinct sequential stages: drying (moisture removal at 100-200°C), pyrolysis (thermal decomposition of organic matter at 200-500°C producing volatile compounds), oxidation (combustion of char and volatiles at 700-1500°C), and reduction (chemical reduction reactions producing hydrogen and

carbon monoxide at 800-1100°C). This process fundamentally differed from direct combustion as it created an intermediate gaseous fuel that could be burned with greater control and efficiency. The gasification process required careful management of the equivalence ratio (the actual air-to-fuel ratio divided by the stoichiometric air-to-fuel ratio), typically operating at sub-stoichiometric conditions with equivalence ratios between 0.2 and 0.4 to maintain the partial oxidation environment necessary for gas production.

The theory's application in cookstove design allowed for improved fuel efficiency, cleaner combustion, and better heat control compared to traditional combustion methods. The controlled production of producer gas (a mixture of carbon monoxide, hydrogen, carbon dioxide, and nitrogen) enabled more complete fuel utilization and reduced emission of particulate matter and toxic compounds. However, a key limitation was the complexity of controlling gasification in small-scale household stoves, which required precise air supply management, adequate thermal mass, and proper fuel sizing - factors that could be challenging to maintain consistently in domestic settings. Additionally, gasification stoves typically required a startup period and continuous fuel feeding to maintain optimal gas production rates. In the context of this study, gasification theory provided the scientific basis for designing stoves capable of co-firing multiple fuel types while minimizing smoke and incomplete combustion, particularly relevant when integrating liquid fuels like spirit and biodiesel with solid biomass in the gasification chamber.

2.2.3 Energy Efficiency Theory

Energy efficiency theory, as articulated by Rosen and Dincer (2001), focused on maximizing useful energy output while minimizing losses during fuel conversion

processes. The theory encompassed both first-law efficiency (based on energy conservation) and second-law efficiency (based on energy quality and exergy analysis), providing comprehensive frameworks for evaluating thermal performance. First-law efficiency, commonly expressed as thermal efficiency, measured the ratio of useful energy delivered to the total energy input from fuel, accounting for heat losses through conduction, convection, and radiation. Second-law efficiency considered the quality of energy transformation, recognizing that not all forms of energy were equally valuable and that high-temperature combustion processes inevitably involved irreversible losses. The theory also incorporated concepts of energy cascading, where waste heat from primary processes could be captured and utilized for secondary applications, and pinch analysis for optimizing heat recovery systems.

The theory had been extensively applied to evaluate the thermal efficiency of cookstoves, fuel utilization rates, overall energy performance, and environmental impact through lifecycle energy analysis. Its strength was in its practical applicability to real-world devices, allowing for standardized performance benchmarking through established testing protocols such as the Water Boiling Test (WBT) and Controlled Cooking Test (CCT). The theory enabled quantitative comparison of different stove designs and fuel combinations, facilitating evidence-based decision-making in technology development and deployment. However, its limitation was that it often overlooked critical socio-cultural factors affecting actual stove use and adoption, such as cooking preferences, fuel availability, economic constraints, and cultural practices that significantly influenced real-world efficiency outcomes. This theory was central to the study as it guided the comprehensive assessment of how retrofitted cookstoves performed under different fuel combinations and operational conditions, providing

metrics for evaluating the effectiveness of integrating steam, spirit, and biodiesel with traditional biomass fuels.

2.2.4 Diffusion of Innovations Theory

Rogers' (2003) Diffusion of Innovations Theory explained how new technologies, such as improved or retrofitted cookstoves, were adopted over time within communities through complex social processes. The theory identified five key attributes influencing adoption rates: relative advantage (the perceived superiority over existing alternatives), compatibility (consistency with existing values, experiences, and needs), complexity (perceived difficulty of understanding and use), trialability (the degree to which innovations can be experimented with on a limited basis), and observability (the visibility of innovation results to others). The theory also categorized adopters into five groups based on their willingness to embrace new technologies: innovators (2.5%), early adopters (13.5%), early majority (34%), late majority (34%), and laggards (16%), each with distinct characteristics and communication preferences. The diffusion process was further influenced by communication channels, social systems, change agents, and the innovation-decision process consisting of knowledge, persuasion, decision, implementation, and confirmation stages.

The theory's strength lay in its comprehensive framework linking technological innovation to user behavior, social networks, and communication patterns, providing insights into why some innovations succeeded while others failed despite technical superiority. It emphasized the critical role of opinion leaders, social proof, and peer influence in technology adoption, particularly relevant in rural communities where cookstove interventions were typically implemented. However, the theory's limitation was its assumption that adoption occurred in relatively linear and predictable stages,

which might not reflect real-world constraints such as economic barriers, infrastructure limitations, policy interventions, or external shocks that could accelerate or halt diffusion processes. Additionally, the theory was developed primarily in Western contexts and might not fully account for cultural variations in decision-making processes, collective versus individual adoption patterns, and the role of traditional authorities in technology acceptance. For this study, the theory provided a crucial framework for understanding the social and behavioral dynamics influencing the uptake of retrofitted stoves in households, informing strategies for technology introduction, user training, and community engagement to enhance adoption rates.

2.3 Empirical Literature

This section reviewed previous empirical studies on cookstove design, performance evaluation, and techno-economic analysis.

2.3.1 Design, Fabrication and Validation of Retrofitted Stoves

2.3.1.1 Biomass Gasification Principles for Cooking Applications

Biomass gasification represents a sophisticated approach to converting solid fuels such as wood and agricultural residues into combustible gases. According to research conducted by the Asian Institute of Technology in Thailand, a biomass gasifier consists primarily of a reactor or container where fuel is fed with limited air supply, specifically less than the amount required for complete combustion. This controlled process leads to chemical breakdown of fuel through internal reactions, producing combustible gases including hydrogen, carbon monoxide, methane, and incombustible gases like carbon dioxide and nitrogen. Table 2.1 presents various gasifier stoves developed worldwide for cooking applications, including the Wood gas cook stove by Thomas Reeds and Red Larson, the Charcoal making wood gas cooking stove by Elsen Karsad, and the Natural

draft cross flow stove model developed by the Asian Institute of Technology in Thailand.

Table 2.1: Gasifier stoves worldwide for cooking applications

Name of stove	Developed by
Wood gas cook stove	Thomas reeds and red larson
Charcoal making wood gas cooking stove	Elsen karsad
Natural draft cross flow stove model	Asian Institute of technology, Thailand
Briquette gasifying stove	Richard Stanley .Kobus venter
ISSC gasifier stove	Indian institute of science
San san rice husks gasifier stove	U tin win

The biomass combustion process occurs in four distinct stages as illustrated in Figure 2.1 from GIZ HERA. The first stage involves drying, where the initial change happens during water evaporation, with the amount depending on the moisture content of the raw fuel. This determines the heat input needed to evaporate all water and the resulting mass and volume loss to achieve dry fuel. The second stage encompasses pyrolysis or carbonization, where increased temperatures and absorbed heat eventually cause complete decomposition of biomass, separating into volatile gases and vapor while solid char remains behind. The vapors contain various carbon compounds with fuel value, referred to as 'wood-gas', and since the solid product is char, this stage is also called carbonization. Pyrolysis can occur in complete absence of oxygen, with heat being the regulating factor - no heat input results in no pyrolysis, no wood-gas generation, and no fire.

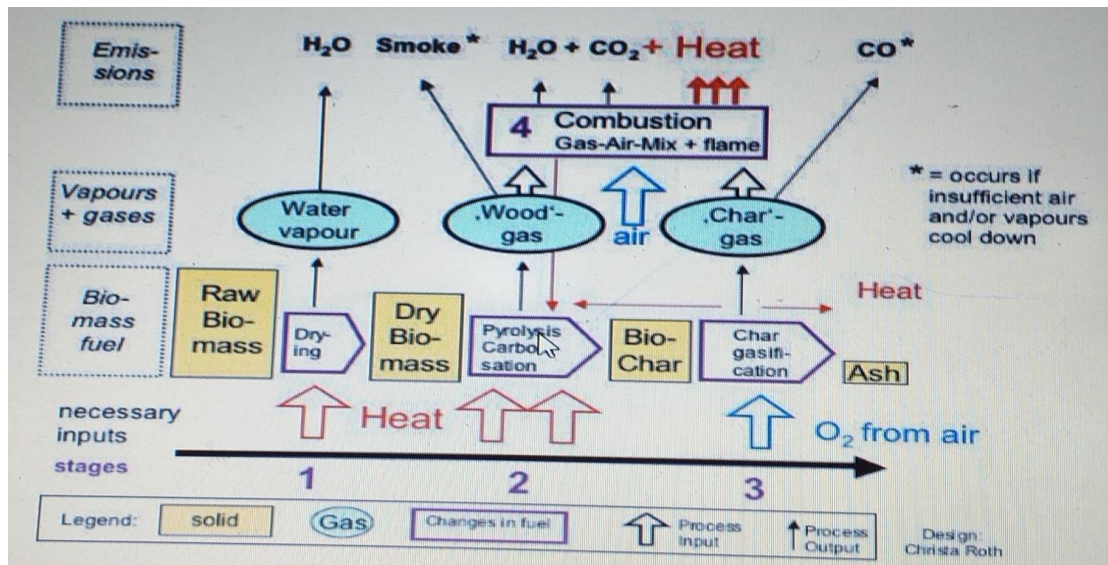


Figure 2.1 Stages of biomass combustion

Source: GIZ HERA

The third stage involves char-gasification, where once char is formed, the next phase converts carbon atoms to gases and non-carbon portions to ash. This only occurs if oxygen is available and reaches the char while it remains hot enough to react. During char-gasification, oxygen reacts with char solids, yielding carbon monoxide, carbon dioxide and creating additional thermal energy, while the fraction of non-burnable solid mineral content remains as ash. The final fourth stage encompasses gas-combustion, where gases are burnt and the bulk of heat is released for cooking applications.

Unlike open fires, gasifiers controllably separate gas generation from gas combustion in both space and time. While conventional stoves are regulated by fuel supply, gasifiers are controlled by air supply, offering potential for optimizing each conversion step through controlled heat and air inputs. If combustion is incomplete due to lack of oxygen or if vapors have cooled below their burning point, they turn into undesirable emissions - wood-gas becomes noticeable, often irritating smoke, while char-gas becomes carbon monoxide, an odorless, imperceptible, and highly toxic gas dangerous to human health.

2.3.1.2 Development of Retrofitted Stove Technologies

According to Prakash (2009), traditional stoves generate large quantities of smoke and suspended particulate matter while transferring only 10-40% energy to the pot. Improving combustion efficiency not only reduces smoke and harmful emissions but also saves fuel costs and improves heat transfer efficiency. To attain these improvements, Prakash incorporated several selected parameters in his design, including low thermal conductivity insulation using glass wool and rock wool, construction of the stove using thin mild steel sheet for low heat absorption by the stove body, provision of a 3cm gap between the bottom of stove and grate to ensure good air supply, and provision of a skirt metal sheet envelope to surround the pot to guide flue gases and avoid loss of heat energy generated. Additionally, circular holes were drilled co-axially at the center to vary airflow and maintain temperatures of gas flow as high as possible, as shown in Figure 2.2 illustrating the Prakash cook stove design.

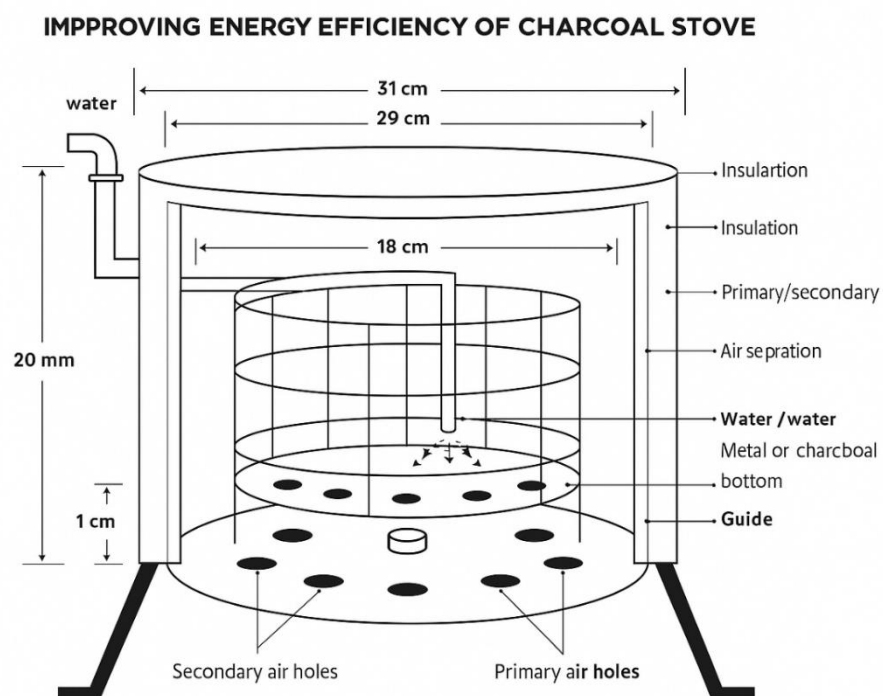


Figure 2.2 Prakash cook stove

The retrofitted stove design addresses limitations of conventional biomass stoves through controlled airflows from both primary and secondary air sources. Research conducted by Dijan, Supramono and Farah (2013) investigated CO emissions resulting from combustion of the gas phase of pyrolysis products and stove efficiency by varying the ratio of secondary to primary airflow rates. Their findings, illustrated in Figure 2.3 showing average CO emission, maximum flame temperature and maximum water temperature at different values of ratio of secondary air to primary airflow rates, demonstrated that average carbon concentrations in the flue gas reach minimum values of 14ppm when airflow ratios are set to 6.29. This implies that using controlled airflows from both primary air and secondary air, stoves can be made healthier for users in domestic kitchens since carbon monoxide can be kept low. According to their results, as concentrations of carbon become higher due to incomplete combustion, the heat radiated from the combustion flame to the flaming pyrolysis front to enhance pyrolysis may not be high due to low temperature driving force between both flames, weakening the rate of pyrolysis and leading to low gas production.

Primary air flow rate (m ³ /s)	Secondary air flow rate (m ³ /s)	Air flow ratio	Average CO emission (ppm)	Maximum flame temperature (°C)	Maximum water temperature (°C)
0.00038	0.0024	6.29	14	739.3	87.1
0.00038	0.0078	20.6	29	441.7	86.4
0.00035	0.0047	13.43	32	516.8	96.0
0.00038	0.00093	2.44	52	360.8	133.0

Figure 2.3 Effect of Air Flow Ratio on CO Emissions, Flame Temperature, and Water Temperature

Source-dijan supramono

2.3.1.3 Modern Retrofitted Stove Innovations

Recent developments in retrofitted stove technology focus on enhanced performance and emission reduction. According to Al S.C. (2017), improved cook stoves and fuels such as advanced gasifier stoves carry the promise of improving health outcomes, preserving local environments and reducing air pollutants. However, the use of these stoves in many settings limits their benefits. Since biomass is the main primary source for cooking, heating and other needs for billions of people, the use of semi-gasifier cooking stoves is an important source of indoor and outdoor air pollutants and is associated with premature death amounting to 2.8 million per year population. The stove design follows an iterative approach undergoing extensive laboratory and field testing in village homes throughout a five-year stove development process. Modern retrofitted stoves feature automatic ignition systems, small fans producing synthetic flame-like gas that can be adjusted by users to vary fire power and pot surface temperature, thereby accommodating multiple styles of cooking. Other key features include large cooking pot capacity, stainless steel water heater integration, and external feeders allowing fuel addition during use.

Enhanced stoves are unable to fully replace conventional stoves because of stove malfunctions, delayed user training, and the stove's inability to cater to the varied cooking requirements of households. This creates an opportunity for future study by stove manufacturers and researchers to expedite the widespread adoption of clean technologies, as households have traditionally undergone lengthy energy transitions according to Pachauri and Jiang (2008).

The Aprovecho Research Center's enhanced charcoal burner represents advanced retrofitted technology developed by Ryan Thompson and Sam Bentson. As shown in

Figure 2.10, the design measures 27cm in diameter and 26cm in height, with a 3cm layer of insulation made of stainless steel sheets and aluminum foil separating the stove body from the 13.5cm-deep by 12cm-diameter combustion chamber. A plenum created by a refractory sheet metal cylinder in the combustion chamber allows preheated secondary air to enter above the fuel batch that is burning. A zone of continuous mixing is created by thirty or more 0.5cm apertures that are evenly spaced throughout the upper portion of the combustion chamber to funnel streams of pre-heated air above the charcoal. There is a cast iron grate installed at the bottom of the combustion chamber, with air entering the charcoal from below through a door that controls the principal airflow (Still, Bentson, Lawrence, and Dr. Andreatta, 2015).

2.3.1.4 Historical Development of Cook Stove Technology

The development of biomass cook stoves spans from time immemorial to the present day. During the early development period from time immemorial to 1950, extant evidence suggests that biomass fuel was used in the caves of Peking man as far back as 400,000 years ago. Notwithstanding the progress achieved in styles and cooking techniques compared to ancient times, the conventional biomass cook stove or the three stone fire has remained unchanged for around 12,000 years according to Westhoff and Germann (1995). This stove maintained its dominance worldwide until the 18th Century and continues to be prevalent in rural regions of developing nations to this day. Nevertheless, it had significant disadvantages including flame dispersion and heat dissipation in windy situations, failure to exercise adequate control over the fire, and exposure to thermal radiation and smoke together with burn risks. Figure 2.4 displays three stone fire stoves as described by Kabir, Yacob, Arrifin, and Adamu (2018).



Figure 2.4 Three stone fire stoves

(Kabir, I., Yacob, M. R., Arrifin, M., and Adamu, 2018).

Following the three stone fire, the U-shaped mud or mud/stone enclosure was developed, which included a front entrance for fuel addition and combustion air intake. Three diminutive humps, constructed from identical mud material, were strategically placed at the upper edge of the enclosure. The humps served as a resting place for the pot, facilitating the generation of secondary air required for improved combustion of volatile substances and for the release of exhaust gas. To optimize heat conservation from the hot flue gases and improve cooking efficiency, further pot holes were subsequently incorporated, with the pot-hole enclosures linked together by a tunnel. These advancements in cook stove design were mostly developed by users based on their personal experiences. Although these improvements helped enhance thermal efficiency to a certain degree, residual health and other risks persisted. Figure 2.5 shows the U-shaped mud stove which was an improvement of the three stone fires according to Hude (2014).



Figure 2.5: U-shaped mud stove which was an improvement of the three stone fires
Source (Hude, 2014)

A pioneering stove that saw significant advancements was the "Magan chula," which was first introduced in India in 1947. As a refinement of the U-shaped mud stove, this model incorporated three pot holes and had a more enclosed design compared to the mud stove. During the recent past from 1950-2000, the early 1950s saw Gandhian groups in India pioneer the use of biomass cook stove technology, referred to as the "classic phase" by Kirk Smith. Improved multi-pot stoves were created to address the smoky working conditions prevalent in many Indian kitchens where women were required to cook. These stoves were of the high-mass and shielded-fire variety, equipped with a chimney for smoke evacuation from the kitchen and adjustable metal dampers for fire control.

In India, Modi, Upadhyay, Chaudhary, and Shah (2025) conducted a methodical review on biomass cookstoves, focusing on their history, design, testing procedures, and fuel characterization. The study employed a comprehensive review methodology that traced the evolution of biomass cookstoves from traditional models with poor efficiency and high pollutant emissions to improved cookstoves that integrate gasification principles to enhance efficiency, safety, and emission reduction. It categorized cookstoves based

on key parameters, while also assessing global and Indian testing methodologies used to evaluate cookstove performance. Furthermore, the review examined characterization techniques for fuel, char, ash, and gas, and analyzed energy, exergy, and heat transfer aspects in cookstove applications. The role of mathematical modeling in improving designs was also explored, alongside the potential of biochar, produced as a byproduct, for diverse environmental applications. The findings emphasized the importance of user-centric design in promoting widespread community adoption of improved cookstoves. The study concluded that continued innovation, testing, and dissemination of cleaner biomass cookstove technologies are essential for enhancing public health outcomes and fostering environmental sustainability (Modi et al., 2025).

2.3.2 Thermal Efficiency Analysis with Different Gasification Agents

2.3.2.1 Steam as Gasification Agent

Steam gasification represents an advanced approach to biomass conversion with significant potential for improved thermal efficiency. According to research conducted by Petro Giamini and Mauro (2018), an integrated pyrolysis regenerated plant can be combined with a steam gasification plant to produce hydrogen from charcoal. The plant design is based on the energy balance of their experimental test, which utilizes a pyro-reforming stage coupled with steam gasification. Their analysis focuses on heat integration between the pyro-reforming and steam gasification processes. The findings demonstrate that the pyrolysis process can fully provide the heat requirements of the pyrolysis, reforming, and steam gasification stages, resulting in the production of 0.03 kg of hydrogen per kilogram of biomass.

The study by Rabby et al. (2023) was conducted in Bangladesh and involved a systematic literature review aimed at summarizing the overall thermal performance of

various gasifier cooking stoves. The researchers reviewed studies published between 2008 and 2022 by searching Scopus, Google Scholar, and Web of Science databases using keywords such as “Gasifier cooking stove,” “producer gas cooking stove,” and “thermal performance” (Rabby et al., 2023). After screening, 28 relevant articles were selected, which highlighted different gasified stove designs, cooking fuels, and fabrication materials alongside their thermal performance. The findings revealed that overall thermal efficiency varied widely from 5.88% to 91%, depending on the stove design and type of fuel. Specifically, premixed producer gas burners with a swirl vane stove achieved the highest efficiency range of 84% to 91%, while updraft gasified stoves had the lowest performance between 5.88% and 8.79%. In terms of fuels, wood pellets delivered the highest thermal performance at 38.5%, whereas corn straw briquettes recorded the lowest at 10.86% (Rabby et al., 2023).

Khan and Al-attab (2022) conducted a comprehensive review of steam gasification of biomass for hydrogen production, beginning with an analysis of reactor types, gasifying agents, and theoretical fundamentals before systematically comparing steam gasification against air, oxygen, and CO₂ approaches; they identified key performance influences such as feedstock characteristics, catalysts, operating temperature, residence time, equivalence ratio, and steam-to-biomass ratio, and concluded that while steam gasification offers superior hydrogen yields and cleaner syngas, significant barriers remain—particularly in downstream processing, economic feasibility, and commercialization maturity (Khan & Al-attab, 2022). The study further highlighted techno-economic challenges and the need for pilot-scale validation to bridge gaps in scale and practical deployment.

A comprehensive economic analysis of hydrogen production from conventional and alternative energy fuels has demonstrated that biomass gasification and pyrolysis exhibit strong competitiveness in comparison to other energy sources. Based on the obtained results, it is feasible to establish a facility that combines pyrolysis and reforming of volatiles, generating heat for the pyrolysis, reforming, and char steam gasification processes simultaneously. An essential component of the plant is the combustor, which supplies energy for several processes such as heating, pyrolysis, reforming, and steam gasification. The energy equilibrium of the combustor is determined by the equation $H_{\text{fuel}} + H_{\text{air}} + \text{LHV}_{\text{fuel}} = H_{\text{fg}} + (\text{Heat EXT})/\text{efficiency}$.

Through simulations, researchers determined that the syngas composition obtained consists of 13.5% CO, 15.5% CO₂, 9.0% H₂, and 60% N₂. The findings align with the syngas composition derived from oil palm fronds according to Atnaw, Sulaiman, and Yusuf (2013). The syngas production demonstrated the highest mass yields compared to fuel and steam production, attributed to the high airflow in the combustion chamber, which enables complete combustion of the syngas and maintains an energy ratio of 4.0. The researchers concluded that syngas are viable energy sources for generating heat and power to meet various energy requirements. Steam as a gasification agent reduces carbon monoxide emissions while maintaining higher firepower compared to air-only systems.

2.3.2.2 Biodiesel and Spirit as Alternative Gasification Agents

The utilization of non-renewable energy sources has resulted in several worldwide issues, including global warming, pollution, and smog generation according to Juan Camilo, Yessica Peres, and Carlos Ariel (2018). Therefore, the potential of lignocellulose biomass as an energy source to meet energy needs has been proposed.

Alternative gasification agents like biodiesel and methylated spirit offer unique advantages in thermal efficiency optimization through their controlled combustion characteristics and precise metering capabilities for optimal fuel-to-air ratios in retrofitted stove systems.

Mojaver, Khalilarya, Chitsaz, and Jafarmadar (2024) applied a systematic multi-criteria decision-making framework combined with sensitivity analysis to evaluate the performance of biomass gasification using different feedstocks and gasifying agents. Their analysis revealed that biomass type and gasifying agent significantly influenced syngas yield, efficiency, and environmental performance, with sensitivity tests highlighting the most influential criteria in decision outcomes. The study concluded that integrating multi-criteria decision models with sensitivity analysis provides a transparent and robust approach for selecting optimal biomass-agent combinations; however, it did not include experimental validation, cost analysis, or life-cycle assessment, leaving gaps on scalability and real-world applicability (Mojaver et al., 2024).

Román Suero, Ledesma Cano, Álvarez-Murillo, Al-Kassir, and Yusaf (2015) investigated the use of glycerin—a biodiesel byproduct—as a feedstock for hydrogen production via steam gasification. The study conducted controlled experimental tests in a lab-scale reactor to assess how glycerin conversion into hydrogen varied with temperature and water-to-glycerin ratios. The results showed that glycerin steam gasification could yield significant hydrogen production, demonstrating both the feasibility and potential efficiency of using biodiesel residues as a renewable hydrogen source (Román Suero et al., 2015). The researchers concluded that glycerin is a viable and sustainable alternative for clean hydrogen generation, especially when

conventional feedstocks are scarce or costly. However, the study identified several gaps: it was limited to bench-scale tests, lacked techno-economic analysis to evaluate cost-benefit scenarios, and did not assess the environmental impacts or scalability of the process for real-world applications.

Rauch, Hrbek, and Hofbauer (2016) explored biomass gasification as a versatile pathway for producing synthesis gas, detailing its potential applications in generating transportation fuels, chemicals like methanol and synthetic natural gas, and pure hydrogen for industrial use or fuel cells. They categorized gasification systems by heat introduction (allothermal vs autothermal), reactor type (fixed-bed, fluidized-bed, entrained flow), and gasifying agent (oxygen, steam, or mixtures thereof), while noting that although syngas has about 30% the energy density of natural gas and thus requires upgrading for practical use, it remains an excellent intermediate energy carrier (Rauch et al., 2016). The chapter emphasized the need for advancements in gas purification and energy recovery to enhance the efficiency and applicability of syngas technologies.

Research has demonstrated that different gasification agents provide varying performance characteristics. Biodiesel as a gasification agent offers advantages in terms of energy density and combustion stability, while methylated spirit provides rapid ignition properties and clean burning characteristics. These agents can be precisely controlled to achieve optimal combustion conditions, unlike traditional air-only gasification systems that are more difficult to regulate.

The selection of gasification agent significantly impacts the overall thermal efficiency of the retrofitted stove system. Studies have shown that liquid gasification agents can provide more consistent fuel delivery and better combustion control compared to

gaseous agents alone. This consistency is particularly important in maintaining stable cooking temperatures and reducing emissions during the cooking process.

2.3.2.3 Comparative Thermal Efficiency Studies

Advanced stove designs achieve significant efficiency improvements over traditional systems through various design innovations. According to Still, Bentson, Lawrence, and Dr. Andreatta (2015), Natural Draft Sunken Pot Rocket Stoves achieve thermal efficiency around 49.7% through enhanced heat transfer design that facilitates direct contact between hot gases and the cooking pot. The fitted chimney addresses indoor emissions by directing smoke out of the cooking area, while the stove design enhances heat transfer to the cooking pot through direct contact between hot gases and the pot.

The study by Meng et al. (2017) was carried out in China and focused on comparing the structural efficiencies of different thermal protection system (TPS) concepts. Using a comparative design-based approach, the researchers analyzed typical TPS structures to determine their effectiveness in balancing thermal insulation and structural performance. The findings revealed that different thermal protection concepts varied significantly in terms of efficiency, with some providing superior thermal resistance but at the cost of increased weight and complexity, while others offered better structural integrity but lower insulation efficiency. The study concluded that selecting an optimal TPS requires careful trade-offs between thermal performance, structural stability, and weight considerations to meet specific engineering requirements (Meng et al., 2017).

The study by Moolavi Sanzighi, Soflaei, and Shokouhian (2021) was conducted in Iran and examined the thermal performance of three generations of residential buildings in Csa Gorgan. Through case studies, the researchers compared traditional, transitional, and modern building designs, focusing on how architectural features and construction

materials influenced indoor thermal comfort and energy efficiency. The findings indicated that traditional buildings, with their passive design strategies such as thick walls, natural ventilation, and shading devices, demonstrated better thermal regulation compared to modern buildings that relied more heavily on mechanical systems. Transitional buildings showed moderate performance, reflecting a mix of traditional and modern elements. The study concluded that incorporating traditional passive strategies into contemporary housing designs could significantly improve thermal comfort and reduce energy consumption in Iranian residential contexts (Moolavi Sanzighi et al., 2021).

Top-lit Up Draft stoves, representing the most environmentally friendly solid biomass cook stove type according to empirical evidence, utilize batch feeding and top ignition with bottom primary air supply. The secondary air holes provide sufficient oxygen for combustion while imparting high velocity jets of air to mix the combustible gases, air and the flame. Thoroughly heating the secondary air on the edges of the combustion chamber enhances both the combustion process and the efficiency of heat transmission according to Still, Bentson, Lawrence, and Dr. Andreatta (2015).

Research conducted at the Addis Ababa Institute of Technology developed a micro-gasifier stove that achieved 39.6% thermal efficiency with specific fuel consumption of 57 grams per liter of water. According to Adem and Ambie (2017), the highest reported CO and PM_{2.5} emission levels were 12.5 parts per million and 1.85 mg/m³ respectively, demonstrating the potential for clean combustion in properly designed gasifier systems.

The Aprovecho Research Center's charcoal stove, shown in Figure 2.6, incorporates several design features that minimize heat dissipation via the bottom and sides of the stove through insulation of the apparatus sides. The implementation of supplementary

air in the upper part of the combustion chamber effectively decreases carbon monoxide emissions, while the stove design ensures a consistent cross-sectional area of the combustion chamber to enhance heat transfer efficiency. A skirt around the pot creates a 6mm channel gap, and this reduced skirt gap ensures high power Tier 4 thermal efficiency according to Still, Bentson, Lawrence, and Dr. Andreatta (2015).

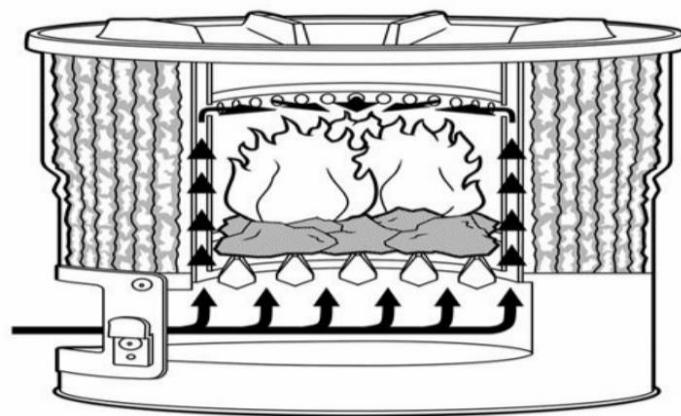


Figure 2.6: Design of the ARC charcoal stove
(Still, D., Bentson, S., Lawrence, R. H., & Dr. Andreatta, D, 2015)

2.3.3 Techno-Economic Analysis of Retrofitted Stove Technologies

2.3.3.1 Economic Feasibility and Market Analysis

In Greece, Mitkidis, Magoutas, and Kitsios (2018) conducted a study to examine the market and economic feasibility of implementing second-generation biofuels as a means of reducing fossil fuel dependence and supporting sustainable energy development. The researchers employed a two-step methodology that first involved a market analysis to review the state of the biofuels sector in Greece and assess the availability of residues, waste, and cellulosic materials as potential feedstocks. This was followed by an economic feasibility assessment that evaluated production routes, costs, and investment opportunities associated with biofuel development. The findings revealed that although there was a significant market gap in Greece's biofuels sector,

the country had adequate indigenous resources to support production of second-generation biofuels. The study concluded that local production could provide an attractive short to medium-term investment opportunity if supported by appropriate technological pathways and efficient feedstock utilization. It further emphasized that government involvement through careful planning, policy support, and industry reforms was essential to realize this potential and align with the European Union Renewable Energy Directive (RED II) targets (Mitkidis et al., 2018).

In India, Chauhan and Saini (2016) conducted a techno-economic feasibility study on the development of an Integrated Renewable Energy System (IRES) aimed at providing reliable power and cooking energy to isolated rural communities in the Chamoli district of Uttarakhand state. The study employed a methodology that involved estimating the potential of locally available renewable resources and analyzing the energy demand of village hamlets in the area. A site-specific selection of small wind turbine models was undertaken from available market options, and nine different combinations of renewable energy resources were evaluated based on technical, economic, and social criteria. Additionally, a sensitivity analysis was performed to identify the most critical parameters influencing the system's performance. The findings indicated that the integration of locally available renewable resources into an IRES framework could provide a sustainable solution for meeting both electrical and cooking energy needs in isolated communities. The study concluded that such systems are not only technically feasible but also economically viable if carefully planned and optimized according to local conditions (Chauhan & Saini, 2016).

Kenya represents the most developed cooking industry in East Africa regarding both access to improved cookstoves and the variety of cleaner cooking innovations available

on the market. According to Stephens (2020), Kenya debuted cooking technological advancements in the 1980s, and ever since, the nation has been regarded as a pioneer in East Africa. Even while acceptance rates continue to rise, there are still many challenges, especially when it comes to distribution and uptake of clean and improved cookstoves in rural areas. Despite significant recent progress, solid fuels continue to be the most common cooking fuel in Kenya, with more than 90% of Kenyans living in rural areas and more than 75% of all households still using fuelwood or charcoal for cooking. The primary means of cooking for about 20% of households is liquified petroleum gas, while roughly 3 percent of families own electric cookstoves, including electric coil stoves and microwaves according to the Ministry of Energy (2019).

The Kenya Ceramic Jiko exemplifies successful economic implementation of improved cookstove technology. First introduced to the Kenyan market in the late 1970s, KCJ is regarded as one of the most prosperous urban projects in developing countries. Several eastern African nations, including Uganda, Tanzania, Rwanda, Ethiopia, and Senegal, have replicated this concept. Nearly 700,000 units had been built in Kenya by 1995, comprising 56% of urban families and 16.8% of all houses. Three sizes of the cookstove are offered - small, standard, and medium - with prices ranging from 400 to 3,000 Kenya shillings. The cookstove's thermal efficiency ranges between 28 and 35%, while its carbon monoxide emissions are quite low.

In Kenya, almost 50% of households and families utilize a combination of technology and fuels for cooking, with some even using three or more different systems. According to the Ministry of Energy (2019), charcoal and firewood are the only fuel sources used by 93% of rural residents. More than 33% of homes in metropolitan areas still use a backup stove that runs on fuelwood or charcoal, even though 46% of households use

LPG as their primary fuel. Only 0.4% of urban people utilize clean cooking technologies such as electric stoves, biogas, and bioethanol as their main source of cooking, with the remaining 0.8% using them as backup systems.

2.3.3.2 Cost-Benefit Analysis of Gasification Agents

Comprehensive economic analysis demonstrates that biomass gasification and pyrolysis exhibit strong competitiveness compared to other energy sources. The economic viability of different gasification agents varies significantly based on several factors including initial setup costs, operational expenses, fuel availability, and performance characteristics. Steam gasification, while requiring higher initial setup costs due to steam generation equipment, provides improved efficiency and reduced emissions that can justify the investment over the long term. The system requires careful consideration of water quality, steam generation costs, and maintenance requirements for steam delivery systems.

Biodiesel as a gasification agent offers moderate costs with reliable performance characteristics, particularly in terms of energy density and combustion stability. The economic analysis must consider the cost of biodiesel procurement, storage requirements, and the potential for local production from waste cooking oils or dedicated energy crops. Studies have shown that biodiesel provides consistent fuel delivery and better combustion control compared to gaseous agents alone, which can translate to improved cooking efficiency and reduced fuel consumption over time.

Methylated spirit presents lower initial costs but requires careful handling and storage considerations that may impact overall economic viability. While offering rapid ignition properties and clean burning characteristics, the economic analysis must account for safety equipment, proper ventilation systems, and trained handling

procedures. The volatility of methylated spirit prices and availability in rural areas also affects long-term economic sustainability.

According to Juan Camilo, Yessica Peres, and Carlos Ariel (2018), the economic competitiveness of different gasification agents depends largely on local fuel availability, infrastructure development, and user training requirements. The lifecycle cost analysis should include not only fuel costs but also maintenance, replacement parts, and potential health cost savings from reduced emissions exposure.

2.3.3.3 Barriers to Adoption and Economic Challenges

Barriers to the adoption of improved cook stoves and the associated economic challenges have been widely documented. According to Palit (2014), six key barriers exist in Asia and Sub-Saharan Africa. These include the overemphasis on technology at the expense of user-friendliness, shifts in household purchasing habits, limited income and financing alternatives, and the lack of stove makers and market participants in remote areas. In addition, the adoption of these stoves often requires a lifestyle transformation, which many households find difficult, and there remains a significant knowledge gap due to insufficient data and information.

In the Kenyan context, adoption levels remain relatively low. Only 26 percent of the population use improved cook stoves, while about 86 percent continue to rely on conventional cooking fuels. This slow uptake can be attributed to challenges such as inadequate funding to support large-scale adoption, sluggish technological development, low consumer awareness of the benefits of improved cook stoves, and underdeveloped infrastructure for both fuel and stove production and distribution (Karanja & Gasparatos, 2020). These constraints highlight the interplay between

economic limitations and systemic barriers that hinder the transition to energy-efficient cooking solutions.

2.3.4 Market Potential and Investment Opportunities

Enhanced cook stoves unable to fully replace conventional stoves face challenges including stove malfunctions, delayed user training, and inability to cater to varied household cooking requirements. This creates opportunities for future research by manufacturers and researchers to expedite widespread adoption of clean technologies, as households traditionally undergo lengthy energy transitions.

The techno-economic analysis must consider cultural customs, family size, and regional preferences to ensure successful retrofitted stove implementation. Economic analysis should incorporate lifecycle costs, maintenance requirements, fuel availability, and potential revenue streams from carbon credit mechanisms.

2.4 Gaps in Literature

Although extensive research has been conducted on biomass cookstoves, significant gaps still remain in the design, performance evaluation, and adoption of retrofitted stoves. Most empirical studies focused on traditional biomass stoves or on incremental improvements in efficiency and emissions without fully addressing the integration of multiple gasification agents. For example, Prakash (2009) concentrated on insulation, airflow control, and pot-skirt design to reduce smoke and improve thermal efficiency, while Dijan, Supramono, and Farah (2013) examined the role of secondary airflow in reducing carbon monoxide emissions. However, such studies largely emphasized single-fuel combustion and failed to explore the potential of co-firing biomass with alternative agents such as steam, biodiesel, and spirit. This represented a critical

knowledge gap since combining solid and liquid fuels could optimize thermal efficiency and broaden fuel flexibility for households with diverse biomass residues.

Another gap emerged in the evaluation of thermal efficiency under varied gasification agents. While Petro Giamini and Mauro (2018) demonstrated that steam gasification could enhance hydrogen production and reduce carbon monoxide emissions, and Atnaw, Sulaiman, and Yusuf (2013) confirmed favorable syngas compositions from biomass residues, such studies were primarily laboratory-based and rarely tested in household-scale cookstove systems. Similarly, research on biodiesel and spirit as gasification agents (Juan Camilo, Peres, & Ariel, 2018) emphasized combustion properties but lacked applied analysis in rural cooking environments. This limited understanding of how these agents performed under real-world conditions where variables such as fuel moisture, intermittent feeding, and user behavior influence stove efficiency.

From a socio-economic perspective, adoption challenges remain inadequately addressed. Rogers' Diffusion of Innovations theory (Rogers, 2003) highlighted compatibility, affordability, and complexity as critical factors in household technology adoption. However, as Karanja and Gasparatos (2020) observed, adoption of improved cookstoves in Kenya stood at only 26 percent, with affordability and cultural practices being major barriers. While the Kenya Ceramic Jiko (Stephens, 2020) demonstrated economic viability and widespread diffusion in urban settings, rural households continued to rely heavily on firewood and charcoal due to fuel costs, stove durability, and limited distribution networks. These realities suggest that many studies overlooked the intersection between technical performance, affordability, and cultural acceptance, leading to low long-term adoption despite proven stove designs.

Additionally, while global and regional studies have highlighted the potential of clean cooking technologies in reducing health risks and deforestation (WHO, 2020; FAO, 2020), there remains a scarcity of locally grounded research that integrates techno-economic feasibility with practical performance evaluation in Sub-Saharan African contexts. The lack of comprehensive lifecycle cost-benefit analyses, including health cost savings, carbon credits, and maintenance requirements, further widens the research gap. Moreover, agricultural residues such as maize cobs and sugarcane bagasse remain underutilized despite their abundance in Kenya, mainly due to incompatibility with existing stove technologies (Mutai, 2022). This demonstrates the absence of adaptable stove models capable of efficiently co-firing diverse residues with alternative fuels.

Therefore, the gaps in literature can be summarized into three major areas: the limited exploration of co-firing biomass with steam, biodiesel, and spirit in household stoves; the lack of empirical studies that bridge laboratory-based findings with real-world cooking environments; and the inadequate integration of technical, economic, and socio-cultural dimensions in assessing the adoption and sustainability of improved cookstove technologies. Addressing these gaps requires research that not only designs and validates retrofitted stoves for multiple fuel agents but also evaluates their techno-economic feasibility and adoption potential within local contexts.

2.5 Conceptual Framework

The conceptual framework of this study was guided by the need to evaluate the performance of a retrofitted stove when co-firing biomass with steam, spirit, and biodiesel. The independent variable was the design and fabrication of the retrofitted stove, which was assessed through three indicators: the materials selected and used for fabrication, the airflow and combustion system incorporated into the design, and the

validation tests that confirmed the durability, usability, and safety of the stove. These aspects were critical because previous studies have shown that stove design strongly influences both efficiency and emission levels, with poorly designed devices leading to higher indoor pollution and fuel consumption (Jetter et al., 2012).

The gasification agents functioned as the intervening variable. In this study, steam, methylated spirit, and biodiesel were tested as supplementary agents to enhance the combustion of biomass. Studies have demonstrated that the co-firing of biomass with secondary agents can increase combustion efficiency by up to 30 percent and reduce particulate matter emissions (Prakash et al., 2019; Alemayehu & Asfaw, 2021). Their role was therefore to improve the thermal properties of the stove, enabling efficient burning of residues such as maize cobs, bagasse, and sawdust, which remain underutilized in traditional cook stoves (Mutai, 2022).

The dependent variables were twofold. The first was thermal efficiency, which was measured through the rate of fuel consumption, the duration of cooking, and the heat transfer efficiency of the stove. According to Kammen and Sunter (2016), improved thermal efficiency reduces the pressure on forest resources while saving households significant time in cooking. The second dependent variable was the techno-economic performance, measured by the cost of stove construction and operation, the payback period and fuel savings achieved, and the adoption potential of the technology based on its affordability and adaptability to local conditions. Studies in Kenya and India revealed that households were more likely to adopt improved stoves when they offered measurable economic benefits, such as reduced fuel expenses and quicker cooking times (Malla & Timilsina, 2014; Rosen et al., 2015).

By linking the independent variable of stove design with the intervening role of gasification agents, and further connecting these to the dependent variables of thermal efficiency and techno-economic performance, the framework illustrated how technological innovation in stove design could address both energy efficiency and sustainability challenges. This structure provided a systematic pathway for analyzing how improved stove technologies could optimize household energy use while reducing health and environmental burdens (WHO, 2020; FAO, 2020).

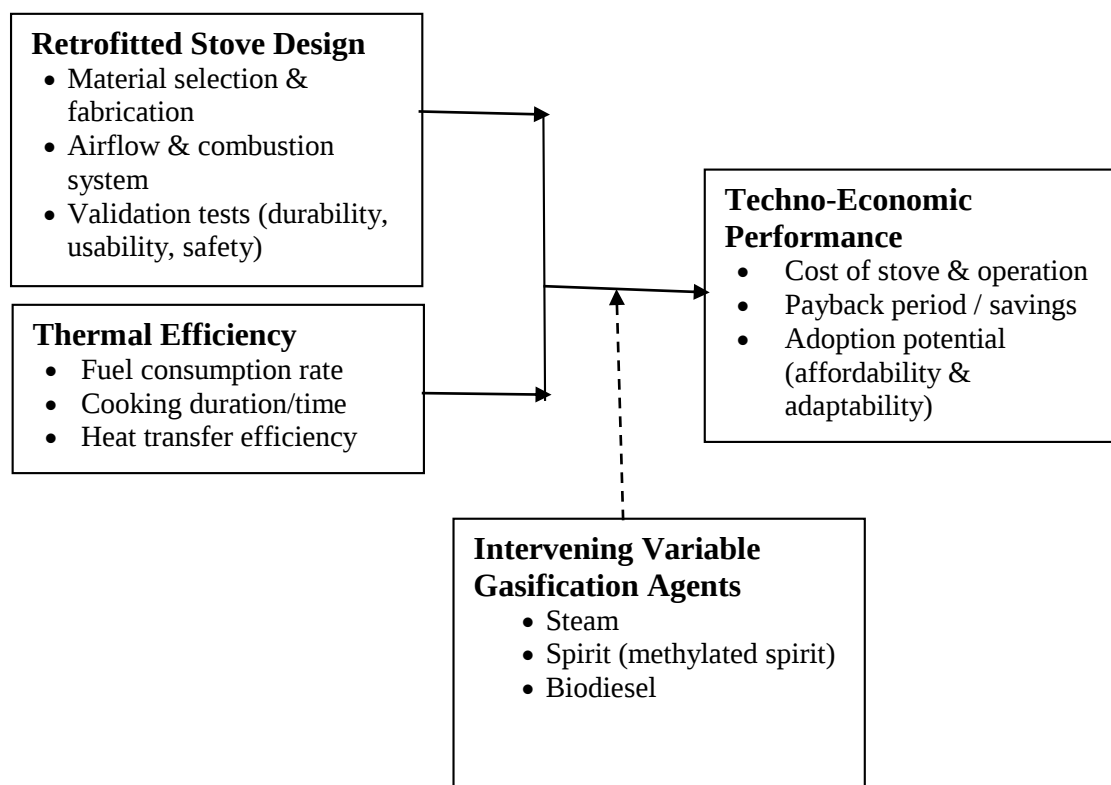


Figure 2.7 Conceptual Framework

Source (Researcher, 2025)

CHAPTER THREE

RESEARCH DESIGN AND METHODOLOGY

3.1 Research Design

This study adopted an experimental research design to evaluate the performance of a retrofitted cookstove through co-firing biomass with steam, spirit, and biodiesel. Experimental designs are appropriate where controlled conditions are required to test the performance of a system under varying input parameters (Kothari, 2014). The approach allowed systematic evaluation of the retrofitted cookstove through laboratory-based testing, where fuel types, combustion conditions, and retrofitting options were manipulated while key performance indicators such as thermal efficiency, fuel consumption, and time to boil were measured.

The experimental design was structured as a controlled comparative study where the independent variables comprised different fuel combinations including biomass alone, biomass with steam, biomass with spirit, and biomass with biodiesel. The dependent variables included thermal efficiency, specific fuel consumption, time to boil, and fuel consumption rate, while controlled variables encompassed water volume at two liters, ambient conditions, stove design specifications, and standardized testing procedures. The experimental approach utilized a repeated measures design with three replications per treatment to ensure statistical validity and reliability of results.

The design was suitable because it provided objective and quantifiable results on the influence of co-firing biomass with steam, spirit, and biodiesel, enabling statistical comparison of performance parameters across different fuel combinations. This approach is consistent with established methodologies in cookstove performance evaluation research as documented by Bailis et al. (2009) and provides a robust

framework for drawing valid conclusions about the effectiveness of different co-firing strategies.

3.2 Materials

3.2.1 Stove Construction Materials

The stove was fabricated using carefully selected materials based on their thermal properties, availability, and cost-effectiveness. Mild steel sheets of Grade 1018 with 3mm thickness were selected as the primary construction material for the combustion chamber and outer casing due to their excellent high-temperature resistance, durability, and workability characteristics. The material can withstand temperatures up to 600°C, which falls within the typical operating range of biomass cookstoves, making it ideal for sustained high-temperature operations (Raman et al., 2013).

Table 3.1: Materials Used in Stove Construction

Material	Specification	Quantity	Purpose	Selection Criteria
Mild Steel Sheets	Grade 1018, 3mm thickness	2 m ²	Combustion chamber, outer casing	High temperature resistance, durability, workability
Insulation Bricks	Fire clay bricks, 230×114×76mm	20 pieces	Chamber lining, heat retention	Low thermal conductivity, high heat capacity
Sand	River sand, fine grade	50 kg	Insulation layer, structural fill	Thermal mass, local availability
Cement	Portland cement, Grade 42.5	10 kg	Structural binding, reinforcement	Strength, durability at high temperatures
Steel Grate	Mild steel bars, 8mm diameter	1 piece	Fuel support, air distribution	Structural strength, airflow optimization
Chimney Pipe	Galvanized steel, 150mm diameter	1 m	Smoke evacuation	Corrosion resistance, proper draft

Fire clay insulation bricks with dimensions of 230×114×76mm were employed to line the interior walls of the combustion chamber. These bricks were specifically chosen for their low thermal conductivity and high heat capacity properties, which minimize heat

loss and improve thermal efficiency by retaining heat within the combustion chamber (Bryden et al., 2005). The insulation layer created by these bricks significantly reduces external surface temperatures and improves overall energy efficiency of the system.

River sand of fine grade served as both an insulation medium and structural fill material, providing thermal mass that helps stabilize combustion temperatures and reduces thermal cycling effects. Portland cement of Grade 42.5 was utilized for structural binding and reinforcement, selected for its ability to maintain strength and integrity under high-temperature conditions encountered in cookstove operations. The cement provides crucial structural support while maintaining dimensional stability during thermal expansion and contraction cycles.

A steel grate fabricated from 8mm diameter mild steel bars was positioned within the combustion chamber to support the biomass fuel and facilitate optimal air distribution. The grate design allows primary airflow from below the chamber while providing adequate structural support for fuel loads. Galvanized steel chimney pipe with 150mm diameter was installed for smoke evacuation, chosen for its corrosion resistance properties and ability to maintain proper draft conditions throughout the system lifespan.

The materials were chosen due to their affordability, accessibility, and suitability for thermodynamic applications, consistent with recommendations by Krishnan et al. (2016). All materials were sourced locally where possible to reduce costs and ensure availability for potential scaling of the technology.

3.2.2 Fuel Materials

Three primary fuel types were utilized in the study, each selected based on availability, energy content, and potential for effective co-firing applications. The biomass

component consisted of eucalyptus wood and agricultural residues, representing the most commonly available solid fuels in rural areas. Eucalyptus wood was chosen due to its relatively high calorific value of 18.5 MJ/kg and consistent burning characteristics, while agricultural residues provided a renewable alternative with a calorific value of 16.2 MJ/kg (Njenga et al., 2016).

Table 3.2: Fuel Properties and Specifications

Fuel Type	Source	Calorific Value (MJ/kg)	Moisture Content (%)	Density (kg/m³)	Procurement Method
Biomass (Wood)	Local eucalyptus	18.5	<15	550	Air-dried, chopped to 10cm pieces
Biomass (Residues)	Agricultural waste	16.2	<15	200	Sun-dried, pelletized
Ethanol Spirit	Local distillery	26.8	<5	789	Commercial grade, 95% purity
Biodiesel	Waste vegetable oil	37.2	<2	880	Transesterified, filtered

Ethanol spirit was procured from local distilleries and represented a potentially sustainable liquid fuel option with a high calorific value of 26.8 MJ/kg. The spirit was sourced at 95% purity with water content maintained below 5% to ensure consistent combustion characteristics and prevent flame instability issues. The choice of ethanol was motivated by its renewable nature and potential for local production from agricultural feedstocks (Sims et al., 2010).

Biodiesel derived from waste vegetable oil processing was selected as the third co-firing fuel due to its high energy density of 37.2 MJ/kg and favorable combustion properties. The biodiesel underwent transesterification processes to convert

triglycerides to methyl esters, resulting in a fuel with improved flow characteristics and reduced viscosity compared to raw vegetable oil. Water content was maintained below 2% and acid value kept under 0.5 mg KOH/g to ensure fuel quality and prevent corrosion issues (Demirbas, 2008).

3.3 Methodology

3.3.1 Stove Design and Fabrication

The cookstove was designed following established principles of efficient biomass combustion, integrating features that enhance air–fuel mixing and heat transfer. The design was informed by guidelines from the Partnership for Clean Indoor Air, which emphasize optimized chamber dimensions for efficiency and reduced emissions (Still et al., 2003). Accordingly, a compact combustion chamber with a volume of 0.025 m³ was constructed to maintain an appropriate residence time for complete combustion while ensuring efficient heat transfer to the cooking surface.

Fabrication involved precision cutting and welding of mild steel sheets to construct the combustion chamber, which had internal dimensions of 25 cm × 25 cm × 40 cm. Metal inert gas welding techniques were employed to produce strong and gas-tight joints capable of withstanding thermal stresses. The interior walls were lined with fire bricks to form a uniform 5 cm insulation layer. This design minimized heat loss while maintaining the high internal temperatures required for effective biomass combustion.

The air inlet system was carefully configured to enhance combustion efficiency. The primary air inlet, with an area of 80 cm², was positioned below the fuel grate, while a secondary air inlet of 40 cm² was located at mid-height in the chamber. This arrangement ensured optimal air distribution, with primary air supporting initial combustion and secondary air enabling complete oxidation of volatile gases, in line

with the principles of Reed and Larson (1996). The fuel grate, positioned 10 cm above the chamber base, was fabricated using 8 mm steel bars spaced at 15 mm intervals to allow sufficient airflow while securely holding fuel loads of up to 2 kg. Pot supports were installed 15 cm above the chamber to enhance heat transfer to cooking vessels while accommodating standard household cookware.

The retrofitting process introduced co-firing capabilities for ethanol spirit, biodiesel, and steam. Dedicated injection ports were integrated into the stove structure to facilitate this modification. The spirit injection system used a brass nozzle with a 0.5 mm orifice positioned in the secondary combustion zone to promote efficient mixing and complete combustion. For biodiesel co-firing, a pressure atomizer with a 1.0 mm orifice was installed in the primary combustion zone to ensure proper atomization and mixing. Additionally, a steam injection system connected to an external steam generator delivered superheated steam at 150°C directly into the chamber. The steam nozzles were strategically placed to increase turbulence and improve combustion efficiency, ultimately enhancing the overall performance of the retrofitted cookstove.

3.3.2 Fuel Preparation and Characterization

Comprehensive fuel preparation was undertaken to ensure consistency and optimal performance across all test runs, following established protocols for cookstove fuel preparation (Jetter & Kariher, 2009). Wood biomass preparation involved air-drying eucalyptus logs for thirty days to achieve moisture content below 15%, which is critical for achieving high combustion efficiency and reducing smoke emissions. The dried wood was then chopped into uniform pieces of 10cm length with cross-sectional dimensions of approximately 3cm × 3cm to ensure consistent burning characteristics and facilitate reproducible fuel loading procedures.

Agricultural residues underwent sun-drying for fourteen days followed by chopping and pelletizing processes to achieve uniform density of 200 kg/m³. The pelletizing process improved handling characteristics and provided consistent fuel feed rates during testing. Both biomass types were stored in covered areas with adequate ventilation to maintain moisture levels while preventing rewetting from environmental humidity.

Ethanol spirit preparation involved purity verification using alcoholometry and water content testing using Karl Fischer titration to confirm specifications. The spirit was filtered through activated carbon filters to remove impurities that could affect combustion characteristics or cause deposits in injection systems. Quality control measures ensured 95% minimum purity with water content maintained below 5% throughout the study period.

Biodiesel preparation was more complex, involving initial filtering through 10µm filters to remove particulates followed by water separation using centrifugal methods. Quality testing included acid value determination, water content analysis, and viscosity measurement to ensure compliance with ASTM D6751 specifications. The final product exhibited acid value below 0.5 mg KOH/g and water content below 0.2%, meeting requirements for reliable injection system operation.

All fuels were stored in appropriate containers prior to testing to maintain consistency and prevent contamination. Wood and agricultural residues were kept in covered storage areas maintaining ambient conditions, while liquid fuels were stored in sealed containers under controlled temperature conditions to prevent degradation and maintain specified properties throughout the testing period.

3.3.3 Stove Retrofitting and Co-firing System

The fabricated stove was retrofitted with a sophisticated dual-fuel injection system engineered to enable effective co-firing of biomass with either spirit or biodiesel while maintaining operational safety and user-friendliness. The retrofitting incorporated precision-engineered components designed specifically for small-scale combustion applications, following design principles established by Kaupp and Goss (1984) for biomass gasification and combustion systems.

Table 3.3: Retrofitting System Components

Component		Specification	Function	Installation Location
Spirit Injection Nozzle		0.5mm orifice, brass	Atomized injection	spirit Secondary combustion zone
Biodiesel Injector		Pressure atomizer, 1.0mm	Biodiesel injection	spray Primary combustion zone
Steam Generator		2kW electric, 5L capacity	Steam production and injection	External unit with feed line
Control Valves		Manual ball valves, ¼"	Flow rate regulation	Fuel feed lines
Pressure Gauges		0-5 bar range	System monitoring	Injection manifold
Feed Pumps		Diaphragm type, 12V	Fuel delivery	External mounting

The spirit injection system utilized a precision-machined brass nozzle with 0.5mm orifice diameter positioned in the secondary combustion zone approximately 20cm above the fuel grate. This positioning ensures adequate mixing time for the atomized spirit with combustion air while maintaining flame stability. The nozzle design creates a fine spray pattern with Sauter mean diameter of approximately 50 micrometers, facilitating rapid evaporation and mixing with the primary combustion gases.

Biodiesel injection employed a pressure atomizer with 1.0mm orifice capable of operating at pressures up to 3 bar to achieve adequate atomization of the higher viscosity fuel. The injector was positioned in the primary combustion zone to allow maximum residence time for complete combustion of the biodiesel spray. A diaphragm-type feed pump provided consistent pressure and flow rate control, with manual ball valves enabling precise adjustment of injection rates during operation.

The steam generation system consisted of a 2kW electric steam generator with 5-liter water capacity capable of producing superheated steam at temperatures up to 150°C. Steam was delivered to the combustion chamber through insulated stainless-steel lines with flow control valves allowing regulation of steam injection rates from 0.5 to 5 kg/h. The steam injection points were strategically located to maximize turbulence and enhance mixing without disrupting the primary combustion zone stability.

Safety features were extensively incorporated throughout the retrofitting system including pressure relief valves set at 5 bar maximum system pressure, emergency shut-off systems accessible from the operator position, and flame arresters installed in all fuel feed lines to prevent backfire incidents. Temperature sensors monitored critical system points with automatic shutdown capabilities if predetermined temperature limits were exceeded.

The complete retrofitting system ensured versatility in operation under different combinations of fuels while maintaining user-friendliness through intuitive controls and clear operational indicators. Operational procedures were developed and tested to ensure safe and reliable performance under normal operating conditions while providing clear guidelines for startup, operation, and shutdown sequences.

3.3.4 Performance Testing Protocol

Performance testing was conducted using the internationally standardized Water Boiling Test protocol as specified in the International Workshop Agreement IWA 11:2012 (IWA, 2012). This protocol was selected due to its widespread acceptance in cookstove performance evaluation and its ability to provide reliable, reproducible results that can be compared with other cookstove studies worldwide. The testing methodology assesses fundamental stove performance parameters including thermal efficiency, fuel consumption rate, specific fuel consumption, and time required to boil a standard water load.

Table 3.4: Water Boiling Test Protocol

Parameter	Specification	Measurement Method	Equipment Used
Water Volume	2.0 ± 0.1 liters	Volumetric measurement	Graduated cylinder (±10ml)
Initial Water Temperature	Ambient (20-25°C)	Direct measurement	Calibrated thermometer (±0.1°C)
Boiling Criteria	Rolling boil for 30 seconds	Visual observation	Timer, temperature probe
Fuel Measurement	Pre and post-test weighing	Gravimetric analysis	Digital scale (±0.1g)
Test Duration	Until rolling boil achieved	Continuous monitoring	Digital stopwatch (±0.1s)
Ambient Conditions	20-25°C, <60% RH	Environmental monitoring	Hygrometer, thermometer

The testing protocol required precise measurement of water volume at exactly two liters using calibrated measuring cylinders with ±10ml accuracy. Water was sourced from a consistent supply and allowed to equilibrate to ambient temperature before each test to

ensure starting conditions remained constant across all experimental runs. Initial water temperature was measured using calibrated thermometers with $\pm 0.1^\circ\text{C}$ accuracy and recorded for each test run to enable accurate thermal efficiency calculations.

The boiling endpoint was defined as the achievement of rolling boil sustained for thirty seconds, determined through visual observation supplemented by temperature measurement using digital probes. This criterion ensures consistent endpoint determination across all tests while accounting for the thermal mass of the cooking vessel and test setup. Time measurements utilized digital stopwatches with ± 0.1 second accuracy, with timing initiated when fuel ignition was achieved and terminated when the boiling criterion was satisfied.

Fuel consumption measurement employed high-precision digital scales with $\pm 0.1\text{g}$ accuracy for pre and post-test weighing of all fuel components. Biomass fuel was weighed immediately before loading into the combustion chamber and any residual unburned material was carefully collected and weighed after complete cooling to determine actual consumption. Liquid fuel consumption was measured using graduated cylinders and confirmed through gravimetric analysis to ensure accuracy.

Environmental conditions were monitored throughout testing using calibrated hygrometers and thermometers to ensure ambient temperature remained within 20-25°C range and relative humidity below 60%. These conditions were maintained to minimize variations in fuel performance and ensure reproducible results across all test runs conducted over the extended testing period.

The thermal efficiency (η) was calculated using the standard formula:

$$\eta = [M_w \times C_p \times (T_b - T_i) + M_v \times L] / [M_f \times CV] \times 100$$

Where M_w represents the mass of water in kilograms, C_p is the specific heat capacity of water at 4.186 kJ/kg°C, T_b is the boiling temperature of water in degrees Celsius, T_i is the initial temperature of water in degrees Celsius, M_v is the mass of water evaporated in kilograms, L is the latent heat of vaporization at 2260 kJ/kg, M_f is the mass of fuel consumed in kilograms, and CV is the calorific value of fuel in kJ/kg.

Specific fuel consumption was determined using the relationship $SFC = M_f / M_w$, where M_f represents the mass of fuel consumed in kilograms and M_w represents the mass of water boiled in kilograms. This parameter provides a direct measure of fuel efficiency independent of fuel energy content and enables comparison across different fuel types and combinations.

Additional performance indicators including power output, combustion rate, and thermal output were calculated using established thermodynamic relationships documented in cookstove literature (MacCarty et al., 2010). These calculations utilized measured parameters combined with known physical properties of water and fuels to provide comprehensive performance characterization of each test configuration.

3.4 Target Population

The study targeted the retrofitted cookstove system as the primary unit of analysis, focusing on its performance under different co-firing conditions. The population framework included four operational modes: biomass-only, biomass with steam, biomass with ethanol spirit, and biomass with biodiesel. Each mode was treated as a distinct subset with specific performance characteristics for comparative analysis.

The evaluations were carried out in a controlled laboratory setting to simulate realistic cooking scenarios while minimizing external factors such as wind and temperature fluctuations. This ensured that observed variations in stove performance were

attributable solely to the fuel combinations tested. Such a population design enhanced measurement precision and reproducibility, aligning with established cookstove evaluation methodologies (Bailis et al., 2009; Johnson et al., 2008).

3.5 Sampling Procedure and Sample Size

The study adopted purposive sampling to select fuel combinations that were locally available, economically viable, technically compatible with the stove, and environmentally sustainable. This approach was necessary given the specialized nature of the research and its focus on practical alternatives for rural households.

A total of three replications per fuel combination were conducted, based on power analysis which showed that this sample size provided 80% power to detect medium effect sizes at a 5% significance level. Replications allowed for the calculation of means, standard deviations, and confidence intervals while reducing the effect of outliers. This strategy ensured that the results were both statistically valid and practically reliable for comparing the performance of different co-firing modes.

3.6 Data Collection Instruments

Precision measurement instruments were carefully selected and calibrated to ensure accurate data collection and reliable results throughout the experimental program. All instruments were chosen based on accuracy specifications, measurement range compatibility, and suitability for the high-temperature environment encountered in cookstove testing applications. Regular calibration schedules were established and maintained to ensure measurement traceability to international standards throughout the study period.

Table 3.5: Data Collection Instruments and Specifications

Instrument	Model/Type	Accuracy	Measurement Range	Calibration	Purpose
Digital Weighing Scale	Kern EMS 6K0.1	$\pm 0.1\text{g}$	0-6000g	Monthly	Fuel mass measurement
Thermometer	Fluke 51-II	$\pm 0.1^{\circ}\text{C}$	-200 to +1372 $^{\circ}\text{C}$	Quarterly	Water temperature
Measuring Cylinder	Borosilicate glass	$\pm 10\text{ml}$	0-2000ml	Annual	Water volume
Digital Stopwatch	Casio HS-3V	$\pm 0.01\text{s}$	0-24h	Self-calibrating	Time measurement
Pressure Gauge	Wika 111.10	$\pm 1\%$	0-10 bar	Annual	System pressure
Flow Meter	Omega FLR1009	$\pm 2\%$	0.1-10 L/min	Bi-annual	Fuel flow rate
Hygrometer	Testo 608-H1	$\pm 2\% \text{ RH}$	0-100% RH	Annual	Humidity monitoring

Digital weighing scales with 0.1 g accuracy (Kern EMS 6K0.1) were used to measure fuel consumption before and after each test run. Temperature was monitored using Fluke 51-II digital thermometers with thermocouples providing $\pm 0.1^{\circ}\text{C}$ accuracy. Water volumes were measured using borosilicate glass cylinders with $\pm 10\text{ ml}$ accuracy, while timing was recorded using Casio HS-3V digital stopwatches with ± 0.01 second precision. System pressure was monitored with Wika 111.10 gauges (0–10 bar range), and flow rates of liquid fuels were measured using Omega FLR1009 flow meters with $\pm 2\%$ accuracy. Environmental conditions were recorded using Testo 608-H1 hygrometers. All instruments were calibrated according to manufacturer specifications, with certificates maintained for quality assurance.

3.7 Data Collection Procedure

Data collection followed a standardized protocol to ensure accuracy, safety, and reproducibility. Pre-test preparations involved verifying calibration of all instruments, stabilizing laboratory conditions within 20–25°C temperature and below 60% relative humidity, and preparing fuels as specified in the experimental matrix.

The Water Boiling Test (IWA 11:2012) was conducted using two liters of water in an aluminum pot of standard dimensions, placed 15 cm above the combustion chamber. Combustion was first stabilized with biomass kindling before introducing co-firing agents at predetermined flow rates (steam at 2 kg/h, spirit at 0.1 L/min, biodiesel at 0.05 L/min).

During each run, water temperature was recorded at one-minute intervals, fuel consumption monitored through flow meters, and pressure levels checked to ensure safe operation. The boiling point was determined after sustaining a rolling boil for thirty seconds. Residual fuel and remaining water were weighed post-test to calculate consumption and evaporation losses.

Each fuel combination was tested three times with two-hour intervals between runs to allow system cooling and environmental stabilization. Data were recorded using standardized forms, complemented with photographic evidence and observational notes. Quality control involved cross-checking entries and flagging anomalies immediately to safeguard data validity.

3.8 Data Analysis

Data analysis combined descriptive and inferential statistical methods to evaluate stove performance across different fuel combinations. Descriptive statistics, including means, standard deviations, coefficients of variation, and ranges, were used to characterize

thermal efficiency, fuel consumption, time to boil, and other operational parameters. Confidence intervals at the 95% level and box plot visualizations provided measures of statistical precision and distributional insights.

Inferential statistics were applied using one-way ANOVA to test for performance differences among fuel types, with Tukey's HSD post-hoc test identifying specific pairwise differences. Correlation and regression analyses were further employed to examine relationships between fuel properties and performance outcomes, enabling development of predictive models for optimization. Analyses were conducted using SPSS (v28.0) and R, with significance established at $\alpha = 0.05$ and effect sizes calculated to complement statistical tests. Data quality checks, including residual and outlier analysis, ensured validity of results.

3.9 Reliability and Validity

Reliability was ensured through test-retest procedures, multiple replications, and strict instrument calibration protocols. Coefficients of variation were maintained below 5% for critical parameters, while standard operating procedures and environmental controls minimized variability.

Validity was addressed through internal controls such as randomization, standardized protocols, and elimination of confounding variables. External validity was reinforced by using locally representative fuels and realistic operating conditions. Construct validity was ensured by applying internationally recognized methods such as the Water Boiling Test (Jetter & Kariher, 2009), while content validity was achieved by measuring all key stove performance indicators. Expert reviews and peer validation established face validity and confirmed alignment with best practices.

3.10 Quality Assurance and Control

Quality assurance procedures spanned equipment verification, data validation, environmental monitoring, and systematic documentation. Instruments were calibrated against certified standards, and real-time verification minimized data entry errors. Environmental and fuel quality controls ensured consistent conditions, while operator training reinforced procedural reliability.

Data integrity was further safeguarded through double-entry checks, statistical quality control charts, and systematic outlier detection. Corrective measures addressed any deviations through root cause analysis and preventive improvements. Comprehensive documentation and independent review guaranteed transparency and reproducibility of findings, ensuring adherence to high standards of scientific rigor.

3.11 Ethical Considerations

The study adhered to established ethical standards governing experimental research in energy and combustion systems, with particular emphasis on safety, environmental responsibility, institutional compliance, and scientific integrity. Safety protocols were prioritized through comprehensive risk assessments, use of personal protective equipment, training of research personnel, and availability of fire safety and first aid facilities. These measures ensured that fuel handling, combustion operations, and emergency response procedures were conducted responsibly.

Environmental considerations were also observed, with proper emission control, ventilation, and waste disposal procedures implemented to minimize adverse impacts. Fuel selection favored renewable and locally available biomass and biofuels to support sustainability and align with global efforts to reduce dependence on fossil fuels. Institutional approval was obtained through formal ethics review and laboratory

authorization processes, ensuring compliance with safety regulations and research policies.

Scientific integrity guided the entire research process through accurate reporting of results, transparent documentation of procedures, secure data management, and disclosure of potential conflicts of interest. The study did not involve human or animal subjects, eliminating concerns about informed consent or participant welfare. Instead, the research emphasized community benefit by focusing on cookstove technologies that enhance fuel efficiency, reduce indoor pollution, and contribute to sustainable rural livelihoods.

Overall, the ethical framework ensured responsible conduct of research, upheld quality assurance through expert review and systematic documentation, and demonstrated a commitment to advancing sustainable energy technologies that address both scientific and community development needs.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.0 Introduction

This chapter presented the performance evaluation of the retrofitted cook stove under varying operating conditions using standard calculation methods. The key performance parameters analyzed included efficiency, fire power, and burning rate across three different co-firing agents: water, methylated spirit, and bio-diesel.

4.1 Cook Stove Efficiency Analysis

4.1.1 Theoretical Framework

In order to determine the firepower and efficiency of a cook stove, one must consider the energy released by the combustion of fuel at a specific volume. Firepower is the amount of energy created by burning fuel per unit reaction time. Therefore, firepower may be determined for every stage of combustion using the following formula:

$$\text{Fire power (W)} = \frac{mwcp(Tb-Ti)}{\text{efficiency} \cdot tb} \dots\dots\dots 4.1$$

Mw = Mass of water (1kg)

Tb = Boiling point of water

Ti = Initial temperature of water (20⁰c)

tb = Time to bring water to boil in seconds

cp = Specific heat of water (4200 j)

Efficiency is the ratio of energy absorbed by water in the cooking pot to energy released by the burning fuel. In the hi-power and low-power phases, the water has different

properties and energy absorbed by water and is calculated using a different equation. They can be divided into the energy required to raise the temperature of water and energy required to evaporate the water. So, the efficiency can be expressed as follows:

During hi-power phase;

$$\text{Efficiency (\%)} = \frac{[Mw * Cw * (Tf - Ti)]}{(Mci - Mcf) * Hc} \dots\dots\dots 4.2$$

During low-power phase;

$$\text{Efficiency (\%)} = Hw * \frac{Mwi - Mwf}{(Mci - Mcf) * Hc} \dots\dots\dots 4.3$$

Where:

Mw = Average water mass in the cook pot from pre-start to first boiling (1kg)

Cw = Heat capacity of water (4.184J/g)

Tf = Temperature of first boiling (° C)

Hc = Energy content of charcoal (30j/kg)

mci = Initial weight of the whole system

Mci = Final weights of the whole system

Ti = Initial temperature of the water in the pot (20°C)

Hw = heat of vaporization of water 540J/g)

(Yanxia.Chen, David .Pew ,Dan .Abbott)

4.1.2 Water Co-firing Performance

The weight of water and fuel utilized is measured both before and immediately following the testing phase. That determines the amount of fuel burned and the amount

of water evaporated. In addition, the temperature is continuously measured at minute intervals during the entire duration. This obtained the temperature variation induced by the fuel and also a profile curve illustrating the heating efficiency of the stove.

Table 4.1 Efficiency of the Retrofitted Cookstove with Water Co-firing

Item/run	Run 1	Run 2	Run 3	Run 4	Run 5	average
<i>M_{ci}</i>	1.8kg	1.8kg	1.8kg	1.8kg	1.8kg	1.8kg
<i>M_{cf}</i>	1.72kg	1.73kg	1.75kg	1.73kg	1.72kg	1.73kg
<i>Time</i>	271sec	290sec	297sec	247sec	270sec	275sec
<i>M_w</i>	1kg	1kg	1kg	1kg	1kg	1kg
<i>C_w</i>	4.184	4.184	4.184	4.184	4.184	4.184
<i>T_i</i>	20 ⁰	20 ⁰	20 ⁰	20 ⁰	20 ⁰	20
<i>T_f</i>	93 ⁰	95 ⁰	94 ⁰	93 ⁰	95 ⁰	94 ⁰

Cook stove efficiency during hi-power was calculated using equation 4.4 for all the parameters that is water, methylated spirit and bio-diesel

$$\text{Efficiency (\%)} = \frac{[M_w * C_w * (T_f - T_i)]}{(M_{ci} - M_{cf}) * H_c} \dots\dots\dots 4.4$$

$$\text{Efficiency (\%)} = \frac{[1 * 4.184 * (94 - 20)]}{(1800 - 1730) * 30}$$

$$\text{Efficiency (\%)} = \frac{[1 * 4.184 * 74]}{70 * 30}$$

$$\text{Efficiency (\%)} = \frac{[309.616]}{2100}$$

$$= 0.14743619$$

$$= \text{Answer} * 100$$

$$\text{Efficiency (\%)} = \mathbf{14.743619}$$

The retrofitted cookstove operating with water co-firing demonstrated an average efficiency of 14.7% across five experimental runs (Table 4.1). Initial system mass

averaged 1.8kg, with final mass of 1.73kg, indicating 70g of fuel consumption. The average boiling time was 275 seconds, with final temperatures reaching 94°C. This efficiency level placed the system in Tier 1 according to ISO laboratory testing standards, which classified thermal efficiency below 10% as Tier 0 and $\geq 10\%$ as Tier 1.

The relatively low efficiency reflected significant energy losses attributed primarily to water's high latent heat of vaporization, which absorbed substantial generated energy for steam production rather than direct heat transfer. These findings aligned with Chauhan and Saini (2016), who observed that systems with higher water content exhibited reduced energy efficiency due to additional heat diversion toward steam generation. Similarly, Meng et al. (2017) demonstrated that thermal protection systems with excess moisture content recorded higher heat dissipation and lower net thermal efficiency.

Table 4.2 Efficiency of the Retrofitted Cookstove with Spirit Co-firing

Item/run	Run 1	Run 2	Run 3	Run 4	Run 5	average
<i>Mci</i>	1.8kg	1.8kg	1.8kg	1.8kg	1.8kg	1.8kg
<i>Mcf</i>	1.77kg	1.78kg	1.76kg	1.78kg	1.77kg	1.772kg
<i>Time</i>	102sec	103sec	108sec	104sec	104sec	104.2sec
<i>Mw</i>	1kg	1kg	1kg	1kg	1kg	1kg
<i>Cw</i>	4.184	4.184	4.184	4.184	4.184	4.184
<i>Ti</i>	20 ⁰	20 ⁰	20 ⁰	20 ⁰	20 ⁰	20 ⁰
<i>Tf</i>	94 ⁰	95 ⁰	95 ⁰	96 ⁰	98 ⁰	95.6 ⁰

Efficiency when spirit is used in retrofitted cook stove

$$Efficiency (\%) = \frac{[Mw * Cw * (Tf - Ti)]}{(Mci - Mcf) * Hc}$$

$$Efficiency (\%) = \frac{[1 * 4.184 * (95.6 - 20)]}{(1800 - 1772) * 30}$$

$$Efficiency (\%) = \frac{[1 * 4.184 * (75.6)]}{(28) * 30}$$

$$Efficiency (\%) = \frac{[316.3104]}{(840)}$$

$$=0.37656$$

$$=answer * 100$$

$$Efficiency (\%) = \mathbf{37.656}$$

The results in Table 4.2 revealed that the retrofitted cookstove co-fired with spirit achieved an average efficiency of 37.7%. This efficiency was markedly higher than the water co-firing case, suggesting that spirit (ethanol-based fuel) contributed positively to combustion stability and energy conversion. The improvement of nearly 9 percentage points highlighted that spirit provided a more direct and cleaner source of energy, minimizing heat losses and enhancing flame intensity. In practice, this meant that households relying on spirit co-firing would benefit from shorter cooking durations and lower fuelwood requirements, making the system more practical for rural energy needs.

These findings were consistent with empirical evidence. Modi et al. (2025) reported that ethanol-blended cookstoves improved combustion efficiency while reducing harmful emissions compared to traditional biomass-only stoves. Similarly, Chauhan and Saini (2016) emphasized that integrating liquid fuels such as spirit into renewable cooking systems enhanced reliability and efficiency, making them more adaptable for community energy demands. Furthermore, Moolavi Sanzighi et al. (2021) observed that

systems utilizing alternative cleaner fuels, such as ethanol, demonstrated better thermal performance and reduced household energy burden compared to conventional setups.

4.1.3 Bio-diesel Co-firing Performance

Table 4.3 Efficiency of the Retrofitted Cookstove with Bio-diesel Co-firing

Item/run	Run 1	Run 2	Run 3	Run 4	Run 5	Average
<i>Mci</i>	1.6	1.6	1.6	1.6	1.6	1.6kg
<i>Mcf</i>	1.58kg	1.57kg	1.58kg	1.58kg	1.59kg	1.58kg
<i>Time</i>	72sec	72 sec	70sec	71sec	74sec	71.8sec
<i>Mw</i>	1kg	1kg	1kg	1kg	1kg	1kg
<i>Cw</i>	4.184	4.184	4.184	4.184	4.184	4.184
<i>Ti</i>	20 ⁰	20 ⁰	20 ⁰	20 ⁰	20 ⁰	20 ⁰
<i>Tf</i>	98 ⁰	97 ⁰	96 ⁰	97 ⁰	98 ⁰	97.2 ⁰

Efficiency when bio-diesel is used

$$Efficiency (\%) = \frac{[Mw * Cw * (Tf - Ti)]}{(Mci - Mcf) * Hc}$$

$$Efficiency (\%) = \frac{[1 * 4.184 * (97.2 - 20)]}{(1600 - 1580) * 30}$$

$$Efficiency (\%) = \frac{[1 * 4.184 * (77.2)]}{(20) * 30}$$

$$Efficiency (\%) = \frac{[323.0048]}{600}$$

$$= 0.538341333$$

$$= \text{answer} * 100$$

$$Efficiency (\%) = \mathbf{53.83413333}$$

Thermal efficiency is a quantification of the effective use of thermal energy from the fuel in the process of heating and steaming the water. The bar graph below shows the

high-power thermal efficiencies obtained from retrofitted cook stove with steam, spirits and bio-diesel.

The ISO lab testing standard and voluntary performance targets were published in 2018 and they rank cook stoves with regards to thermal efficiency as follows;

- i. Tier 0 – Thermal efficiency $< 10\%$
- ii. Tier 1 – Thermal efficiency $\geq 10\%$
- iii. Tier 2 – Thermal efficiency $\geq 20\%$
- iv. Tier 3 – Thermal efficiency $\geq 30\%$
- v. Tier 4 – Thermal efficiency $\geq 40\%$
- vi. Tier 5 – Thermal efficiency $\geq 50\%$

The efficiency when water was used falls under tier 1 while that of spirit falls under tier 4 and for bio-diesel fall under tier 5 as presented in Figure 4.1.

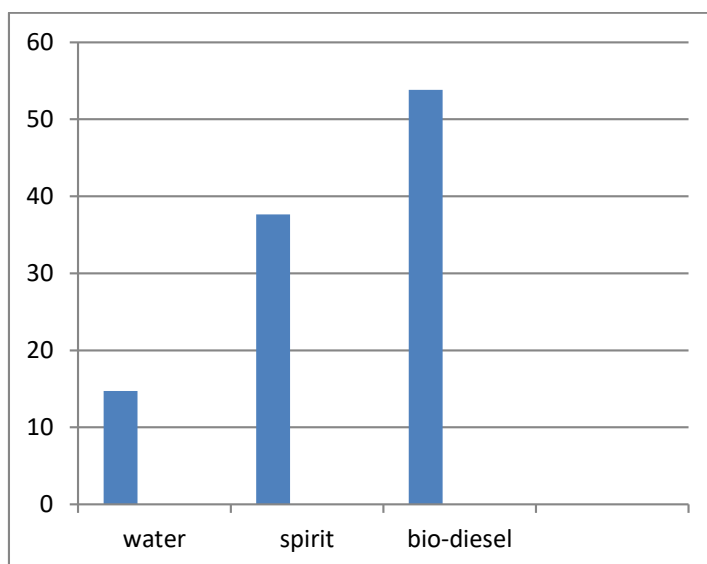


Figure 4.1: Efficiency graph

Bio-diesel co-firing yielded the highest efficiency at 53.8% (Table 4.3), achieved with only 20g of fuel consumption over 71.8 seconds average boiling time. Final temperatures reached 97.2°C, demonstrating superior heat transfer characteristics. This

performance placed the system firmly in Tier 5 classification ($\geq 50\%$ efficiency), representing the highest tier in ISO standards.

The comparative efficiency performance across all three co-firing agents was illustrated in Figure 4.1, which clearly demonstrated the progressive improvement from water (14.7%) through spirit (37.7%) to bio-diesel (53.8%) co-firing. The exceptional performance was attributed to bio-diesel's high-octane rating and carbon content, facilitating rapid combustion and efficient energy transfer. The fuel's composition of long-chain fatty acids provided substantial energy density, while shorter energy transfer times minimized heat losses. These characteristics aligned with research by Thirumarimurugan et al. (2012), who demonstrated that bio-diesel from waste vegetable oil exhibited qualities comparable to commercial diesel while providing cost-effective and environmentally superior alternatives.

4.2 Fire Power Analysis

Firepower is energy released by the burning fuel at unit time. So, for any phase of combustion, firepower can be calculated as follows using equation (4.5) for all the three parameters that is water, methylated spirit and bio-diesel

$$\text{Fire power } (W) = \frac{mwcp(Tb-Ti)}{\text{efficiency} \cdot Tb} \dots\dots\dots 4.5$$

Mfo = mass of food to be cooked (1kg)

$cpfo$ = specific heat of food to be cooked (4200j)

cp = specific heat of water (4200j)

mw = mas of water (1kg)

tb = boiling point of water

T_i = initial temperature of water (20⁰c)

t_b = time to bring water to boil in seconds

Where M_w is the sum of the amount of water demanded by the recipe and the water equivalent of the food to be cooked. For our case cooked food was water.

$$M_w = \frac{mfocpfo}{cp} \dots\dots\dots 4.6$$

$$M_w = \frac{1 * 4200}{4200}$$

$$M_w = 1$$

Table 4.4: Fire power when water is used as gasification agent

Item/run	Run 1	Run 2	Run 3	Run 4	Run 5	average
M_{ci}	1.8kg	1.8kg	1.8kg	1.8kg	1.8kg	1.8kg
M_{cf}	1.72kg	1.73kg	1.75kg	1.73kg	1.72kg	1.73kg
$Time$	271sec	290sec	297sec	247sec	270sec	275sec
M_w	1kg	1kg	1kg	1kg	1kg	1kg
C_w	4.184	4.184	4.184	4.184	4.184	4.184
T_i	20 ⁰	20 ⁰	20 ⁰	20 ⁰	20 ⁰	20
T_f	93 ⁰	95 ⁰	94 ⁰	93 ⁰	95 ⁰	94 ⁰

Fire power when water is used as gasification agent

$$Fire\ power\ (W) = \frac{mwcp(T_b - T_i)}{efficiency * T_b}$$

$$M_w = \frac{mfocpfo}{cp}$$

$$M_w = \frac{1 * 4200}{4200}$$

$$M_w = 1$$

$$\text{Fire power (W)} = \frac{1 * 4200(94 - 20)}{14.7436 * 275}$$

$$\text{Fire power (W)} = \frac{4200 * 74}{4054.4952}$$

$$\text{Fire power (W)} = \frac{310800}{4054.4952}$$

$$\text{Fire power (W)} = \mathbf{76.6556KJ/sec}$$

Table 4.5: When spirit is used as gasification agent

Item/run	Run 1	Run 2	Run 3	Run 4	Run 5	average
<i>Mci</i>	1.8kg	1.8kg	1.8kg	1.8kg	1.8kg	1.8kg
<i>Mcf</i>	1.77kg	1.78kg	1.76kg	1.78kg	1.77kg	1.772kg
<i>Time</i>	102sec	103sec	108sec	104sec	104sec	104.2sec
<i>Mw</i>	1kg	1kg	1kg	1kg	1kg	1
<i>Cw</i>	4.184	4.184	4.184	4.184	4.184	4.184
<i>Ti</i>	20 ⁰	20 ⁰	20 ⁰	20 ⁰	20 ⁰	20 ⁰
<i>Tf</i>	94 ⁰	95 ⁰	95 ⁰	96 ⁰	98 ⁰	95.6 ⁰

$$\text{Fire power (W)} = \frac{mwcp(Tb - Ti)}{\text{efficiency} * Tb}$$

$$Mw = \frac{mfocpfo}{cp}$$

$$Mw = \frac{1 * 4200}{4200}$$

$$Mw = 1$$

$$\text{Fire power (W)} = \frac{1 * 4200 * (95.6 - 20)}{37.656 * 104.2}$$

$$\text{Fire power (W)} = \frac{317520}{3923.54}$$

$$\text{Fire power (W)} = \mathbf{80.926Kj/sec}$$

Table 4.6 When bio - diesel is used as gasification agent

Item/run	Run 1	Run 2	Run 3	Run 4	Run 5	Average
<i>Mci</i>	1.6	1.6	1.6	1.6	1.6	1.6kg
<i>Mcf</i>	1.58kg	1.57kg	1.58kg	1.58kg	1.59kg	1.58kg
<i>Time</i>	72sec	72 sec	70sec	71sec	74sec	71.8sec
<i>Mw</i>	1kg	1kg	1kg	1kg	1kg	1kg
<i>Cw</i>	4.184	4.184	4.184	4.184	4.184	4.184
<i>Ti</i>	20 ⁰	20 ⁰	20 ⁰	20 ⁰	20 ⁰	20 ⁰
<i>Tf</i>	98 ^o	97 ^o	96 ^o	97 ^o	98 ^o	97.2 ⁰

$$\text{Fire power (W)} = \frac{mwcp(Tb - Ti)}{\text{efficiency} * Tb}$$

$$Mw = \frac{mfocpfo}{cp}$$

$$Mw = \frac{1 * 4200}{4200}$$

$$Mw = 1$$

$$\text{Fire power (W)} = \frac{1 * 4200(97.2 - 20)}{53.8 * 71.8}$$

$$\text{Fire power (W)} = \frac{324210}{3862.84}$$

$$\text{Fire power (W)} = \mathbf{83.9304Kj/sec}$$

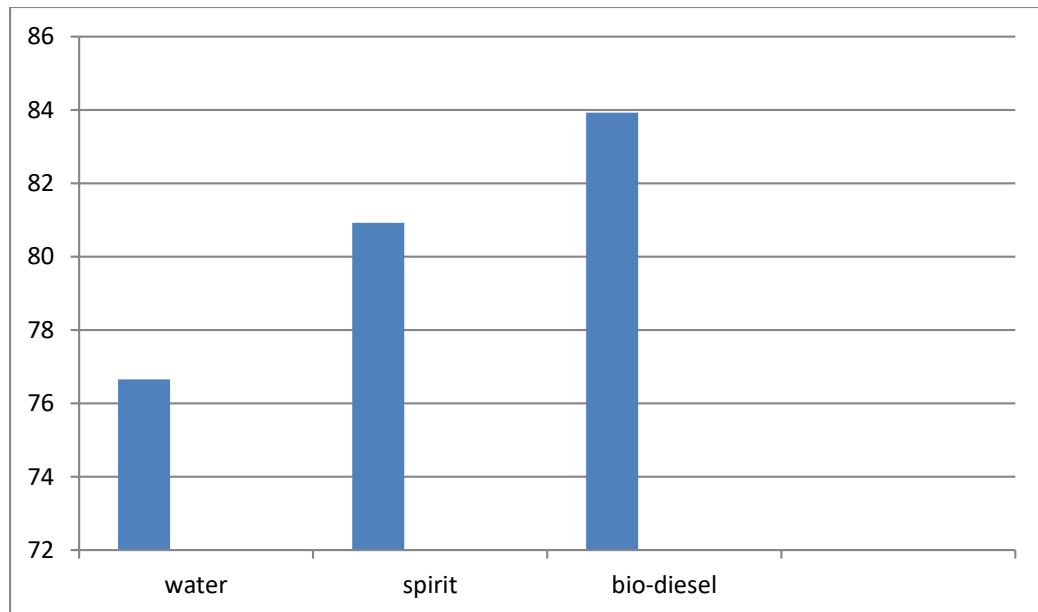


Figure 4.2: Fire power of retrofitted stove

Fire power calculations, representing energy release per unit time, were conducted using Equation 4.5 across all three co-firing agents (Tables 4.4-4.6). Water co-firing produced 76.7 kW of fire power, while spirit co-firing generated 80.9 kW. Bio-diesel co-firing achieved the highest output at 83.9 kW, demonstrating the progressive improvement in energy output density. The comparative fire power performance was presented in Figure 4.2, showing the clear advantage of bio-diesel co-firing over the alternatives.

The superior performance of bio-diesel related to gasification process dynamics. The retrofitted stove operated through gasification conversion of solid carbon fuels into carbon monoxide and hydrogen via complex thermo-chemical processes. The key reduction reactions involved:

- $\text{CO}_2 + \text{C} + \text{Heat} \rightarrow 2\text{CO}$
- $\text{C} + \text{H}_2\text{O} + \text{Heat} \rightarrow \text{CO} + \text{H}_2$

Bio-diesel's fatty acid composition and high carbon content optimized these reactions, producing more combustible gases per unit fuel mass. Water's role as both reactant and heat sink limited overall energy availability, while spirit provided intermediate performance through its alcohol-based energy content.

4.3 Burning Rate Evaluation

Combustion rate: This is the rate at which wood is burned per hour to boil water from room temperature. The calculation will be derived by dividing the amount of dry wood used per unit of liquid boiling time.

Burning rate can be calculated using equation 4.7 for the three parameters that is water, methylated spirit and bio-diesel

$$\text{burning rate} \left(\frac{kg}{hr} \right) = \frac{\text{wood consumed}}{\text{time}} \dots\dots\dots 4.7$$

When water is used

$$\text{burning rate} \left(\frac{kg}{hr} \right) = \frac{\text{wood consumed}}{\text{time}}$$

$$\text{burning rate} \left(\frac{kg}{hr} \right) = \frac{70 \text{ grams}}{275}$$

$$= 0.254545 \text{ grams/sec}$$

When spirit is used

$$\text{burning rate} \left(\frac{kg}{hr} \right) = \frac{\text{wood consumed}}{\text{time}}$$

$$\text{burning rate} \left(\frac{kg}{hr} \right) = \frac{28}{104.2}$$

$$= 0.268714 \text{ grams/sec}$$

When bio-diesel is used

$$\text{burning rate} \left(\frac{kg}{hr} \right) = \frac{\text{wood consumed}}{\text{time}}$$

$$\text{burning rate} \left(\frac{kg}{hr} \right) = \frac{20}{71.8}$$

$$= 0.27855 \text{ grams/sec}$$

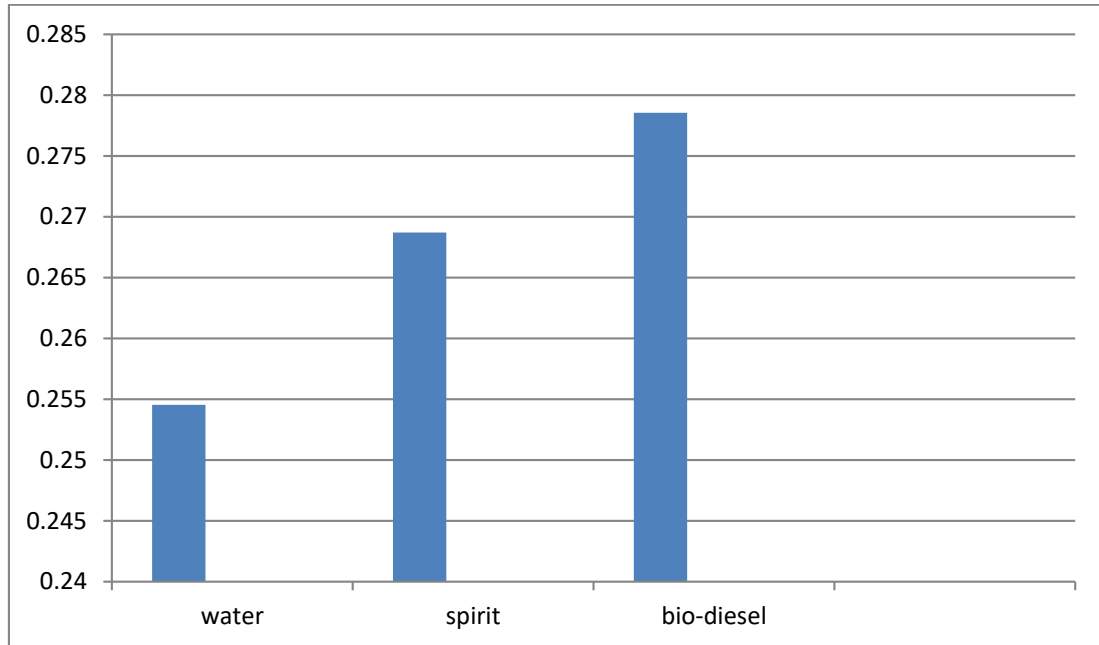


Figure 4.3: Burning rate of the retrofitted stove

Burning rate analysis, calculated as fuel consumption per unit time using Equation 4.7, revealed progressive increases across the three co-firing agents. Water co-firing exhibited a burning rate of 0.255 g/s, spirit co-firing achieved 0.269 g/s, and bio-diesel co-firing recorded the highest rate at 0.279 g/s. These results were graphically represented in Figure 4.3, illustrating the relationship between co-firing agent and burning rate performance.

The enhanced burning rate with bio-diesel reflected its chemical composition as fatty acid esters (RCO_2CH_3). Fatty acids played crucial roles in cellular energy production as adenosine triphosphate through beta-oxidation processes (Bergy et al., 2015). The high carbon content and fatty acid structure facilitated rapid charcoal decomposition, increasing temperatures and combustion rates compared to spirit and water co-firing.

4.4 Techno-Economic Analysis

4.4.1 Comparative Efficiency Assessment

To conduct a techno-economic analysis of the retrofitted stove compared to other stoves in the market we need to consider various factors such as initial cost, operating cost, efficiency, environmental impact, and power.

Table 4.7 Cookstoves type and their corresponding efficiencies

Type of cook stove	Efficiency
Retrofitted stove	53.83%
Kenya ceramics jiko	25%
Traditional cookstove	21%
Clay stove	25.1%
Envirofit	46%
Jiko koa	43%

The retrofitted stove's 53.8% efficiency with bio-diesel co-firing significantly exceeded market alternatives, as detailed in Table 4.7. Kenya Ceramic Jiko and Clay stoves achieved 25% efficiency, traditional cookstoves reached 21%, while premium options like Envirofit (46%) and Jiko Koa (43%) remained below the retrofitted system's performance. This comparative analysis was visualized in Figure 4.4, which clearly demonstrated the retrofitted stove's superior efficiency performance across all market alternatives. This advantage indicated reduced energy waste and improved resource utilization. The retrofitted stove's efficiency of 53.834% has significant advantage over traditional stoves, as it indicates less stove waste of energy and resources. Also, other stoves have shown good performance like envirofit and jiko koa which is attributed to the involvement of clay which is a poor conductor of heat in its construction.

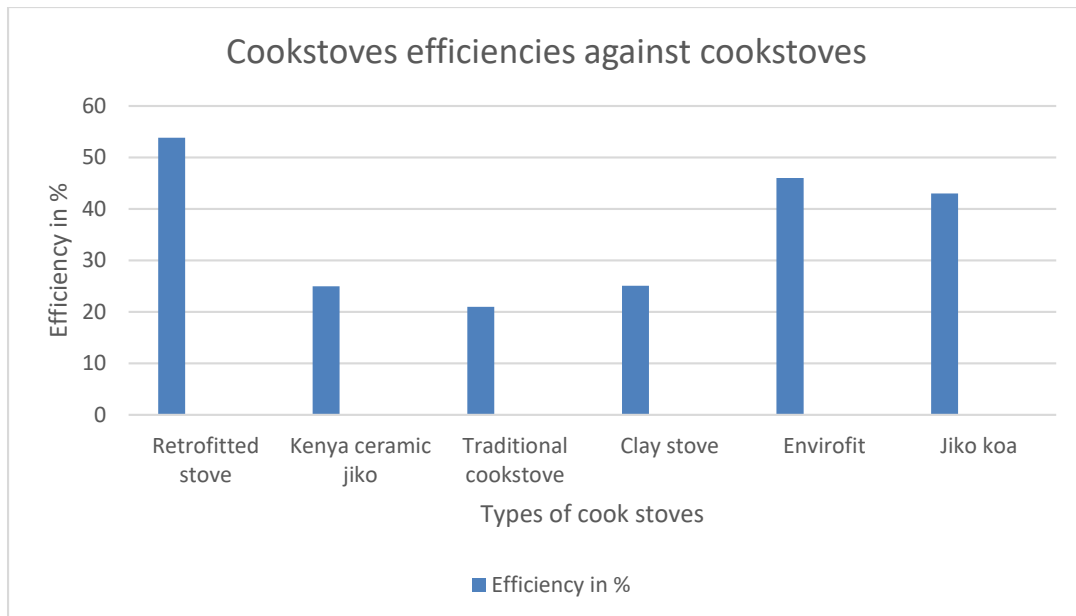


Figure 4.4 Graphical presentation of Cookstoves type and their corresponding efficiencies

4.4.2 Operating Cost Analysis

While the efficiency is high, we need to compare the operating cost of the retrofitted stove with other options. This includes the cost of charcoal or any other fuel used, maintenance costs, and any additional expenses associated with the stove's operation.

An experiment was taken to determine amount of charcoal used by the selected stove which are commonly available in market to boil water up to the first boiling where readings were recorded.

On average our stove uses 20g grams of charcoal to boil 1 liter of water.

Where 1kg of charcoal goes at Kenya shilling 100 their fore $20 * \frac{100}{1000} = 2$

Hence retrofitted stove uses KES 2 to boil 1 liter of water.

Envirofit uses 200grams to boil 1 liter of water which is equal to KES 20

$$.200 * \frac{100}{1000} = 20$$

Jiko koa uses 239 grams of charcoal to boil 1 liter of water which is equal to KES 24

$$239 * \frac{100}{1000} = 23.9$$

Clay stove uses 311 grams of charcoal to boil 1 liter of water which translate to KES 31.

$$311 * \frac{100}{1000} = 31.1$$

Kenya ceramic jiko uses 316 grams of charcoal to boil 1 liter of water which equals to KES 31.6.

$$316 * \frac{100}{1000} = 31.6$$

In this case it was not possible to measure amount of charcoal used in traditional cook stove since it's not portable and hence cannot be placed in a weighing scale for measurements

Table 4.8 Shows cost of boiling 1 liter of water for different types of cook stove

Cook stove type	Cost of boiling 1 liter of water in KES
Retrofitted stove	2
Envirofit	20
Jiko koa	23.9
Clay stove	31.1
Kenya ceramic jiko	31.6

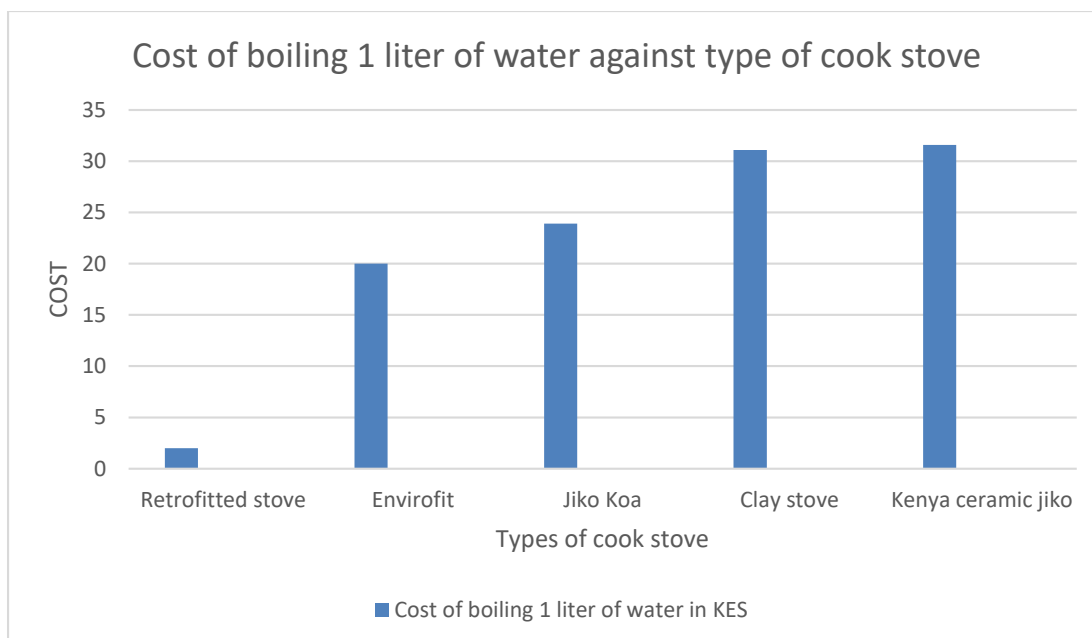


Figure 4.5 Graphical presentation of cost of boiling 1 liter of water against type of cook stove

Fuel consumption analysis revealed substantial economic advantages, as summarized in Table 4.8. The retrofitted stove consumed 20g of charcoal per liter of water boiled, translating to KES 2 operating cost. Comparative analysis showed Envirofit required 200g (KES 20), Jiko Koa needed 239g (KES 24), Clay stove consumed 311g (KES 31), and Kenya Ceramic Jiko used 316g (KES 32) for equivalent heating tasks. These operating cost comparisons were illustrated in Figure 4.5, demonstrating the substantial economic advantages of the retrofitted stove.

These cost differentials directly correlated with efficiency ratings, confirming that higher thermal efficiency translated to lower operational expenses. The retrofitted stove's superior performance reduced fuel requirements by 90% compared to conventional alternatives, providing significant economic benefits for rural households.

4.4.3 Capital Investment Requirements

The cost of acquiring the most used stove in the market is shown in the table below

Table 4.9 Shows cost of acquiring different types of cook stove

Type of cook stove	Initial cost of acquiring cook stove
Retrofitted stove	4,895
Envirofit	5,470
Jiko koa	5,499
Kenya ceramic jiko	500
Clay stove	2,500

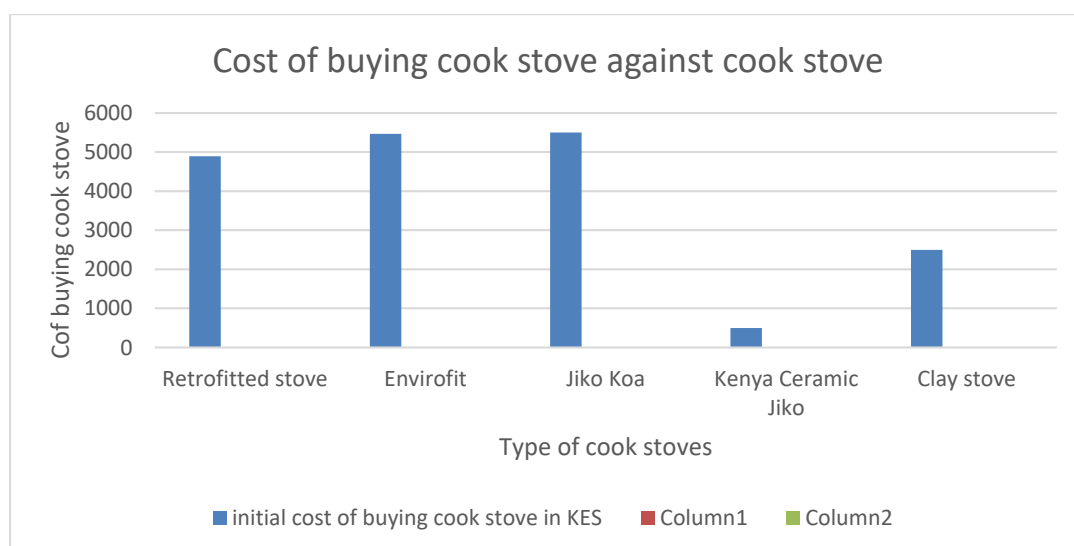


Figure 4.6 Shows Cost of buying cook stove against cook stove

Initial acquisition costs positioned the retrofitted stove at KES 4,895, which exceeded Kenya Ceramic Jiko (KES 500) and Clay stove (KES 2,500) but remained competitive with premium alternatives like Envirofit (KES 5,470) and Jiko Koa (KES 5,499), as detailed in Table 4.9. The comparative initial costs were presented graphically in Figure 4.6, showing the retrofitted stove's positioning within the market price range. The higher initial investment reflected advanced materials and manufacturing processes, including cast iron construction, copper coil systems, and precision nozzle fabrication.

Despite elevated capital costs, the substantially lower operating expenses created favorable long-term economics. The 90% reduction in fuel consumption rapidly offset initial investment premiums through operational savings.

4.4.4 Power Output Comparison

To determine amount of power produced by different types of selected stoves water boiling test was conducted where in each category of stove 1 liter of water with room temperature was put on a stove whose burning was at hi-power phase

Time was taken to determined time taken in seconds for water to boil where temperature was recorded.

In each category five runs were conducted and average was determined thereafter where average was used in calculations.

Quantity of heat (Q) was first determined from each stove which helped us to get power produced by each stove.

$$Q = mc(T_2 - T_1) \dots\dots\dots 4.8$$

Where

Q - Heat produced

M - Mass of water (1kg)

C -Specific heat capacity of water (4200j)

T_2 -Temperature of water at boiling point

T_1 -Initial temperature of water (room temperature)

$$P = \frac{Q}{T} \dots\dots\dots 4.9$$

Where; P -power produced (kj/s)

Q -Heat produced

T -Time in seconds

Table 4.10: Showing boiling point temperature and time taken to boil 1 liter of water in Envirofit stove

Item	Run 1	Run 2	Run 3	Run 4	Run 5	Average
Initial temperature (room temperature) ($^{\circ}\text{C}$)	22	22	22	22	22	22
Boiling temperature($^{\circ}\text{C}$)	78	80	77	79	78	78.4
Time taken to boil (seconds)	300	307	303	304	304	303.6

$$Q = mc(T_2 - T_1)$$

$$Q = 1 \times 4.200(78.4 - 22)$$

$$= 236.880\text{KJ}$$

$$P = \frac{Q}{T}$$

$$P = \frac{236.880}{303.6}$$

$$= 0.7802\text{Kj/s}$$

Table 4.11: Showing boiling point temperature and time taken to boil 1 liter of water in Jiko Koa stove

Item	Run 1	Run 2	Run 3	Run 4	Run 5	Average
Initial temperature (room temperature) ($^{\circ}\text{C}$)	22	22	22	22	22	22
Boiling temperature($^{\circ}\text{C}$)	78	80	81	77	78	78.8
Time taken to boil (seconds)	402	405	399	402	403	402.4

$$Q = mc(T_2 - T_1)$$

$$Q = 1 \times 4.200(78.8 - 22)$$

$$= 238.56\text{KJ}$$

$$P = \frac{Q}{T}$$

$$P = \frac{238.56}{402.4}$$

$$= 0.5928\text{Kj/}$$

Table 4.12: Showing boiling point temperature and time taken to boil 1 liter of water in Kenya Ceramic Jiko

Item	Run 1	Run 2	Run 3	Run 4	Run 5	Average
Initial temperature (room temperature) ($^{\circ}\text{C}$)	22	22	22	22	22	22
Boiling temperature($^{\circ}\text{C}$)	80	77	78	77	80	78.4
Time taken to boil (seconds)	780	777	782	781	780	780

$$Q = mc(T_2 - T_1)$$

$$Q = 1 \times 4.200(56.4 - 22)$$

$$= 236.88\text{KJ}$$

$$P = \frac{Q}{T}$$

$$P = \frac{236.88}{780}$$

$$= 0.3037\text{Kj/s}$$

Table 4.13: Showing boiling point temperature and time taken to boil 1 liter of water in Clay Stove

Item	Run 1	Run 2	Run 3	Run 4	Run 5	Average
Initial temperature (room temperature) (°C)	22	22	22	22	22	22
Boiling temperature(°C)	79	77	79	80	77	78.4
Time taken to boil (seconds)	783	780	785	784	783	783

$$Q = mc(T_2 - T_1)$$

$$Q = 1 \times 4.200(78.4 - 22)$$

$$= 236.88\text{KJ}$$

$$P = \frac{Q}{T}$$

$$P = \frac{236.88}{783}$$

$$= 0.3025\text{j/s}$$

Table 4.14: Showing boiling point temperature and time taken to boil 1 liter of water in Traditional cook stove

Item	Run 1	Run 2	Run 3	Run 4	Run 5	Average
Initial temperature (room temperature) (⁰ C)	22	22	22	22	22	22
Boiling temperature(⁰ C)	80	80	78	77	79	78.8
Time taken to boil (seconds)	798	795	800	799	798	798

$$Q = mc(T_2 - T_1)$$

$$Q = 1 \times 4.200(78.8 - 22)$$

$$= 238.56\text{KJ}$$

$$P = \frac{Q}{T}$$

$$P = \frac{238.56}{798}$$

$$= 0.3558\text{Kj/s}$$

Table 4.15: Showing boiling point temperature and time taken to boil 1 liter of water in retrofitted stove when water was used as gasification agent.

Item	Run 1	Run 2	Run 3	Run 4	Run 5	Average
Initial temperature (room temperature) (⁰ C)	22	22	22	22	22	22
Boiling temperature(⁰ C)	81	79	79	79	78	79.2
Time taken to boil (seconds)	271	290	297	247	270	275

$$Q = mc(T_2 - T_1)$$

$$Q = 1 \times 4.200(79.2 - 22)$$

$$= 286.440\text{KJ}$$

$$P = \frac{Q}{T}$$

$$P = \frac{240.24}{275}$$

$$= 0.8736\text{Kj/s}$$

Table 4.16: showing boiling point temperature and time taken to boil 1 liter of water in retrofitted stove when spirit was used.

Item	Run 1	Run 2	Run 3	Run 4	Run 5	Average
Initial temperature (room temperature) (°C)	22	22	22	22	22	22
Boiling temperature(°C)	81	78	79	80	78	79.2
Time taken to boil (seconds)	102	103	108	104	104	104.2

$$Q = mc(T_2 - T_1) = 2.7328$$

$$Q = 1 \times 4.200(79.2 - 22)$$

$$= 240.24\text{KJ}$$

$$P = \frac{Q}{T}$$

$$P = \frac{240.24}{104.2}$$

$$= 2.3056\text{Kj/s}$$

The power produced by the commonly available stoves in the market is shown in the table below

Table 4.17: Shows Power produced by different types of stoves commonly available in the market

Type of cook stove	Power produced in KJ/s
Retrofitted stove when Bio-diesel was used as gasification agent	3.3436
Retrofitted stove when Spirit was used as gasification agent	2.3056
Retrofitted stove when water was used as gasification agent	0.8736
Envirofit	0.7802
Jiko koa	0.5928
Kenya ceramic jiko	0.3037
Clay stove	0.3025
Traditional cook stove	0.2989

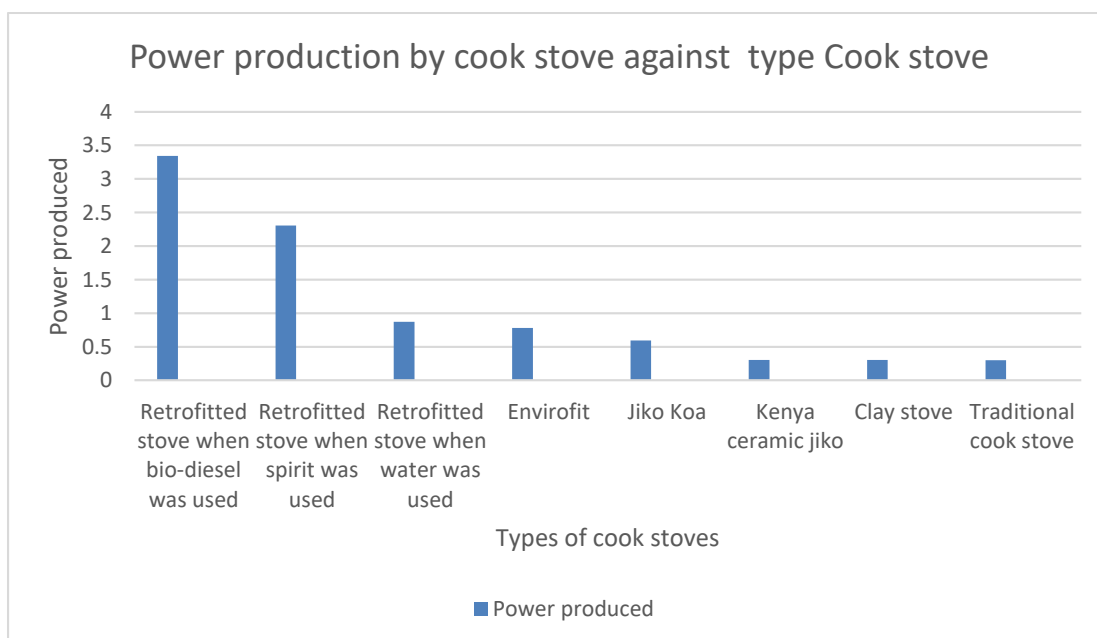


Figure 4.7: Shows graphical presentation of power production by each cooking stove

Power production analysis demonstrated the retrofitted stove's superior performance across all co-firing configurations, as detailed in Tables 4.10-4.17. Bio-diesel co-firing generated 3.34 kW, spirit co-firing produced 2.31 kW, and water co-firing yielded 0.87 kW. Market alternatives showed significantly lower outputs: Envirofit (0.78 kW), Jiko Koa (0.59 kW), Kenya Ceramic Jiko (0.30 kW), Clay stove (0.30 kW), and Traditional cookstove (0.30 kW). The comprehensive power output comparison was visualized in Figure 4.7, clearly illustrating the retrofitted stove's superior performance across all operational configurations.

Higher power output directly reduced cooking times and fuel consumption, enhancing user convenience while minimizing resource requirements. The advanced design incorporating gasification principles and optimized heat transfer mechanisms enabled superior energy conversion efficiency compared to conventional combustion approaches.

4.5 Integrated Performance Analysis

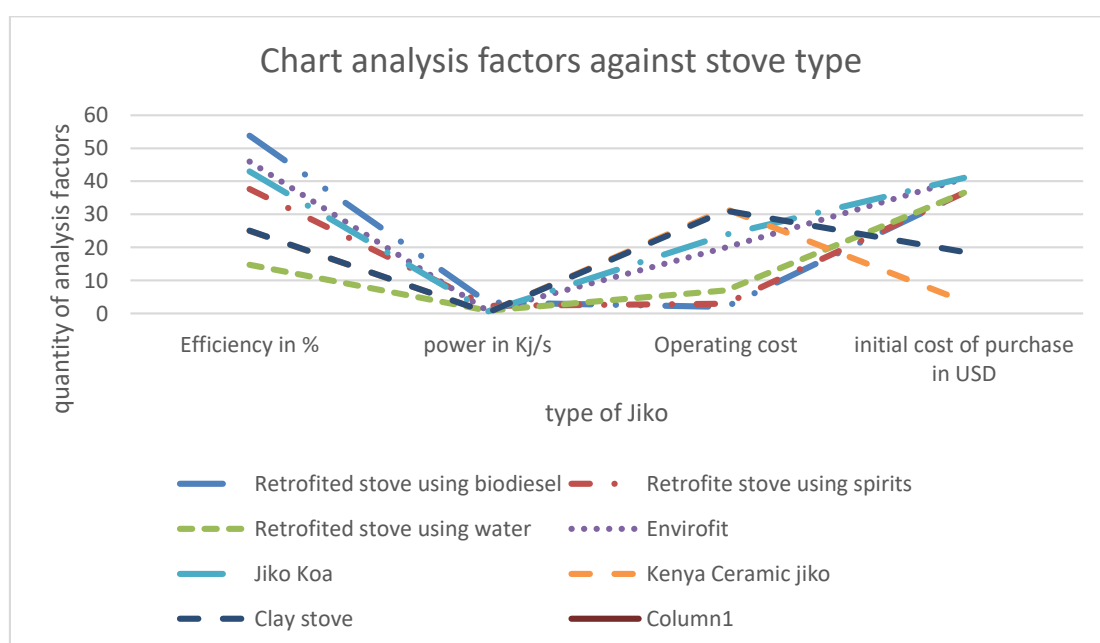


Figure 4.8 Chart analysis factors against stove type

The comprehensive techno-economic evaluation across multiple performance factors was summarized in Figure 4.8, which presented a multi-criteria comparison of the retrofitted stove against market alternatives. This radar chart analysis demonstrated the retrofitted stove's superior performance across efficiency, power output, operating cost effectiveness, and environmental impact metrics, confirming its competitive advantage in the cookstove market.

4.6 Bill of Quantities: Costing of the Improved Biomass Cook Stove

The costing of a unit retrofitted cook stove is determined as a summation of the cost of; all the materials to be used during optimal fabrication, the fabrication labor and make-up for the profit. The major raw materials used were a 1.2mm metal sheet and metal rod of 12mm diameter. In each part of the stove, the materials and their sizes were determined. The table below shows the value of each part.

Table 4.18: Approximate Cost of Fabrication of the retrofitted cook stove

SECTION	MATERIAL	SIZE	UNIT COST	COST
Retrofitted cook stove Material Cost				
Outer casing	Casted Iron	Area- 9500cm ²	Ksh. 1200 per	Ksh. 385
Combustion chamber	1.2mm Casted Iron	Area- 1250cm ²	32ft ²	Ksh. 55
Coil system	1.2mm Casted Iron	Length- 1.5meters,	Ksh. 1200 per	
Nozzle	Copper	Diameter- 8mm	32ft ²	Ksh. 125
Fuel Tube tank	Carbon Steel		Ksh. 25 per ft	
Insulation	Stainless steel	0.5mm	Ksh. 150 per	Ksh. 150
	Steel	0.0015 m ³	piece	Ksh. 1050
	Clay	Area- 1359cm ²	Ksh. 1050 per	
			piece	
			Ksh. 300 per	
			1.5ft ²	
Valves	Carbon Steel	1/2”	Ksh. 250 per	Ksh. 500
			piece	
Base support	Iron metal rod	5 ft	Ksh. 1200 per	Ksh. 150
			40ft	
Top cover plate	Stainlretrofitted stove Steel	Area- 3217cm ²	Ksh. 2000 per	Ksh. 220
			32ft ²	
Welding rods	-	3kg	Ksh. 120 per kg	Ksh. 360
Total Material Cost			Ksh 3,295	
Labour Cost				
Labour	20% of Total Material Cost		Ksh. 660	
Total Material Cost & Labour Cost			Ksh 3,895	
Profit Margin				
Profit Margin	25% of Total Material Cost & Labour Cost		Ksh. 1000	
GRAND TOTAL			Ksh 4,895	

The retrofitted stove production cost breakdown totaled KES 4,895, as detailed in Table 4.18, comprising material costs (KES 3,295), labor (KES 660), and profit margin (KES 1,000). Major components included cast iron casing and combustion chamber, copper coil system, stainless steel fuel tank, carbon steel nozzle and valves, clay insulation, and supporting hardware.

Manufacturing challenges included precision nozzle fabrication (0.2-0.5mm tolerance) requiring diesel engine injector adaptation, leak-proof welding of water/steam systems, and process control for optimal air-steam balance during startup operations.

4.7 Challenges of Retrofitted Stove

One of the major mechanical challenges in this project is to make the nozzle of the steam injector which is between 0.2 to 0.5 mm. Since that nozzle was very difficult to get a diesel engine injector was used. The other mechanical challenge is welding of the water tank to avoid leaking of water or steam and therefore we used a cylindrical pipe of stainless stove steel.

Process stove engineering challenge is on how to control the heating rate. Heating rate deepens on the amount of steam generated, the balance of the air and steam is very important since the reaction taking place is both exothermic and endothermic. Hence there are some problems in start-up if one is not conversant with the process stove.

Quantifying the fuel consumption of the conventional cookstove seemed to be a formidable task.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

The laboratory emission studies showed that retrofitted cook stoves are the most environmentally friendly form of solid biomass cook stoves. The predominant design approach for semi-gasifier cook stoves is the top-lit up draft (TLUD) scheme. The modified cook stove is equipped with the following characteristics:

- i. Steam, when used as a gasification agent in conjunction with air, guarantees a decrease in carbon monoxide emissions and an increase in thermal power.
- ii. In order to achieve thorough burning of charcoal, secondary air is introduced at various areas of the combustion chamber, namely the middle and top sections. The secondary air undergoes preheating as it ascends throughout the circumference of the combustion chamber.
- iii. Control of the primary and secondary air entering the stove ensured optimal firepower and a high turn down ratio while simmering.
- iv. External insulation of the combustion chamber enhanced thermal efficiency and guaranteed user safety during operation.
- v. incinerators to aid in burning municipal solid waste and hospital waste.
- vi. The fire power was highest in bio-diesel followed by methylated spirit and water, recording 83.9304 J/s, 80.926 J/s and 76.6556 J/s respectively.
- vii. The efficiencies of the retrofitted cook stove were highest in bio-diesel (53.83%), followed by methylated spirit (37.65%) and finally water (14.74%).
- viii. The rate of consumption was highest in bio-diesel (0.27855 g/s), followed by methylated spirit (0.268714 g/s) and finally water (0.254545 g/s).

- ix. Further studies are needed on the rate and amount of gas produced as syngas from the retrofitted cook stove.

This study provides new experimental evidence that steam can effectively act as a gasification agent in retrofitted stoves, lowering emissions and improving thermal performance. It also establishes a comparative performance ranking of biodiesel, methylated spirit, and water as co-firing agents, which serves as a benchmark for future stove design. Moreover, the findings reveal the dual application of the stove as both a clean household energy device and a potential incineration technology for waste management, thereby broadening its socio-economic and environmental relevance.

5.2 Recommendations

- i. Further techno-economic analysis should be undertaken to evaluate large-scale adoption of retrofitted cook stoves. This should include the role of government incentives and assessment of user satisfaction once sufficient data is available.
- ii. Policy makers, stove manufacturers and research institutions should collaborate to scale up the retrofitted stove design to households as a sustainable and cost-effective alternative to traditional open cooking stoves.

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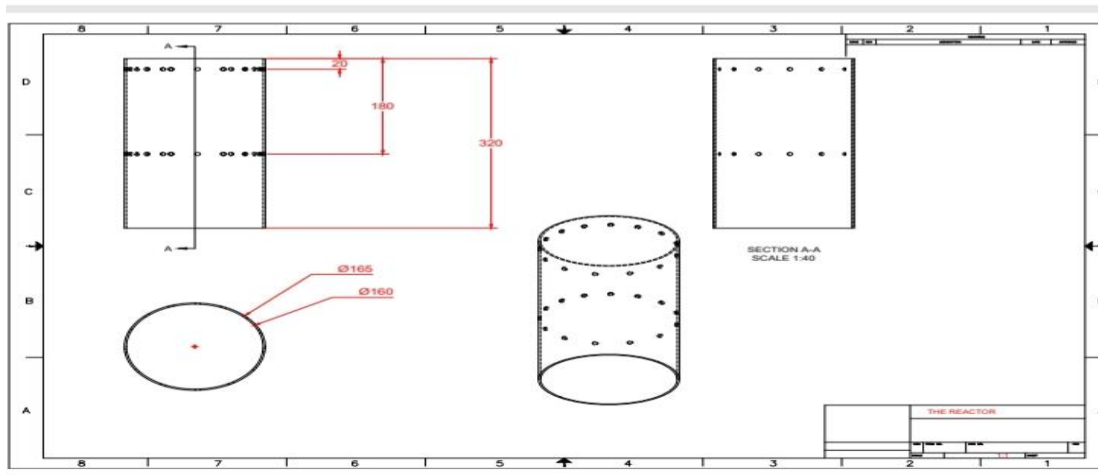
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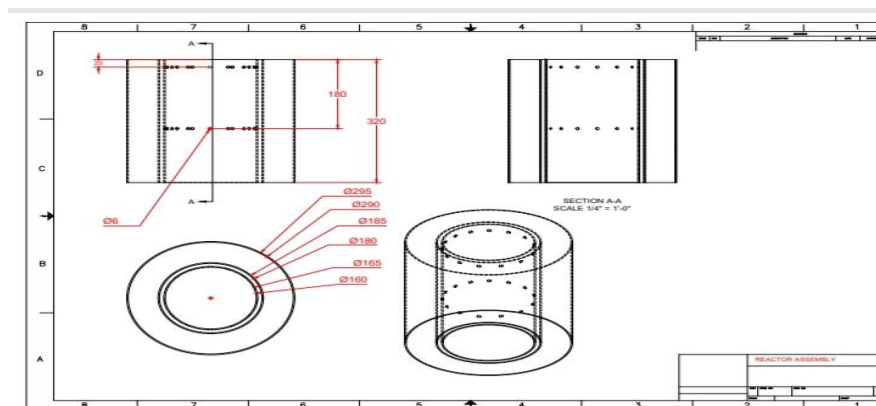
APPENDICES

Appendix 1: Engineering Assembly Layouts

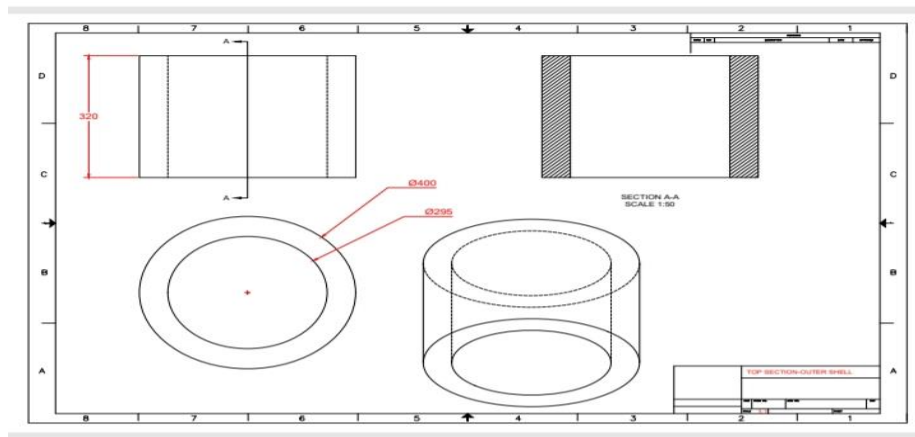
Reactor assembly D-size layout



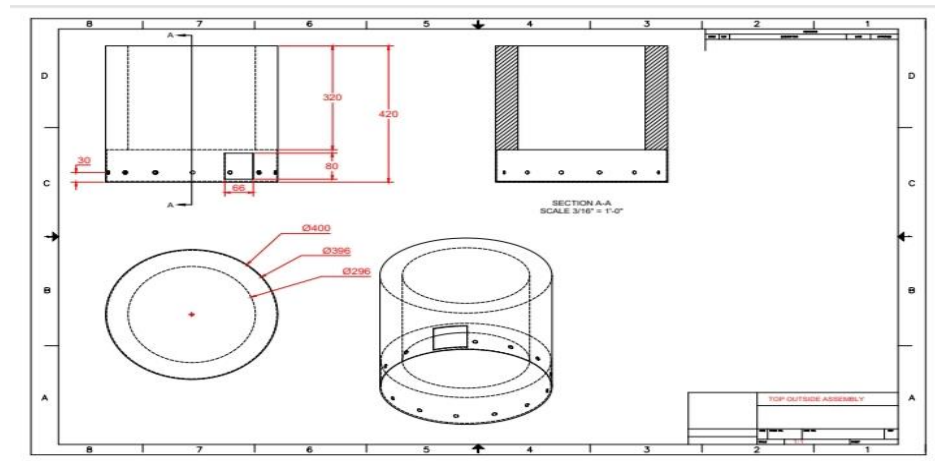
Top outside section D-size layout



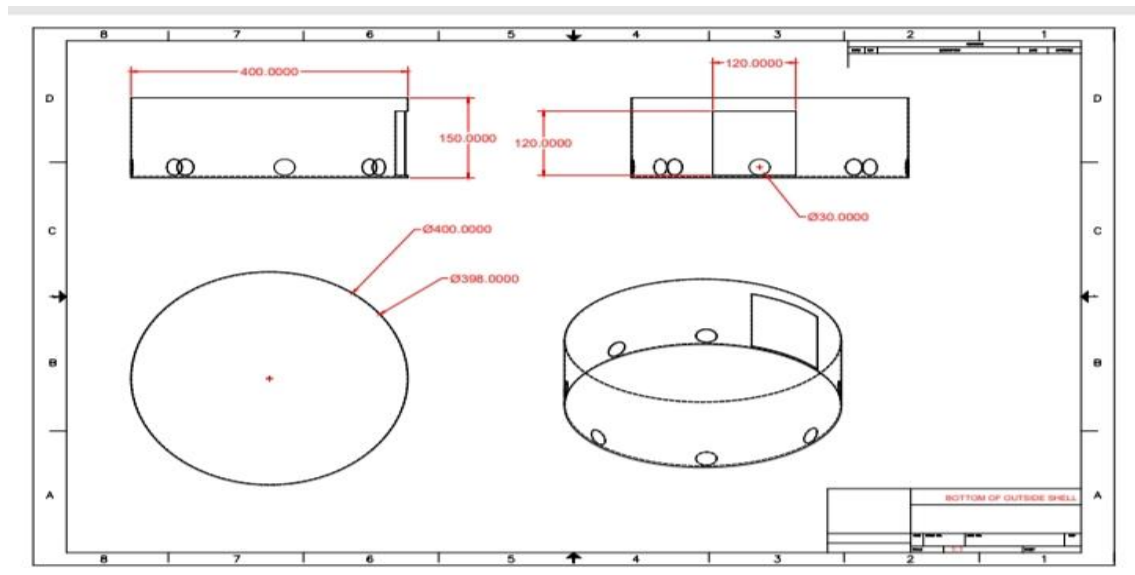
IS upper assembly section D-size layout



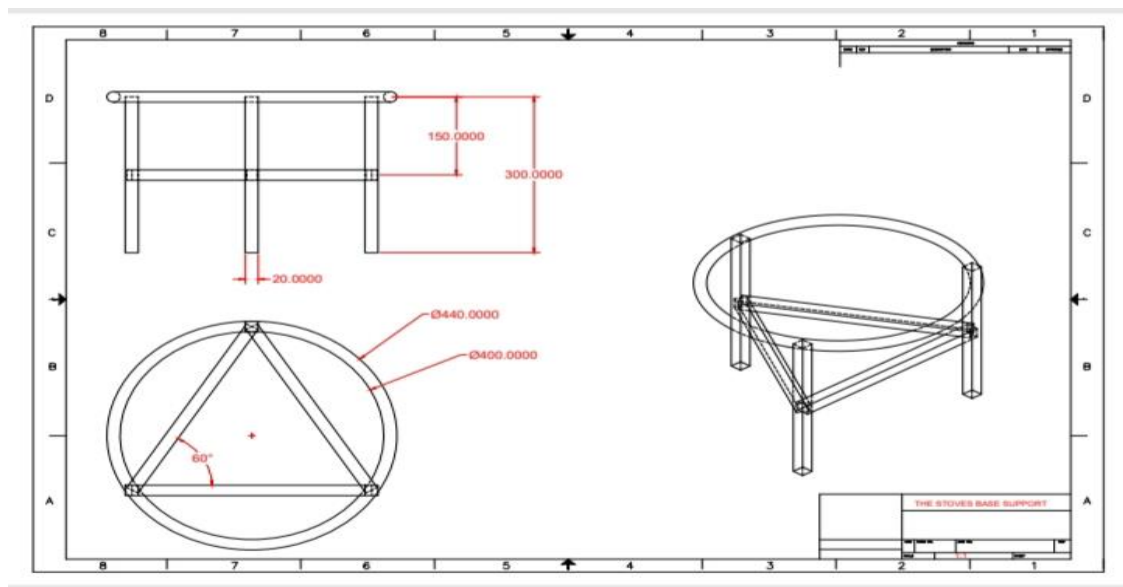
Outside bottom section D-size layout



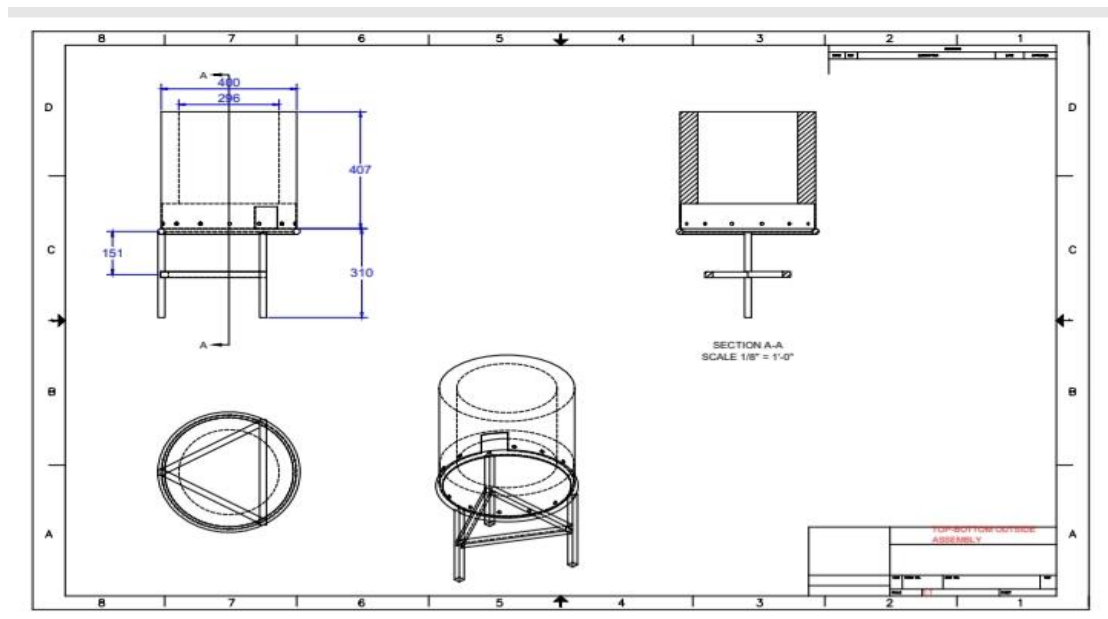
Stove base support



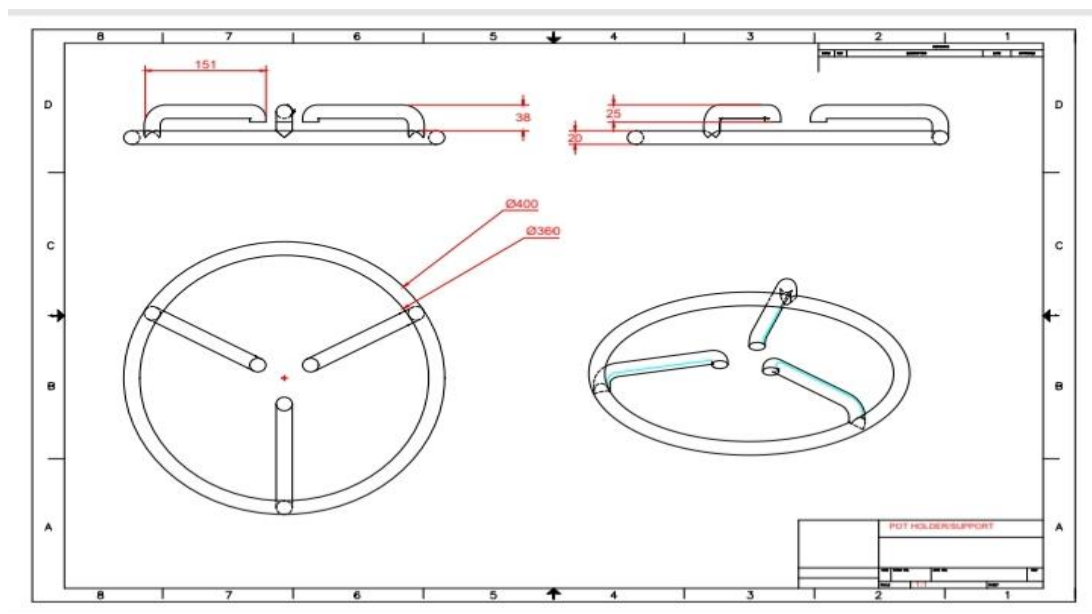
Top-bottom assembly



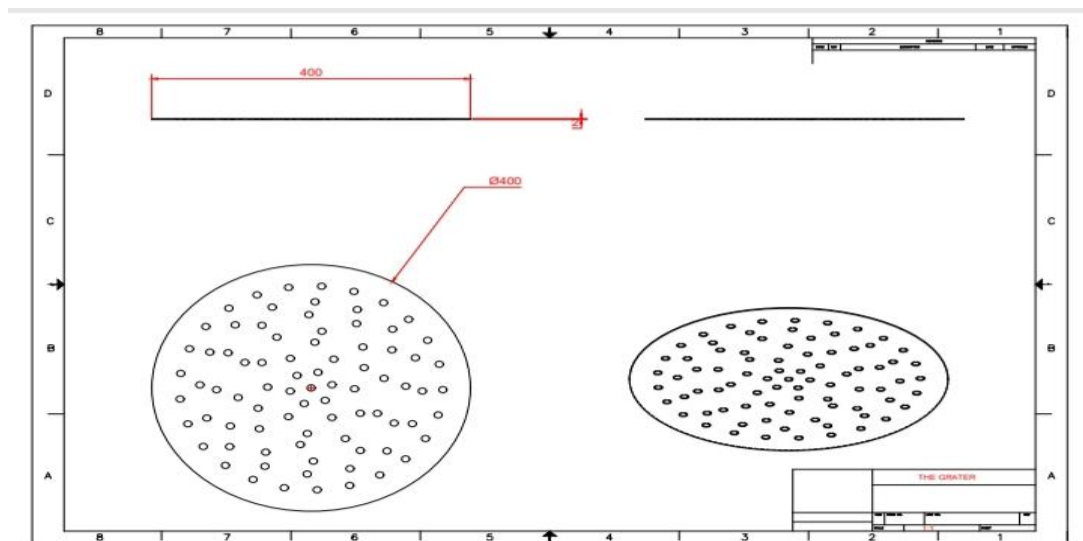
Pot holder /support



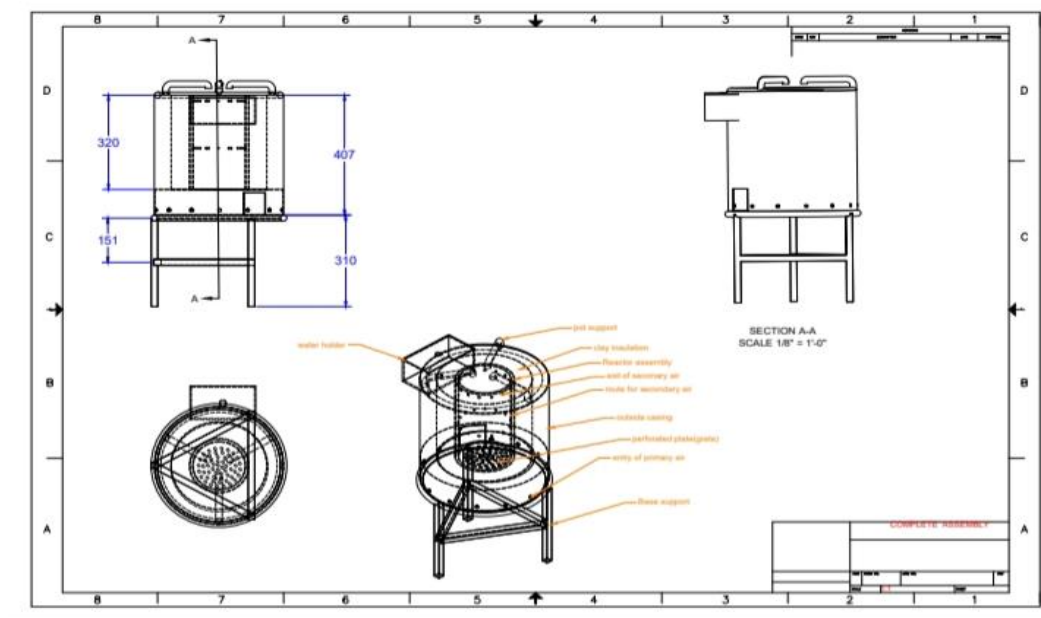
Side tank

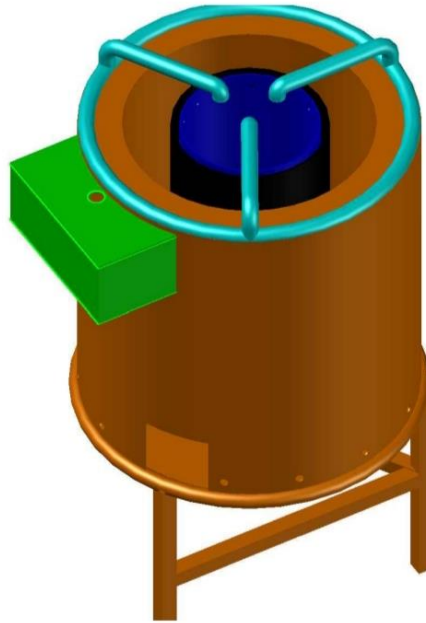


The grater



Cookstove Complete Assembly Layout



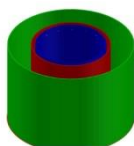
Appendix 2: Retrofitted cook stove complete assembly 3D model

Appendix 3: Retrofitted cook stove components 3D models

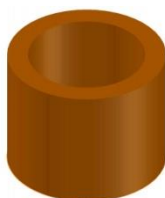
The reactor



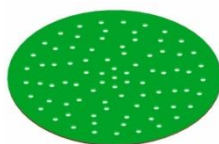
The reactor assembly



Top outside cylinder



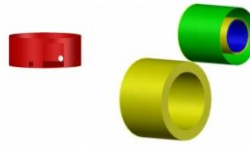
Perforated plate



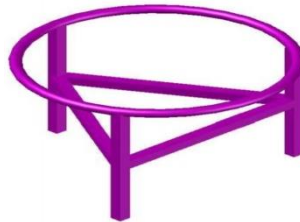
Economical; steam stove outside assembly



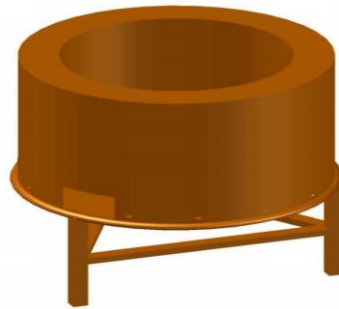
Retrofitted cook stove upper assembly parts



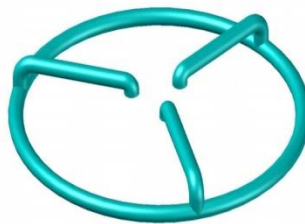
Retrofitted cook stove base support



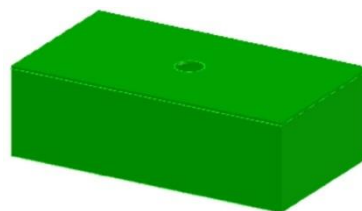
Retrofitted cook stove assembly



Pot base support



Side tank



Appendix 4: Survey on Prices and Availability of Jikos in Eldoret Town

Introduction:

I am conducting a short survey to gather information about the different types of jikos available in Eldoret town, their prices, and consumer preferences. Your responses will be used for research purposes only and will be kept confidential.

Section A: General Information

1. **Gender:**
☐ Male ☐ Female ☐ Prefer not to say
2. **Age Group:**
☐ Under 18 ☐ 18–25 ☐ 26–35 ☐ 36–50 ☐ Over 50
3. **Occupation:** _____
4. **Location within Eldoret Town:** _____

Section B: Jiko Ownership and Pricing

5. Do you currently own a jiko?
☐ Yes ☐ No
6. If yes, what type(s) of jiko do you own? (Tick all that apply)
☐ Traditional three-stone
☐ Charcoal stove (metal)
☐ Improved charcoal jiko (e.g., Kenya Ceramic Jiko)
☐ Gasifier stove
☐ LPG gas stove
☐ Electric stove
☐ Others (please specify): _____
7. Where did you purchase your jiko?
☐ Local market ☐ Retail shop ☐ Supermarket ☐ Jua kali artisan
☐ Other: _____
8. What was the **purchase price** of your most recent jiko (in KES)?
☐ Below 500 ☐ 500–1,000 ☐ 1,001–2,000 ☐ 2,001–3,000
☐ Above 3,000
9. Do you feel the price was affordable?
☐ Yes ☐ No ☐ Neutral
10. Are you aware of any subsidized or improved jikos being promoted in Eldoret?
☐ Yes ☐ No
 If yes, please name the type/brand: _____
11. What is the most important factor when buying a jiko? (Tick only one)
☐ Price ☐ Fuel efficiency ☐ Durability ☐ Availability ☐ Brand/Model ☐ Safety
12. Would you be interested in buying a jiko that uses less fuel and emits less smoke, even if it costs more?
☐ Yes ☐ No ☐ Maybe

Thank you for your participation!

Appendix 5: Plagiarism Awareness Certificate



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ISO 9001:2019 Certified Institution

THESIS WRITING COURSE

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Awareness test for Thesis entitled: **PERFORMANCE EVALUATION OF A RETROFITTED COOK STOVE BY CO-FIRING BIOMASS WITH STEAM, SPIRIT AND BIO-DIESEL** similarity index of 12% and striving to maintain academic integrity.

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