KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY,
KUMASI, GHANA

ASSESSING THE POTENTIAL OF RICE HUSK BRIQUETTE AS A SUSTAINABLE ENERGY SOLUTION AND CLIMATE CHANGE MITIGATION STRATEGY IN KADUNA STATE, NIGERIA

BY

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CERTIFICATION

I hereby declare that this submission is my work towards the Ph.D. in Climate Change and Land Use and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material that has been accepted for the award of any other degree or diploma at Kwame Nkrumah University of Science and Technology, Kumasi or any other educational institution, except where due acknowledgment is made in the thesis.

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ABSTRACT

Overreliance on solid fuels, especially fuelwood and charcoal has contributed enormously to Nigeria's growing rate of deforestation. As part of efforts to curb deforestation, and climate change and have a sustainable cooking energy solution, this study developed briquettes from rice husk using three binders. Before the production, a survey was conducted across 400 households in Kaduna State, Northwestern Nigeria, following a multi-stage sampling approach to comprehend the energy use pattern. To assess the energy potential of rice husk and how it would be a good substitute for fuelwood and charcoal, it was characterized alongside the wood species used as energy sources in the study area. The briquettes were produced in a low-pressure (4.5 MPa) hydraulic piston press utilizing two novel biomass binders (locust bean pulp and sweet potato peel) compared to cassava starch as control. The experiment was designed using Box Behnken Design (BBD) in Design Expert 13, and Response Surface Methodology (RSM) was employed to optimize the process variables and quality metrics. The thermal properties of the briquettes were also assessed using the standard water boiling test (WBT), and a cradle-to-gate life cycle assessment (LCA) was employed to determine the environmental impacts of the briquettes against charcoal. In conducting the LCA, the background data related to energy consumption and material utilization were obtained from the EcoInvent version 3.9.1 database, and other secondary data were sourced from the literature. The LCA model was executed in OpenLCA software (version 2.0) using the environmental footprint (EF) impact assessment method based on a functional unit of 1 MJ of energy. The findings from the household energy use characteristics depict charcoal as the most used cooking energy in the study area, this was followed by fuelwood and Liquified Petroleum Gas (LPG). The energy options were mainly influenced by cost, accessibility, and availability. Furthermore, the results from the multivariate probit regression analysis indicated that the choice of cooking energy is significantly influenced by household factors such as household size, household income, occupation of household head, marital status, age, and education level. The results of wood characterization show that *Anogeissus leiocarpus* (African birch), *Khaya senegalensis* (African mahogany), *Parkia biglobosa* (African locust bean), and *Eucalyptus cam.* (Red gum), are the most energy-efficient wood species. The findings from the assessment of the quality metrics of the developed briquettes show that the briquettes have compressed density between 0.495 g/cm^3 and 0.691 g/cm^3, relaxed density between 0.196 g/cm^3 and 0.306 g/cm^3, impact resistance between 12.5% and 100%, and compressive strength between 20 kN/m^2 and 410 kN/m^2. The optimum process metrics predicted by the model are a 15% binder ratio, 1 mm particle size rice husk, 0.5 min dwell time, and cassava starch binder, while the optimum quality metrics are 0.71 g/cm^3 compressed density, 0.30 g/cm^3 relaxed density, 84.8% impact resistance, and a transformed compressive strength of 0.032 kN/m^2. The comparative environmental life cycle analysis results show that charcoal production and use have a higher environmental impact than briquette. In this vein, a climate change and land use impact of 0.02 kg CO_2 eq and 0.03 kg CO_2 eq; and 0.027 Pt and 6.27 Pt were obtained for briquette and charcoal, respectively. This implies a potential climate change and land use environmental burden mitigation of 0.01 kg CO_2 eq (20%) and 6.23904 Pt (99%), respectively. Thus, the findings affirm that rice husk briquettes with optimal quality for domestic use can be sustainably produced under low pressure, offering a viable solution for energy sustainability and environmental conservation.

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LIST OF ABBREVIATIONS AND ACRONYMS

AC	Ash Content
AK2	Adenylate Kinase 2
ANOVA	Analysis of Variance
APOS	Allocation at Point of Substitution
ARDL	Autoregressive Distributed Lag Model
ASTM	American Society for Testing and Materials
AU	Allocation Unit
B.Sc.	Bachelor of Science
BBD	Box Behnken Design
BR	Binder Ratio
CCA	Clean Cooking Alliance
CCD	Central Composite Design
CD	Compressed Density
Chi2	Chi-Square
CSS	Cassava Starch
CV	Calorific Value
DIN	German Institute for Standardization
DT	Dwell Time
EF	Environmental Footprint
EN	European Norm
FAO	Food and Agricultural Organization
FC	Fixed Carbon
FM	Few Properties Meet the Standards
FU	Functional Unit
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GHV	Gross Calorific Value
HHV	Higher Heating Value
HND	Higher National Diploma
IEA	International Energy Agency
IIA	Independent of Irrelevant Alternative
IRI	Impact Resistance Index

ISO	International Organization for Standardization
IUCN	International Union for Conservation of Nature
JSCE	Junior Secondary School Certificate
L	Lignin
LBH	Locust Bean Husk
LBP	Locust Bean Pulp
LCA	Life Cycle Assessment
LGAs	Local Government Areas
LPG	Liquefied Petroleum Gas
LR	Log Likelihood Ratio
M.Sc.	Master of Science
MC	Moisture Content
MM	Most Properties Meet the Standards
MPa	Megapascal
Mt	Megatonnes
NCV	Net Calorific Value
NGOs	Non-Governmental Organizations
OAT	One At a Time
ÖNORM	Austrian Standard Institute
Ph.D.	Doctor of Philosophy
PPL	Sweet Potato Peel
PS	Particle Size
R2	R-square
RH	Rice Husk
RSM	Response Surface Methodology
SDG	Sustainable Development Goal
SSCE	Senior Secondary School Certificate
STIRPAT	Stochastic Impacts by Regression on Population, Affluence, and Technology
UN	United Nations
USA	United States of America
VM	Volatile Matter
WB	With Bark
WoB	Without Bark

DEDICATION

I dedicate this PhD thesis to my Parents, **Mal. Yunusa Usman and Halima Muhammed.** Indeed, their contribution to my lifetime successes, including this pinnacle of academic degrees is unquantifiable.

To my lovely wife and children for enduring my absence and always motivating and praying for me to succeed.

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CHAPTER 1 : GENERAL INTRODUCTION

1.1 Background

As climate change impacts keep manifesting across the globe, it becomes pertinent to develop coherent and practical mitigation and adaptation measures (Kaygusuz, 2010). To achieve this, the factors inducing climate change need to be identified and approached appropriately. One of the most critical factors that cause climate change and affects the ecosystem is deforestation (Duguma et al., 2019). Deforestation does not only impact the climate but also ravages the livelihood of people who rely on forest resources (Duguma et al., 2019). Many people rely on solid fuels to meet their energy needs. With the increase in population, coupled with the rising cost of energy, over one-third of the world's population lives in energy poverty (UN-ECOSOC, 2022). Based on this, about 2.6 billion people rely primarily on solid fuels especially fuelwood and charcoal to meet their energy needs (Schilmann et al., 2021). This is more predominant in Africa where over 80% of the population relies on different forms of solid fuels (Boafo-mensah et al., 2020). Thus, about 10 million ha of forest is lost per annum across the globe (FAO, 2022), and about 3.4 million hectares in Africa (FAO, 2010). The implication of this is that about 3.6 gigatons of carbon dioxide equivalent (GtCO2) will be emitted within three decades (2020 to 2050), thereby inducing climate change (FAO, 2022). Thus, a sustainable solution that would help mitigate climate change, decrease deforestation, and improve energy security is pertinent.

Over the years, renewable and sustainable energy resources have been widely advocated as a measure for mitigating climate change. Biomass is a renewable energy resource abundantly available around the globe (Liu et al., 2018). It has a substantial potential for energy production using various valorization techniques (Nikhom et al., 2024). Thus, it could potentially curtail the use of non-renewable fuel with both environmental and economic benefits (Kunatsa & Xia, 2022; Orisaleye et al., 2022). Rice husk is one major biomass produced globally because rice is a significant dietary staple (Jyothsna et al., 2024). Globally, it has an estimated energy potential of about 16 EJ/a (Baetge & Kaltschmitt, 2018). Nigeria is the largest producer of rice in Africa. The country’s production capacity increased from 4.0 million tons in 2018 to 8.4 million tons in 2021 (FAO, 2021). In every kilogram of milled paddy, about 0.28 kg of rice husk is generated (Siddika et al., 2021). On this basis, about 2.4 million tons of rice husk is produced annually in Nigeria. However,

there is still no definite strategy for managing or recycling the generated waste (Japhet et al., 2020). They are commonly landfilled or burned, contributing to the emission of greenhouse gases. Thus, transforming these biomass residues into energy is a means of achieving carbon neutrality and mitigating climate change (Wang et al., 2024).

Several methods have been recommended for converting bio-feedstocks into clean and sustainable resources (Ranjbar et al., 2022). Biomass briquetting is one of the effective and promising approaches of harnessing energy from biomass, as it yields briquettes that are environmentally benign with the potential to replace non-renewable fuels (Nagarajan & Prakash, 2021; Suryani et al., 2022; Yunusa et al., 2024). Briquetting is the manual or mechanical compression of feedstocks into a solid, uniformly stable, and more compact form called briquette (Orisaleye et al., 2022; Sugebo, 2022). With the resulting briquettes having an improved shape and size uniformity, the technology simplifies the transportation, handling, and storage of biomass materials (Sugebo, 2022; Vaish et al., 2022). Furthermore, briquettes are cost-effective with the potential to save household energy expenditure and improve income (Ifa et al., 2020). Most importantly, because briquettes are often made from nonwoody biomass, they have the potential to replace/substitute the use of fuelwood and charcoal, thereby curtailing deforestation and mitigating the impacts of climate change.

Although briquetting is not a new technology, it is still emerging in most parts of Africa despite having huge biomass resources (Kuparinen et al., 2014; Japhet et al., 2020). If a substantial amount of the generated agricultural waste is processed into energy through briquetting or pelleting, the use of fossils and associated carbon emissions would be curtailed (Nagarajan & Prakash, 2021). Unlike other forms of renewable energy technologies, briquetting eases transportation and storage. The technology has recently been hailed as one of the most potential answers to deforestation, energy scarcity, and climate change (Kefalew et al., 2021). This is because biomass is a naturally occurring and renewable source of energy (Schnürer & Jarvis, 2018), which is emission neutral.

1.2 Problem Statement and Justification

Kaduna State is among the most populated states in Nigeria with more than nine (9) million people. With the growing population, there has been an increase in energy demand. However, the available energy resources are incommensurable to the growing demand. Based on this and other household factors, more than 70% of households in the state rely on solid fuels predominantly charcoal and fuelwood to meet their cooking and heating energy needs (Yunusa et al., 2024). This has substantially contributed to the rate of deforestation and climate change. Based on this, the State is already experiencing climate change impacts like drought, rainfall variability, and increased temperature (Pius et al., 2020). About 70% of the population in Nigeria depends on solid fuels especially fuelwood to meet their cooking energy needs (Oyeniran & Isola, 2023). This is similar to the regional trend as over 80% of the population in Africa depends on solid fuels to meet their energy needs (Boafo-mensah et al., 2020). This has greatly induced cooking-based carbon emissions. The emissions from the use of solid fuels account for 30 - 55% of the total anthropogenic carbon monoxide (CO) and black carbon (BC) emissions globally (Tao et al., 2016). From an estimate released by the Clean Cooking Alliance CCA, the burning of solid fuels especially fuelwood in cooking accounts for about 1.9% - 2.3% of the global CO_2 emissions (CCA, 2021). Although several households in the country have shown their willingness to switch from using traditional solid fuels to improved bioenergy options (Onyekuru et al., 2021), the use of biofuels is grossly lacking among households, as fuelwood and charcoal use keeps exacerbating.

Nigeria has over 200 million people (Jekayinfa et al., 2020), with a growing socio-economic activities. This has increased anthropogenic influences and has made the country vulnerable to climate change. Nigeria is currently the second largest producer of charcoal in the world following Brazil, with an annual average production capacity of 4,828,689.00 tons as of 2022 (FAO, 2023). Based on this production capacity and the fact that an averagely sized tree yields about 3.4 bags of charcoal (Mba, 2018) which is equivalent to 131 kg, about 36.9 thousand trees are lost in Nigeria per year. In the same vein, the country's annual fuelwood consumption is around 80 million m^3 (Alade & Betiku, 2014). This, coupled with other anthropogenic factors has placed Nigeria among the top countries globally with the highest rate of deforestation (5.0 %), as approximately 410,000 hectares of forests are lost per year (FAO, 2016).

In addition to the intense use of solid fuels, Kaduna state is dominated by agricultural activities. Hence, a large quantity of agricultural waste is generated. However, no strategy is in place to ensure the effective utilization or valorization of the mammoth waste produced. Based on this, the use of raw biomass as fuel was observed among households (Yunusa et al., 2024). While loosed or raw biomass serves as an alternative source of energy, it is important to note that it emits toxic gases especially particulate matter ($PM_{2.5}$) and carbon monoxide (Nagarajan & Prakash, 2021; Velusamy et al., 2022). Based on this, it becomes pertinent to adopt efficient valorization methods such as briquetting as a sustainable energy solution and waste treatment method (Ferronato et al., 2022). Although there are studies on briquette production, most studies rely on starch-based binders (Yunusa et al., 2024). These binders are produced from edible products such as cassava, potato, corn, etc., which influences food security and affects the sustainability of food-based raw materials required in industries, especially pharmaceuticals. On this note, this study assessed the potential of some biomass materials as binders in briquette production.

On average, 55.9 Tg (55.9 million tonnes) of agricultural waste is generated per year in Nigeria (Iye & Bilsborrow, 2013). Rice husk is among the most generated agricultural wastes in the country as Nigeria is the largest producer of rice in Africa. The country's production rose from 4.0 million metric tons in 2018 to 8.4 million tons annually in 2021 (FAO, 2021). Through this, a large quantity of rice husk to the tune of 2.4 million tons is produced annually (Yunusa et al., 2024). Because there are no waste management measures, the generated wastes are commonly landfilled or burned contributing to the emission of greenhouse gases. Thus, valorizing the waste biomass into energy is an avenue to achieving carbon neutrality and mitigating the impacts of climate change (Wang et al., 2024).

Against the stated problems and justification, this study deemed it pertinent to harness an alternative form of energy from rice husk using a low-pressure technique as a potential and sustainable alternative to fuelwood and charcoal. In the same vein, it will serve as a waste treatment strategy, aligning with the four Rs of waste management (reduce, reuse, recycle, and recovery), and also a method of reducing deforestation and mitigating the impacts of climate change. In addition, the study conforms with three (3) pivotal Sustainable Development Goals (SDGs). Viz: Access to clean, reliable, affordable, and sustainable energy for all corresponding to SDG 7, life on land, corresponding to SDG 15 which includes promoting sustainable use of terrestrial ecosystem, and sustainable management of

forests (UN, 2022), and most importantly climate action corresponding to SDG 13. A summary of all the highlighted problems is presented in Figure 1.1.

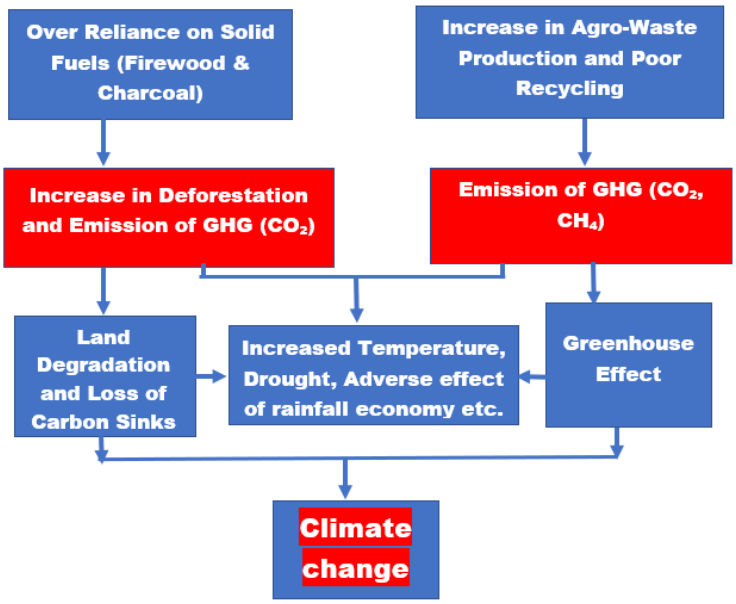

Figure 1.1. Problem Flowchart

1.3 Aim and Objectives

1.3.1 Aim

The study aims to assess the impact of rice husk briquette as a sustainable energy solution and a strategy for mitigating climate change.

1.3.2 Specific Objectives

The specific objectives of the study are to:

i. Characterize the different forms of energy used for heating and cooking at the household and their consumption levels
ii. Assess the properties of the wood species used as energy sources in the study area
iii. Determine the effect of the binder type on the quality metrics of rice husk briquettes
iv. Assess the environmental impact of rice husk briquette and the commonest wood fuel energy source in the study area using Life Cycle Assessment (LCA) modeling

1.4 Research Questions

Based on the specific objectives, the following research questions were posed:

i. What is the commonest form of energy used for heating and cooking in the study area, and what are their consumption levels?
ii. What are the wood species used as energy sources in the study area and which ones are the most energy efficient?
iii. What is the effect of binder type on the quality metrics of rice husk briquette?
iv. What are the environmental impacts of using rice husk briquette against alternative wood fuel energy sources?

1.5 Structure of the Thesis

The thesis is structured based on the manuscript format. It contains eight (8) chapters. **Chapter one** presents the general introduction of the study which comprises the background, the problem statement and justification, the aim and objectives, the research questions, and the scope and limitations of the study. **Chapter two** presents a conceptual and theoretical literature review of the topic. The conceptual review contains a definition of terms and concepts used in the study, a brief overview of the global energy landscape, solid fuels with emphasis on fuelwood and charcoal, and biomass briquetting technology. The empirical review consists of briquetting process parameters, briquetting feedstocks, briquetting binders, briquette quality parameters, and an overview of recent studies on briquette production.

Chapter three addresses specific objective one which deals with the characterization of household cooking and heating energy use and their consumption levels. **Chapter four** reports specific objective two which deals with the suitability assessment of wood species used as energy sources in the study area. However, chapter five and chapter six address specific objective three which looks at the effect of binder type on the quality metrics of rice husks briquette. In **chapter five**, a comprehensive report on the characterization of the feedstocks, briquette production, and process optimization based on two quality metrics (compressed density and impact resistance) was provided. **Chapter six** deals with production, evaluation, and process optimization based on relaxed density and compressive strength. In addition to the optimized responses, the briquettes were characterized to assess

the energy content, proximate, elemental constituents, functional groups, and thermal and emission performances in this chapter. **Chapter seven** addresses specific objective four which deals with the environmental impact assessment of rice husk briquette and charcoal. Under which the comparative thermal and emission performance of the briquettes were reported. **Chapter eight** presents the summary, conclusion, and recommendation of the study.

1.6 Research Scope and Limitation

The study is limited to Kaduna state, Northwestern Nigeria, and only considers household energy used for cooking and heating. Thus, the characteristics of energy use and its influencing factors in the household, the potentiality of using rice husk as a feedstock in briquette production, and the comparative environmental impact of the resulting briquette against charcoal were considered.

The limitations of the study are:
In the socioeconomic aspect of the study under which household energy use was characterized, the actual household income could not be assessed directly. It was determined based on the enumerator's perception following some physical assessments such as the type of household (e.g. nature of the building, etc.), and energy use pattern (including the type of energy used). This may not be the actual status of the household's income. Similarly, while the study has assessed the presence of bio-based fuels such as briquettes and biogas, they were not included as variables in the modeling phase because none of the households used these energy options.

In the pretreatment and characterization of feedstock, no measure was considered to eliminate contaminants that may be embedded in the core layers of the samples. Similarly, there wasn't a practical evaluation of blends and additives in the characterization of wood samples to determine the improvement in ash content and calorific value. Thus, only a theoretical approach was used to predict the improvement.

In terms of densification, only three factors, viz: binder type, binder ratio, particle size, and dwell time, were considered. Thus, compression pressure, despite being an important process parameter, could not be assessed as a variable due to the limitations of the briquette press used (a constant pressure press). In addition, the economic analysis could not be carried out due to time constraints and the steeply rising inflation in Nigeria.

CHAPTER 2 : LITERATURE REVIEW

2.1 Conceptual Review

2.1.1 Definition of Key Concepts

- **Renewable energy:** Renewable energy is an energy source that does not deplete, but can be replenished over a certain period. They are perceived as being environmentally benign with the potential to replace fossil fuels (Blondeel et al., 2021; Christophers, 2022), and mitigate climate change.

- **Biomass energy:** This is a form of renewable energy derived from biomass materials. Biomass can be transformed into energy through direct combustion in their loose or densified forms (briquettes/pellets) or indirectly into biofuels (biogas, biodiesel, bioethanol, etc.) through anaerobic digestion and pyrolysis (Niño et al., 2020). In recent years, biomass energy has shown promising potential that made it one of the major and affordable renewable energy sources (Ibitoye et al., 2021).

- **Solid fuel:** Any dense or loosed solid biomass conventionally used as a fuel or energy source. This includes coal, charcoal, fuelwood, agro-residues, animal dung etc. There are almost 3 billion solid fuel users globally (Adeeyo et al., 2022). This has been intensified by the continuous increase in the cost of LPG, electricity, and kerosene which are commonly used in middle to high-income households (Yunusa et al., 2024). If solid fuels are sustainably used, they would have less environmental impact. However, if otherwise, it contributes to deforestation, household air pollution (HAP), and the emission of greenhouse gases. On this note, solid fuel emissions account for about 30% - 55% of total anthropogenic carbon monoxide (CO) and black carbon (BC) emissions globally (Tao et al., 2016). From an estimate released by the Clean Cooking Alliance CCA, the burning of solid fuels especially fuelwood in cooking accounts for about 1.9% - 2.3% of the global CO_2 emissions (CCA, 2021).

- **Biomass**: Biomass is a non-fossilized and biodegradable biological material derived from living organisms, animals, and plants (Obi et al., 2022). They contain lignin, cellulose, hemicelluloses, and extractives like fats, resins, and ash (Kpalo et al.,

2020a). Thus, they can be classified as lignocellulosic (fibrous and non-starchy) and non-lignocellulosic (non-fibrous and starchy) (Adeleke et al., 2021). Globally, biomass accounts for almost 80% of the total renewable energy and contributes about 10% of total energy supplies (Aggarwal & Chandel, 2022). Its environmental benefits coupled with its potential to replace fossil fuels have made it attract a lot of interest (Nazari et al., 2020). Through this, the value and demand of biomass has increased (Koppejan & Cremers, 2019). Hence, considered one of the most important renewable energy sources globally (Obi et al., 2022). While harnessing energy from biomass is strongly recommended, some of its features such as low density, low carbon, and high silica make it difficult for direct utilization, storage, and transportation. Therefore, densifying into briquettes and pellets is recommended (Narra et al., 2010; Obi et al., 2022). Densified biomass (briquettes) fuels, reduce over-reliance on solid fuels (fuelwood and charcoal) especially in developing countries, thus reducing deforestation.

- **Briquetting:** A process of compacting loosed biomass feedstocks manually or mechanically. The process enhances the energy density, durability, and compactness of biomass feedstocks (Simões et al., 2024), thereby aiding transportation and storage.

- **Briquette:** Briquettes are solid, uniformly stable, and compact biofuels produced through controlled densification. They are gradually gaining popularity as sustainable cooking energy solutions, especially as other forms of cooking energy become expensive and unavailable in some parts of the world. In line with this, research interest in briquette production has increased recently.

- **Binders:** Binders are materials that bind particles together and prevent them from disintegrating (Sanjika & Chipula, 2021). They are essential inputs in briquette production. Hence, the quality of the briquette especially in low-pressure densification depends on the quality of the binder (Sanjika & Chipula, 2021; Zhang et al., 2018).

- **Optimization:** Optimization is the process of determining the optimal or best condition of a process or output. The optimal process conditions are expected to minimize cost and improve efficiency (Arora, 2015). Optimization usually begins with the design of the experiment. Although there are several designs, the Central Composite Design (CCD) and Box Behnken Design (BBD) are the most reported. Response Surface Methodology (RSM) is one of the common approaches employed in optimization. RSM is a collection of statistical and mathematical techniques used in developing, improving, and optimizing processes (Myers et al., 2016). The first step in optimization using RSM is to determine the most important process factors and screen out trivial factors (Okello et al., 2011). Factor screening aims to minimize the variables to make subsequent experiments more efficient with fewer runs (Myers et al., 2016).

- **Life cycle assessment (LCA):** LCA is an internationally accepted method of estimating the environmental impact of product systems, processes or services (Ferronato et al., 2023; Muazu et al., 2017). It consists of four stages: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation. Depending on the requirement and area of application, LCA analysis is conducted from cradle (raw material extraction) to grave (end life), or from gate (any stage between the raw material extraction phase and the end life) to grave, or from cradle to gate, or from gate to gate.

2.1.2 Global Energy Landscape

Energy security is pivotal in attaining sustainable and socio-economic development (Kakodkar et al., 2022; Mucha-Leszko et al., 2022; Zhao et al., 2022). Over the years, there has been a notable change in the global energy landscape (Blondeel et al., 2021). This is not unconnected to the growing population of the world. Currently, the demand for energy has significantly outweighed the available energy resources, thereby compelling people to seek alternative energy options (Kpalo et al., 2020; Komarova et al., 2022). In contrast, fossil fuels are being overburdened and gradually depleting due to overdependence (Rawat & Kumar, 2021). This has equally increased fossil-based CO_2 emissions and has made achieving net carbon neutrality a major challenge (Jiang et al., 2022; Kakodkar et al., 2022). As widely reported, economic growth and the use of non-renewable energy are the key

drivers of greenhouse gas emissions (Li & Haneklaus, 2022). On this note, the use of renewable energy has been largely recommended as it has the potential to reduce CO_2 emissions and mitigate climate change (Cai et al., 2022).

2.1.2.1 Renewable Energy Use

The use of renewable energy has increased in recent years, with a notable rise of 3% in 2020 due to the decline in the demand for other forms of energy (IEA, 2020). This has remarkably reduced CO_2 emissions, thereby enhancing the attainment of carbon neutrality (Zhao et al., 2022). Renewable energy has the potential to meet about two-thirds of global energy demand (Gielen et al., 2019). Its continuous and sustained use will aid the attainment of the targeted global surface temperature (< 2 °C) between now and 2050 (Gielen et al., 2019). The transition from the use of non-renewable energy to renewable energy has progressed significantly. In recent years, the G7 countries (Canada, France, Germany, Italy, Japan, the UK, and the USA) have recorded a significant improvement in the use of renewable energy (Ding et al., 2021). However, due to some factors including the lack of technologies, the use of renewable energy is still slow in developing countries. Thus, for a swift transition, renewable energy must be made affordable and available to all (Christophers, 2022). It was observed by Zhao et al. (2022), that developing renewable energy sectors will help alleviate global energy poverty. Thus, more countries are required to subscribe to various international consensus that recommends using low-carbon energy by formulating policies and measures that will enhance the development of the renewable energy industry (Zhao et al., 2022).

2.1.3 Solid Fuels (Fuelwood and Charcoal)

The increasing population growth coupled with the rise in the cost of energy has compelled many households, especially in the rural and peri-urban parts of developing countries to use solid fuels (Imran et al., 2022; Kyayesimira & Florence, 2021; Padhi et al., 2022). This, among other factors, has negatively impacted the climate (Adeleke et al., 2021), especially as forest covers, which are major carbon sinks, keep depleting due to the extraction and production of solid fuel (charcoal and fuelwood).

About 3 billion people globally use different forms of solid fuels to meet their primary energy needs (Adeeyo et al., 2022). Out of these, about 2.6 billion people mostly of poor and rural backgrounds (90%) rely solely on fuelwood and charcoal (Schilmann et al., 2021). Through this, approximately 1 Gt of CO_2 equivalent is generated annually from fuelwood combustion for cooking (CCA, 2021). Overall, cooking contributes about 5% of global greenhouse gas emissions (Adria & Bethge, 2013), with 1.9 – 2.3% of the total CO_2 emissions from using fuelwood in traditional cookstoves (CCA, 2021). This has resulted in a significant rise in household air pollution, which is a critical problem in developing countries (Aggarwal & Chandel, 2022). The stated emissions are largely black carbon and particulate matter resulting in millions of premature deaths and health disorders annually (Kyayesimira & Florence, 2021; Witinok-huber et al., 2022). Hence, the continuous or intense use of charcoal and fuelwood is considered unsafe and unsustainable (Qin et al., 2021), especially as it impacts health and the environment. Thus, with the stated negative impacts, densified biomass (briquettes) is perceived as the best and most sustainable alternative to fuelwood and charcoal with improved socioeconomic and environmental benefits (Ibitoye et al., 2021; Yank et al., 2016). Thus, to achieve this at a large scale interventions and policies are pertinent (Woolley et al., 2022).

To meet the United Nations (UN) Sustainable Development Goal (SDG) 7 which focuses on the provision of clean, sustainable, and affordable energy for all (UN-ECOSOC, 2022), there is a need for adequate intervention and outreach to rural and peri-urban areas (Sawyerr et al., 2020). The intervention may include the provision of clean cookstoves and bio-fuels such as biomass briquettes/pellets as well as a comprehensive sensitization on the importance of switching from the conventional method to the sustained use of cleaner fuels (Kyayesimira & Florence, 2021; Schilmann et al., 2021). According to Akolgo et al. (2021) transiting from charcoal to briquette has the potential to curtail particulate matter PM and carbon monoxide (CO) emissions by 14% and 80%, respectively. However, this may vary depending on the material used in production. For example, Wongwuttanasatian & Sakkampang (2016), observed that briquettes made from rice husk char emit a higher level of CO_2 (13.2–15.5%) than those of rice husk (11.5–14.3%). However, the same study observed a higher level of CO and nitrogen oxide (NOx) emission in rice husk briquettes compared to briquettes made from rice husk char. Therefore, it is important to have a good understanding of the feedstocks, by first characterizing to determine their physical and thermal properties.

2.1.4 Biomass Briquetting Technology

Briquetting is a form of biomass densification that involves the mixing and compaction of feedstocks with the aid of pressure (Ibitoye et al., 2021). It enhances the density of loosed biomass into a more compact and uniformly stable product called a briquette (Sugebo, 2022). Briquettes are solid biofuels produced through a controlled densification process under specified process variables (Costa et al., 2019).

As other forms of energy are becoming more expensive and unavailable in some parts of the world, briquetting technology is gaining wide acceptance (Yunusa et al., 2023). In line with this, research interest in briquetting has increased in recent years, and now includes the use of non-biomass feedstocks such as industrial waste (Abdelrahim et al., 2022; Mousa et al., 2022), and mineral deposits such as coal (Adeleke et al., 2022; Tulepov et al., 2022) and limestone (Jovanovic et al., 2022). Though, applied in various forms and not purely cooking.

2.1.4.1 *Process of Briquette Production*

The briquette production process is an agglomeration approach that involves transforming loosed biomass into a compact end product following a series of steps as highlighted in Fig. 2.1 and elaborated below.

a. Biomass Collection

The collection of biomass or raw materials is the first step in briquetting. This includes the collection of both biomass fibers and binding material. At this stage, it is encouraged to use biomass waste materials that are largely available in an environment for sustainable production and to enhance environmental waste management. This may include plant and animal waste which can be found both on land and in water. However, with recent advances in briquetting, most of the feedstocks reported in the literature are non-woody lignocellulosic biomass. This is a measure of reducing deforestation and improving carbon capture. In addition to using lignocellulosic biomass, some recent studies are now evaluating sludge, microalgae, municipal solid wastes (MSW), and plastics in briquette production.

b. Biomass feedstock characterization

The characterization phase usually involves the determination of the physical and thermochemical properties of the feedstock. Parameters such as moisture content, bulk density, particle size distribution, lignocellulosic composition, calorific value, and proximate and elemental composition are determined following a standard test method. The results of these analyses usually give an insight into the feedstock's densification potential as well as an estimate of the quality of the briquettes that will be produced from the feedstock (Asamoah et al., 2016). For example, the level of ash from the proximate analysis indicates the slagging and fouling behaviors of the feedstock during combustion, and the lower it is, the better the heating value (Thabuot et al., 2015). Based on this, an ash content of less than 4% is generally preferred for briquetting as it reduces slagging potential (Nagarajan & Prakash, 2021). Thus, it is important to characterize the feedstocks before densification. This will help in subsequent stages, especially when selecting a pre-treatment or pre-processing method.

c. Pretreatment

Pretreatment is the preprocessing phase where the core elements in the feedstocks are activated to improve the quality of the resulting briquette. The pretreatment process is necessary as biomass feedstocks have a diversity of properties that are both beneficial and in certain applications not beneficial (Koppejan & Cremers, 2019). Pre-treating a feedstock enhances its grade sizes and saves the cost of energy incurred in milling (Thabuot et al., 2015). This further enhances the briquette quality as feedstocks with smaller particle sizes homogenize and compact better than feedstocks with large grade sizes, yielding briquettes with better quality (Miao et al., 2019). The two most reported pre-treatment methods in briquetting are physical (screening, milling, drying, etc.) and thermal (torrefaction, carbonization, steam explosion, etc.). The selection of a certain method depends on the type of feedstock, its properties, and the type of densification. Irrespective of the applied method, studies have shown that pre-treated feedstocks are generally more efficient than un-pretreated ones. For example, fuels produced from torrefied biomass have better energy density, storability, and significantly higher corrosion resistance than those made from non-torrefied biomass (Koppejan & Cremers, 2019).

d. Material Preparation

The material preparation phase is very essential in briquette production. The binding material is gelatinized and mixed with biomass and water in this phase. The mixing can be done manually or mechanically using mixers. In both approaches, mixing continues until the biomass and binder are homogenized completely. The matrix composition depends on the type and nature of materials, the briquetting machine to be used, and the expected quality of the briquette. Thus, the higher the machine pressure the lower the binder required and vice versa.

e. Densification

Densification involves compressing the mixed materials into a solid and compact form. Different machines are employed in this stage, ranging from simple hand presses, such as plungers to mechanically driven hydraulic presses and extruders. While various briquetting machines exist, the hydraulic, mechanical, or roller presses are the most common (Tumuluru et al., 2011). In this phase, the mixed materials are fed into the machine and compressed at a certain dwelling period.

f. Drying/Cooling

Immediately after ejection from the mold, the briquettes are dried for a certain period depending on the drying temperature and medium. Generally, briquettes are dried for a few hours to days in an oven or for several days or weeks when drying under the sun. In some instances when using a high-pressured machine, the briquettes are dried in a chamber incorporated into the machine before ejection. In such cases, the briquettes are ejected at high temperatures from the mold and must be cooled for a certain period before evaluation or use. However, cooling also applies to some low-pressured techniques where the briquettes are dried at a very high temperature. Thus, it must be kept at room temperature to cool down before evaluation or use.

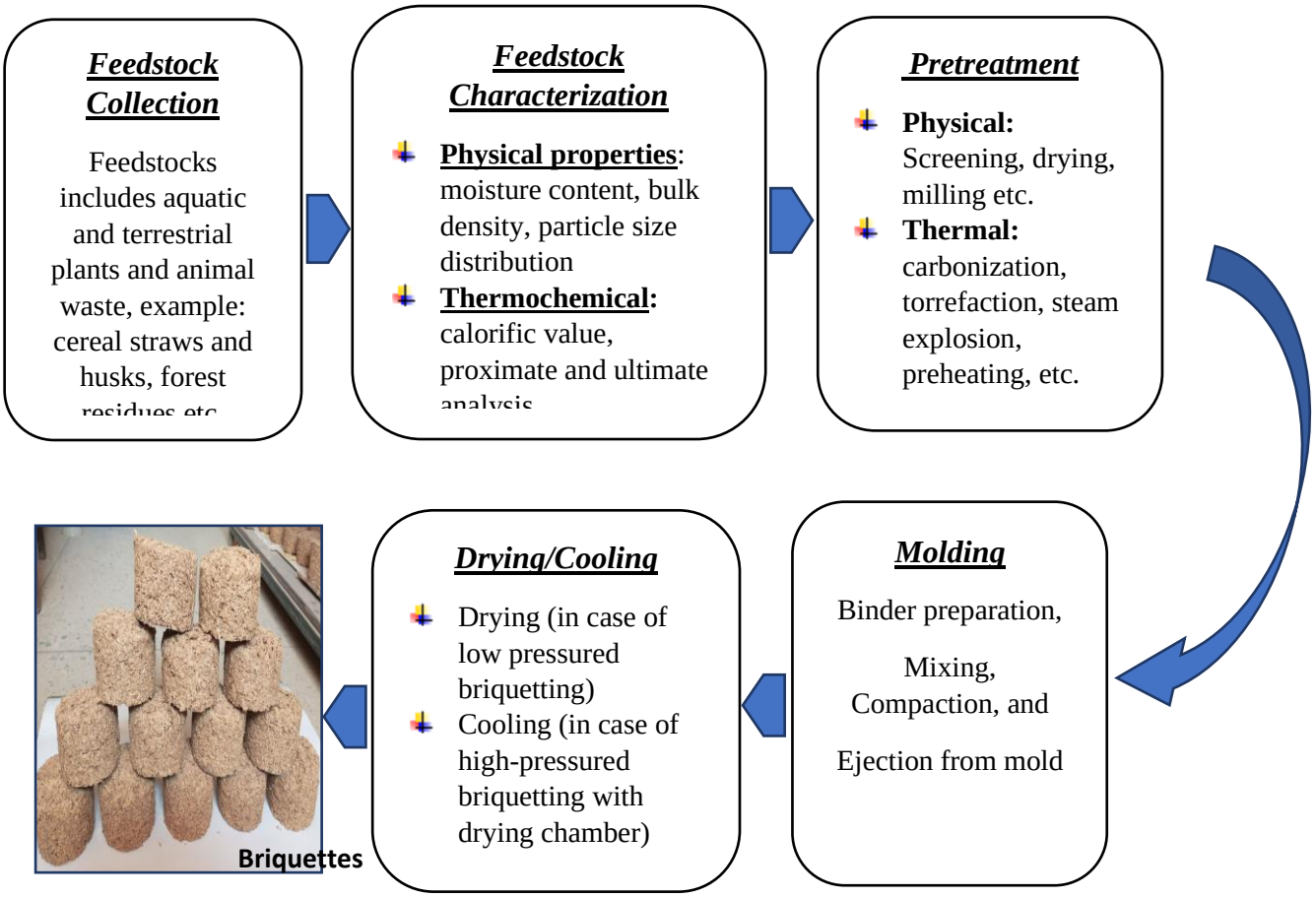

Figure 2.1. Briquette production process. Modified from Yunusa et al. (2023)

2.1.4.2 Briquetting Machines

Briquetting machines or presses are mechanical or manual equipment used in densifying biomass into a compact and dense form called briquettes. The machines range from simple manual presses (Fig. 2.2a) to mechanical presses such as hydraulic piston presses (Fig. 2.2b and 2.2c) and screw extruders (Fig. 2.2d), etc. The manually operated machines are mostly employed in small-scale briquette production while the mechanically operated types are usually used in large-scale production (Asamoah et al., 2016). Overall, the hydraulic piston press, and screw press are the two most commonly used briquetting machines (Asamoah et al., 2016; Ibitoye et al., 2021), with the piston press being more widely used as it has a simple setup and is easy to operate (Dinesha et al., 2019). Another advantage of the piston press is that it has a low energy requirement, and can densify briquettes at all pressure levels (low, medium, and high). Unlike pelleting machines, some briquetting machines can handle feedstocks with large particle sizes and high moisture contents without the addition of binders (Tumuluru et al., 2011).

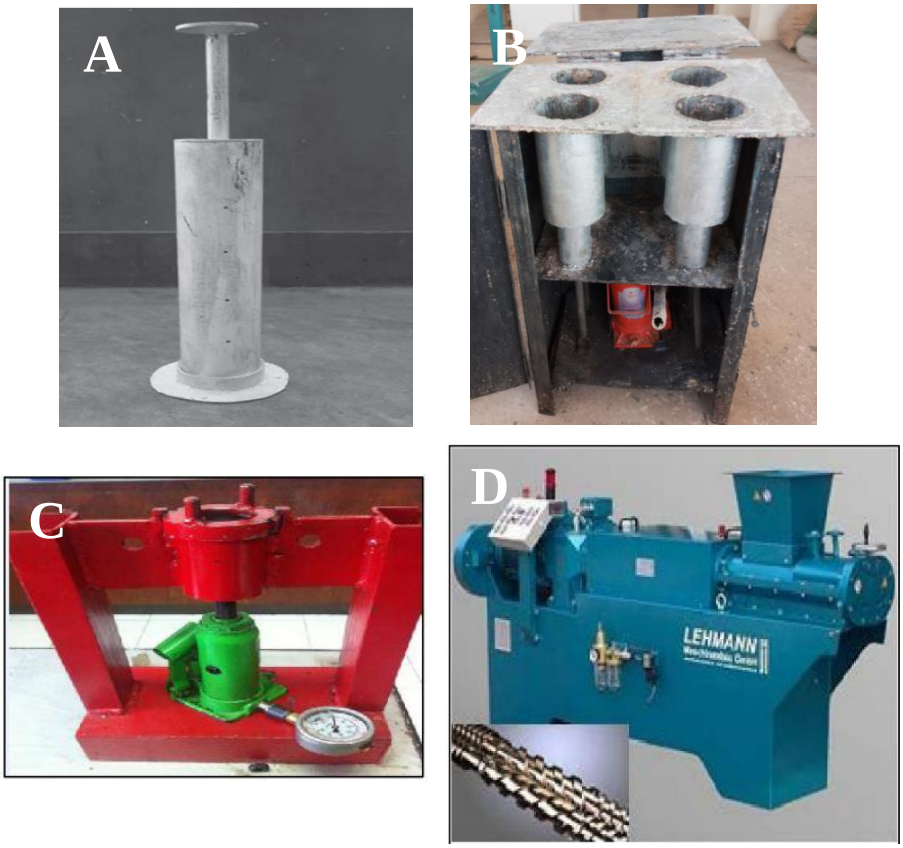

Figure 2.2. Briquetting machines (a) hand plunger (Tamilvanan, 2013) (b) multi-piston hydraulic press (c) single-piston hydraulic press (Handra & Hafni, 2017) (d) Screw extruder (Narra et al., 2012)

Table 2.1 presents a comparison between the three main briquetting machines in terms of operational conditions and briquette quality.

Table 2.1. Comparison of different briquetting machines

	Hydraulic Piston Press	**Screw Extruder**	**Roller Press**
Required Feedstock moisture content (%)	10–15	4–8	10–15
Particle size requirement (mm)	6–12	2–6	< 4
Binder Requirement	Depends on the material and applied pressure	Depends on the material and applied pressure	Depends on the material and applied pressure
Shape	Cylindrical	Cylindrical	Generally elliptical (depends on the shape of the die)
Wear of contact parts	Low	High	High
Output from machine	In strokes	Continuous	Continuous
Specific energy consumption (kWh/ton)	37.4–77	36.8–150	29.91–83.1
Throughput (ton/hr)	2.5	0.5-1	5-10
Unit density (g/cm^3)	<0.1	1–1.4	No Information
Bulk density (g/cm^3)	0.4–0.5	0.5–0.6	0.48–0.53
Maintenance	High	Low	Low
Combustion performance of briquettes	Moderate	Very good	Moderate
Homogeneity of densified biomass	Not homogeneous	homogeneous	Not homogeneous

Source: Adapted and modified from (Tumuluru et al., 2011)

2.1.5 Briquette Utilization

Briquettes have several domestic and industrial applications as highlighted in Table 2.2. However, the main focus of this study is to develop briquettes for domestic applications to serve as a substitute or potential replacement to fuel wood and charcoal. Hence, it is important to review the cookstoves (traditional and improved) available in the households/literature as a basis for assessing the best medium for utilizing the briquettes.

Table 2.2. Potential applications of briquettes

Areas	Possible Application
Domestic	Cooking, water heating, and space heating
Commercial	Cooking, water heating, grilling, etc.
Hospitality	Cooking, water heating, space heating (outdoor dining areas)
Industries	Powering of boilers and heating systems
Food processing	Distilleries, bakeries, canteens, restaurants, drying
Textiles	Dyeing, bleaching
Crop processing	Tobacco curing, tea drying, oil milling
Ceramic production	Brick kilns, tile making, pot firing, etc.
Gasification	Fuel for gasifiers to produce electricity
Charcoal production	Initiating pyrolysis to make charcoal production more efficient
Poultry	Incubators and brooding

Source: Modified from Mwampamba et al. (2013)

2.1.5.1 An overview of biomass cookstoves as a medium of briquettes utilization

As shown in Fig. 2.3, the dynamics in biomass cookstove innovation stems from the open flame fires to three brick fires (TBF) to metallic shielded models, and to improved and advanced cookstoves (Sutar et al., 2015). The effort to develop improved cookstoves began as far back as the 1950s with technological attempts to upgrade the design of the then biomass-powered cookstoves. However, improved cookstoves were first developed in the 1970s as a way of augmenting the oil crisis and solving the fuelwood crisis thought to curb deforestation and desertification (Mutuku et al., 2022). Several models and types of improved biomass cookstoves exist. There are mainly two broad classifications: traditional biomass cookstoves (Fig 2.3 a-d) and improved cookstoves (Fig 2.3 e-h).

Figure 2.3. (a) Three stone open fire, (b and c) metallic open fire, (d) traditional charcoal stove, (e) Natural-draft double burner biomass cookstove (Yunusa et al., 2022), (f) husk biomass cookstove (Kole et al., 2022), (g) Inverted downdraft gasifier cookstove (Osei et al., 2020), (h) Improved biomass cookstove (Rupnar & Chauhan, 2016)
Source: (Yunusa et al., 2023)

a. Traditional biomass cookstoves (primitive designs)

Traditional biomass cookstoves are the rudimentary or primitive types used with conventional solid fuels like fuelwood, charcoal, agro-residues, and dung. Because they are poorly designed without adequate combustion metrics, they have low fuel efficiency, thermal, and emission performance (Barbour et al., 2021; Mekonnen, 2022; Panwar & Rathore, 2015). Based on this, about 600,000 mortality is reported annually in Africa with millions of chronic illnesses (ACCES, 2014). Similarly, the intense use of solid fuels has contributed to the growing rate of deforestation in Africa. Out of the 3.4 million hectares of forest woods lost annually in Africa through deforestation (FAO, 2010), wood harvest for fuel results in an annual loss of about 500 million tons (USAID, 2017).

b. Improved biomass cookstove (advanced designs)

The improved biomass cookstoves are developed to cushion the drawbacks of traditional biomass cookstoves (Gumino et al., 2020; Keese et al., 2017). The word "improved" in the context of cookstove implies a potential reduction in fuel use and toxic gas emissions. However, the benefits are beyond that as it also includes safety, cost reduction, and time-saving among others (USAID, 2017). While improved cookstoves are primarily designed to enhance fuel, thermal, and emission performance (Manaye et al., 2020), they are occasionally viewed to accommodate multi-fuel types, especially conventional solid bio-fuels like briquettes and pellets. A similar design has been developed by Yunusa et al. (2022).

Lahai et al., (2022) believed that for a cookstove to be considered improved, it must be able to curtail $PM_{2.5}$ emissions by at least 50%. Generally, improved biomass cookstoves are classified based on performance, mode of combustion, and type of construction material (Mehetre et al., 2017). On this basis, there are Top-Lit Up-Draft (TLUD) designs (De La Hoz C & González, 2020), i.e. cookstoves lit from the top with primary airflow from the bottom. While some are designed as Top-Lit Down-Draft (TLDD) (Orisaleye et al., 2018; Osei et al., 2020) (Fig. 2.3g), i.e., cookstoves lit from the top with primary airflow coming from the top. Others include natural draft design (Yunusa et al., 2022) (Fig. 2.3e), force draft design (Barbour et al., 2021), or a combination of both (Kumar & Panwar, 2019; Sood et al., 2018). In terms of feeding methods, there are batch-fed (Gupta et al., 2020), i.e. designs that involve feeding fuel in batches and designs in which fuels are fed continuously (Krüger & Mutlu, 2023; Rupnar & Chauhan, 2016).

Some studies that reported the superiority of improved cookstoves include that of Rasoulkhani et al. (2018) which discovered that the improved cookstove tripled the traditional open-fire stove in performance with a fuel saving of more than 60%. Similarly, Dresen et al. (2014) reported a 40% fuel saving while in a different study, a 30 – 60% fuel saving was reported (Mehetre et al., 2017). Bantu et al. (2018) also recorded as high as 79% fuel savings. In another study, black carbon emissions were lowered by 50 – 90 % using an improved biomass cookstove (Mehetre et al., 2017). While the nature or type of biomass cookstove design affects the cookstove's performance, the actual cooking process equally contributes to the performance, particularly the emission of gases. Based on this, Padhi et al. (2022) revealed that when biomass cookstoves are used for boiling and frying, they emit more gases than when used for baking and sautéing. Hence, future designs could consider unifying the various operational processes under low emission.

Despite the enormous benefits of improved biomass cookstoves on health and the environment, the developed models and designs have received less attention from many parts of the world where the use of traditional cookstoves is high (Sutar et al., 2015). This has been confirmed in several studies including Karanja & Gasparatos, (2020) in Kenya where only 38.5% of households were found to have adopted improved cookstoves. Similarly, in Ghana, a low adoption rate was reported majorly because the improved cookstoves are not available in local markets (Dickinson et al., 2019). As reported in the literature, developing countries are dominated by traditional cookstoves. Out of the 166 million households that use improved cookstoves globally, 116 million are in China, more than 13 million are in East Asia, about 22 million are in South Asia, and the remaining 7 million are in Sub-Saharan Africa (World Bank WB, 2011). Against the stated facts, this study primarily focused on producing briquettes that would potentially substitute conventional solid fuels (fuelwood and charcoal) to curtail deforestation and climate change. While the improved and multi-fuel cookstove models are recommended for being superior, low-income households who may not afford the improved models can tentatively use the briquettes in their conventional cookstoves.

2.2 Empirical Review

2.2.1 Briquetting Process Parameters

The process parameters are the various variables used in the production process. As reported by Kpalo et al. (2020a), they include compression conditions such as temperature, pressure, dwell time, and feedstock properties such as moisture content, particle size, shape, and feedstock composition. While these parameters affect the mechanical strength (compressive strength, durability, impact, and water resistance) and other properties of the briquettes, each parameter affects the process differently, hence the effect may not necessarily be significant when considered separately. Based on this, it is essential to select the parameters carefully to have durable briquettes (Bazargan et al., 2018).

Briquetting temperature

Briquetting temperature is the temperature at which feedstocks are densified into briquettes. According to (Niño et al., 2020), temperature is one of the most important parameters that determines the performance of briquettes. Briquettes could be produced at room temperature, moderate, or high temperatures, or simply at low and high temperatures as reported in some studies. Briquette production at low or room temperature is commonly achieved with manual presses such as plungers or manual hydraulic piston presses as most machines are without a heating element. Therefore, if a controlled temperature is required when using the manual presses, then the most reported approach is to preheat the feedstocks to the desired temperature before compression. This could be achieved by mixing the feedstock with hot water or by heating it in a microwave or oven as done by (Niño et al., 2020). Generally, it is believed that briquettes produced at low temperatures have lower mechanical strength compared to those made at high temperatures. While this could be true, it highly depends on other parameters and quality metrics. For example, Kpalo et al. (2022) employed a low temperature and obtained briquettes with low densities (0.24–0.37 g/cm^3) but with good drop strength (79.18–99.9%). Similarly, Yank et al. (2016) densified at room temperature and obtained a compressive strength and durability of 2.54 kN and 91.9%, respectively. In the case of Antwi-Boasiako & Acheampong, (2016), a room temperature (25 ˚C) was employed, and good compressive strength (305MPa) was obtained. Moreover, this may be due to the nature of the biomass (sawdust) used, the application load (60 kN), and pressure. Thus, this confirms the fact that one process parameter may not necessarily determine the overall quality of the briquette.

Some machines like those used by Khlifi et al. (2020), and Obi (2015) have a heating element or unit main for heating the piston die and feedstocks during consolidation and compression. Although briquettes densified at high temperatures have been reported to be more efficient in density and stability, they are uneconomical, energy-intensive, and in some cases highly emissive (Rahaman & Salam, 2017). On this note, Marreiro et al. (2021) suggest that briquetting at high temperatures should only be considered when densifying at room temperature fails. In the study conducted by Obi (2015), it was observed that high-temperature briquettes have better physical properties, while low to moderate-temperature briquettes have better combustion performance. On this note, it is important to determine the optimum temperature needed for a given process. This can be obtained through optimization. Having an optimum temperature will save costs and minimize the potential environmental impacts.

a. Briquetting pressure

The briquetting pressure is the total force applied per unit area of the compression mold during densification. Depending on the type of machine and compaction pressure employed, briquetting can be classified into high, medium, and low-pressured (Ibitoye et al., 2021). Eriksson & Prior, (1990) further elaborated the classes of pressure as low (5 MPa), medium (5–100 MPa), and high (100 MPa and above). However, the required pressure per compression depends on the type of feedstock, moisture content, particle size, and shape (Kpalo et al., 2020a). This shows that briquettes produced at high pressure will not necessarily have the best quality (Marreiro et al., 2021).

i. Low and medium-pressure briquetting

This is the process of producing briquettes with an applied pressure of ≤ 5 to 100 MPa. When densifying at low pressure, a binding agent is usually required to bind the particles together (Kpalo et al., 2020a). Briquetting within the low to medium pressure range is generally less costly and easier as it is less technical. Hence, a simple hand press or a manual hydraulic press is usually sufficient. While low to medium-pressured briquettes are generally less durable compared to those of high-pressure, recent findings have shown that it is feasible to obtain highly durable briquettes within the stated pressure range (Kpalo et al., 2020). This includes the study of (Mitchual et al., 2013), where an impact resistance as high as 500% was obtained within a pressure level of 20 to 50 MPa. However, if the pressure is very low as in the study of Magnago et al. (2020a) (100 Pa), attaining good

mechanical strength is difficult even with the influence of other factors. This is because other process parameters are highly dependent on applied pressure. Unlike the high-pressured process which usually has a heating chamber, briquettes made through the low-pressured process have to dry for days or weeks before use.

ii. High pressure briquetting

This involves briquette production at a pressure level ≥100 MPa. Unlike the low-pressure technique that typically requires a binder, the high-pressure method can activate and utilize the embedded binding elements in a feedstock, such as lignin, starch, protein, and pectin (Kaliyan & Morey, 2009; Kpalo et al., 2020a). High-pressure briquetting is usually applied on an industrial or commercial scale and, thus, requires more sophisticated machines like extruders. Briquettes production at this pressure level is typically between 100 –150 MPa or higher in pellet mills, and within 100–200 MPa, and above in roller press (Kaliyan & Morey, 2009). Other conventional high-pressure driven machines such as the screw press, piston press, extrusion, or hydraulic piston press typically operate between 100 and 200 MPa, or above (Ibitoye et al., 2021).

With the high-pressure process, interparticle adhesion and mechanical interlocking of feedstocks are achieved, thereby yielding briquettes that are compact and uniformly stable with densities between 1200-1400 kg m^{-3} or more (Handra & Hafni, 2017; Ibitoye et al., 2021). This may not be unconnected to the fact that high pressure develops solid bridges through the diffusion of molecules from the individual feedstock particles (Kaliyan & Morey, 2009).

iii. Optimum briquetting pressure

In addition to temperature, type of feedstock and binder, etc., attaining a quality and thermally efficient briquette is a function of applying an optimum pressure. On this note, several studies have reported a range of optimum pressures for high, medium, and low-pressure briquetting. Essien & Oke (2019) have obtained 6.86 and 9.81 MPa as optimum for homogeneously compacting sawdust and rice husk at low to medium pressure. In the same study optimum pressure between 7.10 and 9.75 MPa was reported for heterogeneous compaction. Similarly, Rahaman & Salam (2017) observed that a medium compression pressure of 34.5 MPa is sufficient in producing briquettes with a stable density of > 600 kg/m^3, while Zhang et al. (2019) have noted a pressure of 122.7 MPa as optimum for millet bran. Overall, there is no unified optimum pressure range for briquette production but an

optimum range per material and machine type. Hence, while studies can refer to previously optimized values, optimizing the process parameters in a new experiment is recommended.

b. Dwell time

This is the duration when the piston consolidates and compresses the blended mixtures in a mold to prevent the spring-back effect of the particles. Like other process parameters, the dwell time depends on the material and machine type. While some materials can easily consolidate at low dwell time, some may require a longer residence time. Most of the reported studies used an average of 10 seconds to 5 minutes dwell time. However, very few studies including Obi (2015) used higher residence time. Some previously tested dwell time includes 10 seconds (Mitchual et al., 2013; Sunnu et al., 2021; Yank et al., 2016), 20 -30 seconds (TT et al., 2022), 30 seconds (Law et al., 2018), 40 seconds (Rahaman & Salam, 2017)**,** 1 minute (Anggraeni et al., 2021; Magnago et al., 2020b), 1 minute 40 seconds (Amrullah et al., 2020), 120 seconds (Saeed et al., 2021), 3 minutes (Arewa et al., 2016), 4 minutes (Martinez Mendoza et al., 2019), 5 minutes (Ajimotokan et al., 2019; Ifa et al., 2020)**,** 7.5 minutes (Orisaleye et al., 2019), and 30 minutes (Obi, 2015).

2.2.2 Briquetting Feedstocks

Several feedstocks are used in briquette production. While some are still emerging, some have been in use for quite a long time. Some of the emerging feedstocks include; grass as reported in Alade & Betiku (2014), water hyacinth (Sanjika & Chipula, 2021), palm kernel shell (Bazargan et al., 2018; Sunnu et al., 2021), oil palm waste (Cabrales et al., 2020; Handra & Hafni, 2017), olive mill waste (Khlifi et al., 2020), citrus peel (Magnago et al., 2020b), bamboo powder (Ito et al., 2022), coffee waste (Fehse et al., 2021; Sugebo, 2022), tea waste (Thekedar et al., 2021), and *Pterocarpus indicus* leaves (Anggono et al., 2017). Others include forest and wood residues such as shredded logging residues (Nurek et al., 2021), *Macauba epicarp*, and pine wood waste (Costa et al., 2019), Ulin and Gelam wood residue (Amrullah et al., 2020), and sawdust (Mitchual et al., 2013; Mitchual, 2014; Orisaleye et al., 2022; Zepeda-Cepeda et al., 2021).

Agricultural residues are the most used feedstock for briquette production. This is because they are the most abundant and easily accessible biomass feedstocks (Magnago et al., 2020b). Agro-waste such as rice husk and rice bran (Arewa et al., 2016; Chukwuneke et al., 2021; Navalta et al., 2020; Yank et al., 2016), maize cob (Nagarajan & Prakash, 2021;

Ojediran et al., 2020; Sunnu et al., 2021), and sugarcane bagasse (Nagarajan & Prakash, 2021; Navalta et al., 2020) have been widely used in briquette production.

To assess the suitability of a feedstock for briquette production, it is important to know its properties (Ibitoye et al., 2021; Ito et al., 2022). This includes knowing the physical properties and thermochemical properties such as the energy content, ash, carbon, lignin, cellulose, hemicellulose, and extractives (Kpalo et al., 2020a). However, if feedstocks are found unsuitable, they can be pretreated to activate the embedded elements to make them suitable. In addition to pretreating the feedstocks, they can be blended or co-densified with another feedstock to improve the quality (Marreiro et al., 2021). This has been evaluated in several studies including Ajimotokan et al. (2019b) using Corncob and Rice Husk, Chukwuneke et al. (2021) using sawdust and rice husk, and Magnago et al. (2020) with citrus peel and rice husk, etc. Overall, the choice of a feedstock should depend on availability and sustainability (Okwu & Samuel, 2018).

2.2.1.1 Feedstock pretreatment

Feedstock pretreatment is an instrumental aspect of bioenergy production as it enhances the quality of the resultant fuel which is essential in boosting the global economy (Koppejan & Cremers, 2019). The pretreatment of feedstocks is an important aspect of briquette production because it activates the embedded elements responsible for quality enhancement. Hence, it is strongly recommended because it saves energy and yields high-quality briquettes (Adeleke et al., 2021; Ibitoye et al., 2021; Tumuluru et al., 2011). However, depending on the type of feedstock and the resultant properties, some may not necessarily require pretreatment. On this note, it is important to characterize the feedstock before choosing a pretreatment method.

There are several pretreatment methods. They are mainly classified into four, viz: physical, thermal, biological, and chemical. The physical and thermal pretreatment methods are the most reported in briquette production as they are easier and more promising (Tumuluru et al., 2011). The physical method includes screening, drying, grinding, and sieving while the thermal pre-treatment includes steam explosion, preheating, torrefaction, and carbonization. The thermal pretreatment is energy intensive as it requires heating in specially designed systems to an elevated temperature of 180 to 500 °C or more (Marreiro et al., 2021; Nazari et al., 2020). Overall, the choice of a pretreatment method depends on the feedstock's characteristics and the availability of technology (Marreiro et al., 2021).

2.2.2 Briquetting Binders

The binders used in briquette production are divided into three, viz: organic binders, inorganic binders, and compound binders (Zhang et al., 2018). While organic binders are good in interparticle adhesion and combustion performance, they have poor mechanical strength and thermal stability (Miao et al., 2019; Zhang et al., 2018). Despite their limitations, organic binders are gaining popularity because they are widely available, affordable, possess good energy content, and have low ignition temperatures (Obi et al., 2022). There are four types of organic binders, viz: biomass (agricultural residues, animal, and forestry waste, etc.), petroleum bitumen and tar pitch (tar residues, coal tar pitch, etc.), polymer-based and lignosulphonate binders (resins, polyvinyl, and starch) (Obi et al., 2022).

Inorganic binders have excellent thermal properties but with poor ash content, low fixed carbon content, and combustion efficiency (Zhang et al., 2018). Briquettes made with inorganic binders possess good quality metrics (compaction ratio, compressive strength, and hydrophobic nature) compared to those made with organic binders (Kpalo et al., 2020a). Some common examples of inorganic binders are clay, cement, lime, plaster, and sodium silicate (Kpalo et al., 2020a).

Combining two or more binders belonging to both the organic and inorganic groups gives the compound binder (Kpalo et al., 2020a). This form of binder performs better than others as it combines the properties of two or more binders (Zhang et al., 2018).

The selection of a binding material depends on some factors which include the expected or desired binding strength, availability, cost, sustainability, as well as the thermal performance (Obi et al., 2022). Some commonly used binders in briquette production are cassava starch (Ajimotokan et al., 2019a; Akolgo et al., 2021), banana waste pulp (Nyathi et al., 2022), paper waste pulp (Arifianti et al., 2020; Kpalo et al., 2022), sawdust (Rahaman & Salam, 2017), corn starch (Khlifi et al., 2020), starch paste (Anggraeni et al., 2021; Chukwuneke et al., 2021), cassava peel (Arewa et al., 2016), molasses (Benk et al., 2021), maize straw treated with sodium hydroxide (Miao et al., 2019), bentonite (Adeleke et al., 2022), etc.

Lignin, which is naturally embedded in most feedstocks is also emerging as a binder due to its phenolic nature (Mili et al., 2022). Its presence in most agricultural residues made it possible to densify feedstocks without necessarily adding a binder. Based on this, Granado et al. (2021) produced briquettes from cassava rhizome waste at high pressure without a binder. However, it is important to note that this is usually feasible in high-pressure and

temperature briquetting. In low-pressure briquetting, the use of a binder is inevitable (Essien & Oke, 2019; Kpalo et al., 2020a). However, with certain high moisture feedstocks like water hyacinth, obtaining good quality briquette at low pressure without a binder is possible (Sanjika & Chipula, 2021). In addition, it is also possible to densify at a medium pressure range without a binder. This was observed in Mitchual et al. (2013); Mitchual (2014) (Fig. 2.4b) where maize cob and sawdust were densified at medium pressure of 20 MPa to 50 MPa without a binder.

While it is possible to densify some feedstocks without a binder, it is also evident that most binder-less briquettes are less durable and cannot be easily transported (Zhang et al., 2018). Overall, not using a binder depends on the type of feedstock, particle sizes, and properties. One important property needed for binders is that they should be combustible; however, without such binders, a non-combustible binder may be used in small quantities (Ibitoye et al., 2021). While several binders have been used in briquetting, starch-based (cassava starch and flour, corn starch, maize flour, wheat flour, rice flour, wheat starch, potato starch, etc.) binders are the most ideal and common type of binder (Zhang et al., 2018). They are, however, expensive with poor water resistance (Zhang et al., 2018). Hence, to have an overall cost-effective briquette, it is essential to select binders that are less costly and readily available (Nyathi et al., 2022). To curb the issue of cost, Benk et al. (2021) made use of molasses (a by-product of processed sugarcane) blended with crude glycerol, a by-product of biodiesel as a binder. In another approach, Miao et al. (2019) used maize straw treated with sodium hydroxide as a binder. Locust bean pulp has also been recently evaluated as a potential binder (Yunusa et al., 2023). Fig. 2.4a shows sample briquettes of rice husk bonded with locust bean pulp.

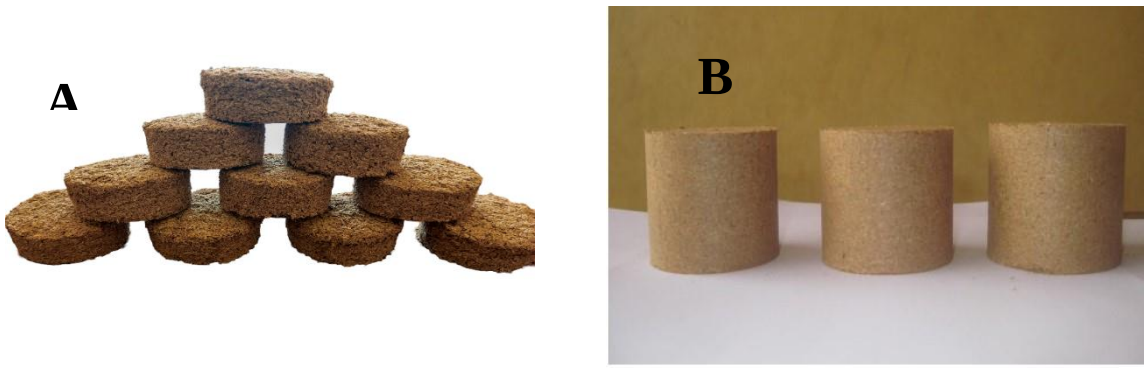

Figure 2.4. Briquettes. (a) briquette of rice husk and locust bean pulp binder (Yunusa et al., 2023). (b) sawdust briquette without a binder (Mitchual, 2014).

2.2.3 Briquettes Quality Parameters

Briquette quality parameters are the performance indicators that depict how good a briquette is in strength and durability. The following parameters are the quality metrics widely employed in testing briquettes: density, impact or shatter resistance, abrasion resistance (mechanical durability), compressive strength, and water absorption resistance (Kpalo et al., 2020a). The quality parameters are classified into physical (density), mechanical (compressive and tensile strength), and thermal properties (proximate parameters, burning rate, heating value, etc.).

a. Density

The density is an important quality parameter and is usually the first evaluated after compression and drying. Briquettes with higher densities often show better performance than those of lower densities. The density of briquettes is expressed in terms of compressed density or relaxed density. The compressed density is the density measured immediately after ejection from the mold while the relaxed density is the density measured after drying and cooling when the briquette has dried and is ready for use (Obi et al., 2022). Onyango et al. (2020), measured the relaxed density after 21 days, Obi et al. (2013) measured it after 27 days while Mitchual et al. (2014b), Ujjinappa & Sreepathi (2018), Kpalo et al. (2020b), and Sunnu et al. (2021), determined the density after 30 days. The density is computed as the mass of the briquette per unit volume.

b. Impact resistance

An impact resistance test also called shatter resistance test or drop test, simulates the forces experienced in the course of discharging or offloading the briquettes from trucks onto the ground (Sunnu et al., 2021). Briquette's impact resistance test is regarded as the overall best diagnostic of briquette quality (Richards, 1990). It is determined by dropping the samples from a certain height usually 1-2 m onto a concrete surface or a steel plate several times (Fig. 2.5). After the drop, the weight loss is determined using Equation 2.1 and the impact resistance is estimated using Equation 2.2.

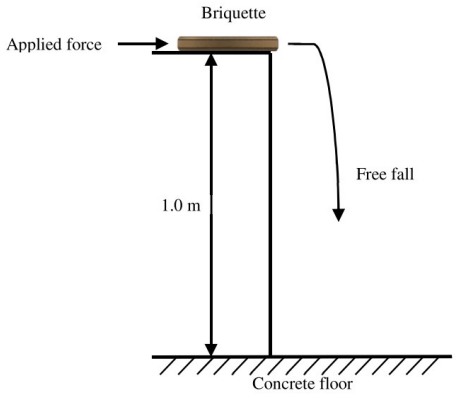

Figure 2.5. Schematic diagram of drop test (Law et al., 2018)

Antwi-Boasiako & Acheampong (2016), Kpalo et al. (2020b), and Zepeda-Cepeda et al. (2021) determined the impact resistance following ASTM D440-86, which involves dropping the briquettes two to three times from a height of 2 m, and after each drop, the sample was passed through a sieve size of 2.36 mm to retain the unshattered mass, and the Impact Resistance Index (IRI) was estimated using Equations 2.1 and 2.2. In a different approach using the same standard, Sunnu et al. (2021) used five drops from a height of 2m and used Equation 2.3 for IRI estimation. However, Okot et al. (2018) and Ndindeng et al. (2015), measured the impact resistance by dropping the briquettes four times from a height of 1.85 m onto a metal plate, whereas the impact resistance was estimated as the percentage residual weight after the 4th drop.

While the number of drops differs in various studies, Richards (1990) believed that averaging a range of 3-6 drops from a height of 2 m is sufficient to give a good estimate. In general, briquettes produced for industrial or domestic use should have a minimum IRI of 50 % (Richards, 1990).

$$IRI\ (\%) = \frac{B_z}{B} \times 100 \qquad (2.1)$$

$$Impact\ resistance\ (\%) = 100\% - weight\ loss\ (\%) \qquad (2.2)$$

$$IRI\ = \frac{N}{n} \times 100 \qquad (2.3)$$

where B_z is the weight of the briquette after shattering and B is the weight before shattering, N is the number of drops and n is the number of pieces that weighed 5% or more of the initial weight of the briquette after N drops.

c. Compressive strength

Compressive strength is the maximum crushing force that briquettes can withstand before failure (cracking or breaking) (Marreiro et al., 2021). The parameter is important as it simulates the maximum compressive load a briquette can withstand during transportation, handling, and storage (Obi et al., 2022). It is worth knowing that the compressive strength of briquettes largely depends on the properties of the biomass such as particle size distribution as well as the physical structure and resistance between the particles bond in the briquette (Afra et al., 2021). The test involves placing the briquette sample between two horizontal plates (Fig. 2.6a) and compressing with a constant load and rate until it fails. In addition to compressive strength, some studies measured the tensile strength by applying a tensile load (Fig. 2.6b). The compressive strength test is usually carried out with a universal strength testing machine. This has been used by Ajimotokan (2019a), Akogun et al. (2022) and Gendek et al. (2018), or a compressive testing machine as used by Afra et al. (2021) and Okot et al. (2018). The compressive strength is estimated as the ratio of the applied load to the cross-sectional area of the briquette (Akogun et al., 2022).

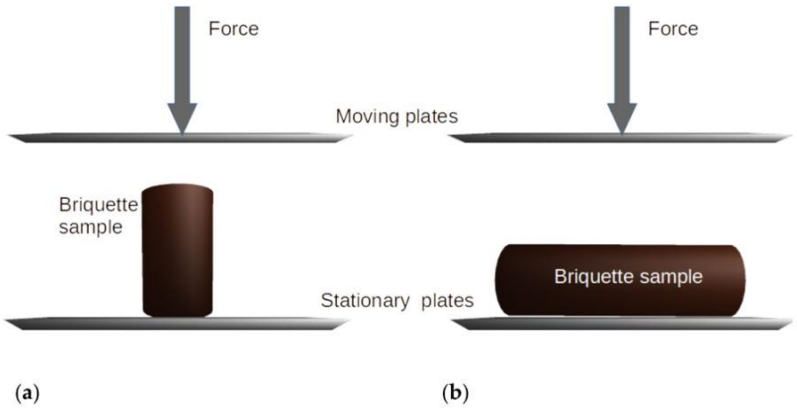

Figure 2. 6. Typical orientation of biomass briquette sample during (a) compressive strength, and (b) tensile strength testing (Obi et al., 2022)

d. Water retention resistance

Water resistance measures how the briquette can resist water absorption over some time. This quality parameter is important as it determines the resistance of the briquette during storage and transportation in a highly humid environment or when exposed to rain (Obi et al., 2022). The duration to which briquettes could react when exposed to water differs depending on the binder type, biomass material, and the briquette's density. Hence, it is a

measure of the hydrophobicity of the briquettes. Simulating this at a laboratory scale involves immersing the briquettes in a known volume of water for a given period. While the immersion time differs in various studies, Kaliyan & Morey (2009) believed that short-term exposure to water could adversely affect the quality of briquettes. Hence, water resistance should be tested over short-term exposure. However, TT et al. (2022) believe that water resistance tests should involve immersion for up to an hour. In a different approach, Richard's method suggests immersion for 30 minutes with a checking interval of 10 minutes by applying finger pressure, after which if the briquette retains its form, it will be reweighed. The water absorbed and water retention index (WRI) can be estimated using Equations 2.4 and 2.5 (Richards, 1990). This method was used by Adeleke et al. (2022). In a different approach, Law et al. (2018) and Ikubanni et al. (2020) determined the water resistance by submerging the briquettes in water at room temperature for 30 seconds. In a slightly different approach, Anggraeni et al. (2021) and Kpalo et al. (2020b) immersed the briquette in water for 2 minutes.

$$Water\ absorbed\ (\%) = \frac{w2-w1}{w1} \times 100 \qquad (2.4)$$

$$WRI = 100\% - water\ absorbed \qquad (2.5)$$

Where w1 and w2 = initial and final weight of briquette

e. Abrasion resistance (mechanical durability)

Abrasion is the percentage of fines returning from the briquette/pellet after being subjected to mechanical or pneumatic agitation (Narra et al., 2011). Hence, the abrasion resistance test simulates mechanical handling. It shows the ability of the briquettes to resist mechanical and abrasive forces during handling. A uniformly stable briquette is expected to have low abrasion and high strength values (Narra et al., 2011). The quality of binding materials plays a vital role in improving briquettes' abrasion resistance (Tumuluru et al., 2011). The equipment commonly used in testing the durability of briquettes is a rotating drum and tumbler (Fig. 2.7) (Obi et al., 2022). However, Yang et al. (2021), used the drop and tumble tests to assess the mechanical durability. In their study, each briquette was dropped onto a concrete floor via a tube of 10 cm diameter and 1.2 m height. After that, briquettes with weight loss below 10% were considered "Pass", while those with weight loss above 10% were considered "Fail". The briquettes were loaded into a tumbling box and rotated at ~57

rpm (0.95 Hz) for 2 min for the tumble test. The mechanical durability of briquettes is estimated as the percentage of weight lost during tumbling (Yang et al., 2021). Brunerová et al. (2020) and Gendek et al. (2018) tested the mechanical durability using the tumble test following EN ISO 17831-2 standard. Samples of briquettes weighing 2 ± 0.1 kg were rotated 105 times at 21 rpm in a rotary drum of 600 mm diameter (Brunerová et al., 2020; Gendek et al., 2018).

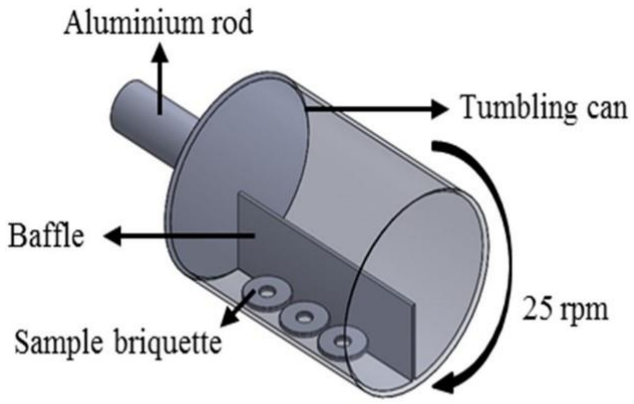

Figure 2.7. Schematic diagram of the tumbling test (Law et al., 2018)

2.3 Overview of Recent Studies on Briquette Production

In line with the growing interest in developing alternative fuels from biomass feedstocks (Ibitoye et al., 2021), several studies were carried out on briquette production. This includes the production of briquettes from a mixture of rice husk and sawdust using starch and clay binders **(**Chukwuneke et al., 2021). The process variables were optimized using response surface methodology (RSM), and the optimum binder, feedstock, and compaction pressure obtained were 15%, 28%, and 9 MPa, respectively, yielding an energy value of 5.69 kcal/g and 3.35 kcal/g for briquettes made with starch and clay binder, respectively. Ojediran et al. (2020) in a different approach, compared the thermal performances of briquettes made from blended maize cob and stalk with that of a pure maize cob and discovered that briquettes made from blended maize cob and stalk perform better with 17.3 % thermal efficiency, 0.97 kg/h fuel consumption and 20 mins boiling time.

In another study by Magnago et al. (2020), briquettes were produced from the blends of citrus peels and rice husks using a gelatinized grounded potato (Irish) peel as a binder. On evaluation, the briquettes had an average apparent density between 0.35 and 0.46 g/cm^3,

moisture content between 10 % and 19 %, and ash content between 3.9 % and 4.9 %. Furthermore, the higher heating value (HHV) ranges from 14.6 to 17.2 MJ/kg and the lower heating value (LHV) ranges from 13.1 to 15.8 MJ/kg. The study however differs from that of Yank et al. (2016) where rice husk of constant weight was mixed with bran, water, and three different binders (cassava wastewater, CSW; rice dust, RD; and okra stem gum, OG) under different ratios. The performance result revealed that the briquettes bonded with 15% cassava starch wastewater and 10% bran had the highest density (471.3 kg m^{-3}), while those produced with 10% rice dust, 70% water, and 0% bran had the highest durability (91.9%). The highest compressive strength (2.54 kN) was noted at 15% rice dust, 60% water, and 0% bran combination. This indicates that briquette performance differs with material type and mixing ratio. While some materials thrive better in physical or mechanical performance, others may thrive better in thermal performance. Based on this, it is important to characterize the feedstocks before use, to have an idea of their potential performance. In addition, optimizing the process parameters will be a good option to save costs and improve efficiency.

Ajimotokan et al., (2019a) in a different approach compare the compressive strengths of briquettes made at variable particle sizes (0.25, 1.0, and 1.75 mm), mixing ratio (80:20, 70:30, 60:40, and 50:50), and compaction pressure (25, 50, and 65 kPa) using corncob and rice husk blend. The briquette was made from 0.25 mm particle size, 80:20 mixing ratio, and 65 kPa compaction pressure and had the highest compressive strength of 111 kN/m^2.

Similarly, Sunnu et al. (2021) produced and characterized charred briquettes using rice husk, maize cobs, palm kernel shell, and sawdust at variable particle sizes (0.6 mm, 1.8 mm, and 2.36 mm) and briquetting pressures (10 MPa, 20 MPa, and 30 MPa). The briquette made with palm kernel shell with 0.60 mm particle sizes, densified at 30 MPa indicated the best performance, with a moisture and ash content of 3.5% and 2.7%, compressed and relaxed density of 411.85 kg/m^3 and 753.291 kg/m^3, respectively.

In another study by Arewa et al. (2016), briquettes were made from rice husk using different ratios of cassava peel and starch binders. The production was at a constant pressure of 80 bar and a dwell time of 3 minutes. Therein, it was observed that briquettes bonded with cassava peels have better physical and combustion properties than those made of cassava starch binder where a density range of 977.6 to 1176.5 kg/m^3, moisture content of 10.36 to 12. 31% and a burning rate of 1.03 to 1.96 g/min were obtained.

Akolgo et al. (2021) assessed the properties of briquettes made from a mixture of charred feedstocks (rice husk, sawdust, and coconut husk) using cassava starch as a binder under low pressure (89.14 kN/m^2). The result showed an ash and moisture content of 5.60% and 7.30%, a calorific value of 24.90 MJ/kg, and volatile matter content of 61.38%. In a similar study, Wongwuttanasatian & Sakkampang (2016) produced briquettes from rice husk and rice husk char using molasse and glycerin as binders. Therein, briquettes made from rice husk char possess a higher calorific value (13.9–17.3 MJ/kg) than rice husk with a calorific value of 13.2–15.9 MJ/kg.

2.4 Identified research gaps

i. Studies on rice husk briquette production and optimization are grossly limited
ii. Comparative analysis between briquettes and conventional solid fuels like fuelwood and charcoal are largely ignored in previous studies
iii. Previous studies substantially rely on inorganic and starch-based binders as studies that utilized biomass materials as binders are limited
iv. Overall, studies that determined the impact of briquette on the environment are grossly limited. Specifically, there is no study on the life cycle assessment of rice husk briquette production and its comparison with charcoal

CHAPTER 3 : CHARACTERIZE THE DIFFERENT FORMS OF ENERGY USED FOR HEATING AND COOKING AT THE HOUSEHOLD AND THEIR CONSUMPTION LEVELS

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Assessing the nexus between household dynamics and cooking energy choice: Evidence from Kaduna state, northwestern Nigeria

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Abstract

Cooking is the most energy-intensive activity in the household sector. It accounts for about 90% of the total domestic energy use in developing countries. With this, knowledge of its energy choice and use dynamics is imperative. This study explored the nexus between household dynamics and cooking energy choice in Kaduna State, Northwestern Nigeria. The data was collected from 400 households using a structured questionnaire following a multi-stage sampling approach. Descriptive statistics was used to analyze the data and a multivariate probit regression model was employed to assess the impact of household factors on the choice of energy. The results from the descriptive analysis depict charcoal as the most used cooking energy in the surveyed area, followed by fuelwood and Liquified Petroleum Gas (LPG). These choices are influenced by cost, accessibility, and availability. Furthermore, the results from the multivariate probit regression analysis indicated that the choice of cooking energy is significantly influenced by household factors such income, size, age, occupation of household head, marital status, and education of the cook, and the household head. These findings can be crucial for policymakers and organizations advocating for clean and sustainable energy, climate change mitigation, and the reduction of household air pollution.

Keywords: Household, Cooking energy, Cookstove, Energy choice, Multivariate probit model

3.1 Introduction

Access to clean and affordable energy for all corresponding to the United Nations Sustainable Development Goal (SDG) 7 is one of the pivotal goals targeted for realization by 2030. While a lot has been invested in attaining the stated goal, about 2.4 billion people are still cooking with harmful fuels (UN-ECOSOC, 2022). This implies that more than one-third of the world's population is living in energy poverty (Li et al., 2023). The continuous rise in population across the globe has significantly increased energy demand and has made it incommensurable to the available energy resources. Similarly, as energy consumption keeps increasing the emission of greenhouse gases also increases. According to the International Energy Agency IEA (2023), the global carbon dioxide (CO_2) emissions that emanate from the burning of energy have increased by 0.9% or 321 Mt in 2022. While a substantial proportion of the said emissions are induced by anthropogenic activities, especially through the use of fossils, it is worth noting that attaining the 1.5°C or 2°C target surface temperature must involve a rapid decline from the use of non-renewable fuels (Clark et al., 2020). In the phase of household cooking energy, it becomes imperative to curtail the use of solid fuels and traditional cookstoves and adopt clean cooking solutions such as the use of Liquefied petroleum gas (LPG) and electricity (Guta et al., 2022), or improved biomass cookstoves in the case of biomass users (Yunusa et al., 2023). For low-income households that cannot afford or access clean cooking energy, Yunusa et al. (2023) recommended using biomass briquettes as they are products of lignocellulosic biomass that are emission neutral. Furthermore, the use of briquettes in place of fuelwood and charcoal curtails deforestation and climate change.

The household or residential sector is one of the major energy-consuming sectors. This trend of energy consumption in the household sector is said to continue and increase even further as population and economic activities increase (Nababan, 2015). In Sub-Saharan Africa, cooking is the most energy-intensive activity in the household sector (Dioha & Kumar, 2020). In developing countries cooking accounts for about 90% of domestic energy consumption (Sedighi & Salarian, 2017). From an estimate released by the Clean Cooking Alliance (CCA, 2021), the burning of solid fuels especially fuelwood in cooking accounts for about 1.9% - 2.3% of global CO_2 emissions. If the stated emissions are combined with the impact of deforestation recorded through fuelwood and charcoal production, it

significantly impacts climate change. More than 2.8 billion people globally rely on solid fuels (charcoal, fuelwood, coal, dung, and agro-residues) and kerosene to meet their cooking energy needs (Stoner et al., 2021). Owing to this, about half of the world's population is exposed to household air pollution (McCarron et al., 2020). In Africa over 82% of the population relies on solid fuels to meet their energy needs (Boafo-mensah et al., 2020).

Population growth is one of the major factors increasing energy use and toxic gas emissions. With over 200 million people in Nigeria (Jekayinfa et al., 2020), the country is exposed to a high carbon footprint making it vulnerable to climate change. Despite being blessed with diverse socioeconomic resources, Nigeria battles with an unstable electricity supply as the cumulative wattage is below the country's requirement (Ibrahim et al., 2021). With this, most households rely on solid fuels and kerosene owing to their inability to afford cleaner options (Okedere et al., 2021). This, coupled with other factors has made the country energy inefficient (Adom & Adams, 2018). Hence, an extensive study on the factors influencing energy choice and use is essential for understanding household energy dynamics (Kowsari & Zerriffi, 2011). Household income is a major factor that influences the choice of cooking energy (Oyeniran & Isola, 2023; Yang & Wang, 2023). On this basis, transiting to cleaner options such as biofuels, LPG and electricity would require interventions from the government, NGOs, and other relevant stakeholders. However, without adequate intervention, several studies have developed low-cost biofuels and improved biomass cookstoves with enhanced energy efficiency and low emissions compared to conventional fuels and cookstoves. These include a double-burner biomass cookstove developed by Yunusa et al. (2022), a rock bed cookstove developed by Bailis et al. (2021), and a twisted tape-incorporated cookstove (Honkalaskar et al., 2013). Using the stated cookstoves is better than traditional cookstoves and open fires, and is perceived to be cleaner than LPG because the cookstoves are powered with biomass, whereas LPG is a non-renewable energy. This assertion was verified in the study of Dioha & Kumar (2020) where transiting from using fuelwood to LPG was found to reduce indoor air pollution but with the potential of increasing CO_2 emissions by 2050.

Considering the relevance of cooking energy in the household sector, several studies have employed different approaches ranging from descriptive analysis, dynamic modeling, and simulations to comprehend the dynamics influencing household energy choice, adoption, and use especially in developing countries where the use of clean and renewable energy is

limited. In the study of Shari et al. (2022), a system dynamics model was employed to predict how some strategies could influence the adoption of clean cooking. The simulation revealed that clean cooking adoption occurs faster in the early years among urban households than in rural households, as factors such as awareness are required to enhance adoption in rural households which comes up in the later years. Imran et al. (2022), used the STIRPAT model to examine the impact of some household factors on energy consumption. The result revealed biomass (fuelwood, dung, and crop residue) as the most consumed form of energy, and further found out that its consumption increases as the size of households increases and as the income level decreases. Nwaka et al. (2020) determine the determinants of household fuel choice among family heads by gender. The study revealed heterogeneity by gender of household heads as biomass usage was more dominant among de-jure female-headed households than male-headed households. However, because the male-headed households were found to be more educated, the use of clean fuels such as electricity, biogas, and LPG was more prevalent in such households. Ogbeide-Osaretin (2020) has examined the nexus between energy consumption and poverty reduction using the Autoregressive Distributed Lag Model (ARDL). The study observed that using traditional fuels like fuelwood and coal significantly impacts poverty, whereas using clean energy negatively correlates to poverty. Overall, some of the factors influencing the choice of cooking energy are income and education (Chen et al., 2023; Oyeniran & Isola, 2023), health status, and family records (Zhu et al., 2022), geographical location, access to credit, assets, and the internet (Twumasi et al., 2021), access to sanitation facilities and information (Ali & Khan, 2024; Bakhsh et al., 2020), as well as affordability and accessibility to the source of energy (Aziz et al., 2022).

Several studies have examined the factors influencing household energy choices in Nigeria. This includes the study of Oyeniran & Isola (2023), Ifegbesan et al. (2016), and Ozughalu (2023), where secondary data previously collected on a national scale were adopted and used to determine cooking energy choices and use patterns. The findings in these studies revealed firewood as the primary energy used by most households in Nigeria. However, these studies are from secondary data collected between 2013 and 2019. Others include the study of Bisu et al. (2016), and Danlami et al. (2018) carried out in Bauchi State, Northeastern Nigeria, where fuelwood was also found to be the most used cooking energy. However, in the Southwestern part of Nigeria, kerosene was found to be the most used

cooking energy based on a survey conducted in Ondo, Lagos, and Oyo State (Adeyemi & Adereleye, 2017; Emagbetere et al., 2016; Olugbire et al., 2016). In the southeastern part, LPG was discovered as the most used cooking energy (Onyekuru et al., 2020).

Though several studies have attempted to comprehend the nexus between energy choice and household factors, the nexus is still not adequately studied (Matsumoto et al., 2022). The bulk of the literature on cooking energy choices among households is predominantly focused on rural and peri-urban areas where the use of solid fuels has intensified. Knowledge of the various cooking options and choices in the urban parts is grossly limited. This could be because the rural parts are more vulnerable to unclean cooking and deforestation as they primarily rely on solid fuels. However, it is imperative to note that the users of charcoal and fuelwood have also increased significantly in the urban parts especially now that the cost of electricity and LPG has skyrocketed in many parts of the world. In this vein, fuelwood and charcoal are transported from the rural parts into the cities contributing to CO_2 emission. Therefore, knowledge of the cooking energy dynamics in rural and urban parts is instrumental as it will provide information about the real-time differences and the influencing factors. Similarly, previous studies were focused more on cooking fuels with just a few reports on the types and conditions of the cookstoves. Recent studies on household cooking energy in Nigeria are grossly unavailable, as the available studies were conducted between 2009 and 2020. The few recently reported studies were carried out with secondary data obtained on a national scale. Apart from the fact that secondary data are susceptible to errors, they may not reflect the status of cooking energy in the country as they were collected more than a decade ago (2013), with some collected about a decade ago (2015), and half a decade ago (2019). Also worthy of note is that no such studies were conducted in the northwestern part of Nigeria as previous studies were carried out in the southeastern, southwestern, and northeastern parts. Similarly, none of these studies assessed the presence and use of biofuels such as briquettes, pellets, and biogas as energy options in the surveyed households. It is pertinent to note that evaluating the adoption and use of these cookstoves would inform the scientific community of the progress made regarding awareness, acceptance, and use of these renewable energy options in the study area. Most importantly, while only a few studies modeled household factors relating to cooking energy choice, factors involving the main cooks were not previously considered.

Against the stated background, this study deemed it necessary to explore the nexus between household dynamics and cooking energy choice in Kaduna State, Nigeria while assessing the progress in the use of biofuels in the study area. Another novelty of the study is that it considers the main cooks in the households as the respondents and integrates factors related to them such as age, gender, marital status, and education level into the fuel choice modeling. This is contrary to the existing approach of using only factors related to household heads.

3.2 Materials and Methods

The flowchart of the stages followed in conducting the survey ranges from the design of a structured questionnaire to the analysis of collected data using descriptive analysis and a multinomial logit regression model (Appendix 2).

3.2.1 Study area

The study was conducted in six Local Government Areas (LGAs) of Kaduna State, Northwestern Nigeria. The state lies on latitude 10° 34′ 5″ North and longitude 7° 27′ 7″ East (Figure 3.1). Kaduna State has a land mass of 46,053 km^2 and is characterized by a unimodal rainfall pattern with an annual average of 1323 mm (Abaje et al., 2018; Ben-Chendo et al., 2017). The state lies within the northern Guinea Savanna ecological zone comprising typically of woodland and deciduous vegetation type with grasses and shrubs of the *androgenae* family occurring in tussocks (Pius et al., 2020).

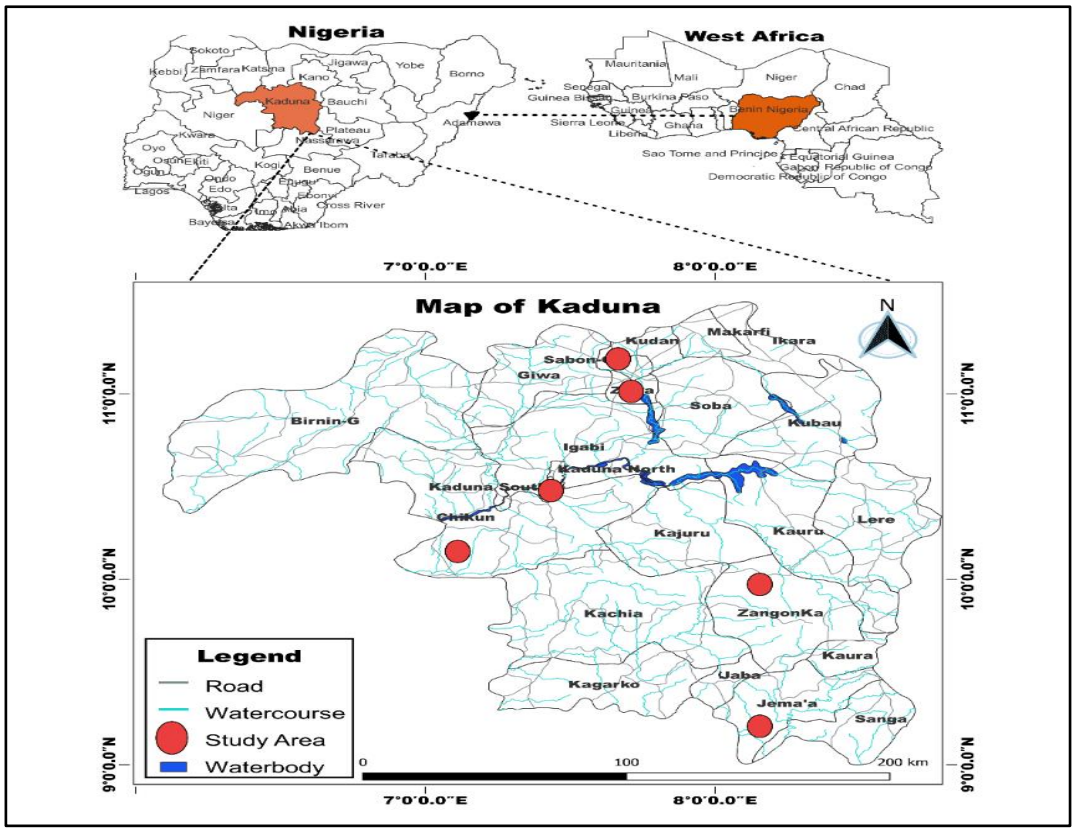

Figure 3.1. Map of the study area

3.3 Household sampling and data collection

The sample size (n = 400) was computed based on a 5% margin of error (e) using Equation 3.1 as brought by Yamane (1967).

$$n = \frac{N}{1+Ne^2} \qquad (3.1)$$

The population N (1,155,029) is the number of households in the study area. This value was obtained from the Kaduna State Bureau of Statistics. A multi-stage sampling technique was employed to distribute the sample size (400 households). The study area was first stratified into three (3) existing districts: Kaduna North, Kaduna Central, and Kaduna South. In the first sampling stage, two Local Government Areas (LGAs) were randomly selected from each of the state's three (3) districts (making six LGAs). Consequently, Sabon Gari and Zaria LGAs were selected from Kaduna North. While Chikun and Kaduna South were selected from Kaduna Central, and Jema'a and Zangon Kataf were selected from Kaduna South. In the second sampling stage, five (5) Wards were randomly chosen from each of the

six LGAs (making a total of 30 Wards), and in the third stage, 10 – 15 households were randomly selected from each of the 30 Wards to obtain the 400 households.

The criteria for selecting the respondents in this study were based on the person most familiar with household cooking energy use, defined as the main cook. To ensure a hitch-free session, respondents were made to consent to take part in the survey by signing a consent form. Due to the volatile nature of the study area in terms of security, questions on household income were kept confidential. They were analyzed based on the type and level of energy use and the type of building. Thus, the households were classified as either low-income or middle to high-income households.

The data obtained were classified into three main categories, viz: data on respondents and households (age, gender, marital status, education level, occupation, household size, and income), data on cooking energy use (cooking energy, primary cooking energy, energy purchase frequency, the reason for selection, quantity used per day, and daily cooking hours) and data on cookstove usage (daily usage of cookstove and cookstove type). Before collecting the data, the questionnaire was validated through a pre-test survey.

3.4 Theoretical framework and model

Like the study of Bofah et al. (2022), this study theoretically follows the 'utility-theory' approach. The utility theory assumes that energy users have preferences, thus their choice of cooking energy also depends on those preferences. Though household energy choices usually follow the energy-ladder and energy stacking hypothesis, an econometric theory was deemed more fit as it aligns better with the study objective. Nonetheless, the outcome of this study was compared with the energy-ladder hypotheses. The energy-ladder hypothesis assumed that advancing to cleaner energy options such as LPG and electricity depends on the households' income. Thus, according to the model, household income and wealth are the key factors (Liu et al., 2023). The energy stacking hypothesis suggests that a household will only partly switch to a different cooking energy option or accumulate and continue to use multiple energy options (Yadav et al., 2021). This implies that users of traditional energy might occasionally switch to modern energy options based on peculiar needs or household income and vice versa.

Thus, following the utility theory, if a variable Y represents a set of options, a consumer-choice model can be considered in the form Y ⊂ Rn, which implies that there are n different cooking energy choices (firewood, charcoal, LPG, electricity, etc.,). In addition, it can be assumed that y ⊂ Y so that y = (y1, ..., yn), where y = clean energy and other energy types (i.e., wood and charcoal). Thus, the utility function for the household cooking energy options can be explained by Equation 3.2 (Bofah et al., 2022).

$$V_{ij} = B_j Y_i + U_{ij} \qquad (3.2)$$

Where V_{ij} is the indirect utility function of household i for cooking with energy j; Y_i stands as the vector of individual households and other factors that influence a household's choice of cooking energy; B_j, on the other hand, is a vector of coefficients of explanatory variables which quantifies the average likelihood that a household chooses a particular cooking energy type; and U_{ij} is the stochastic component that captures the unobserved utility.

3.4.1 Multivariate probit model

Multivariate probit regression is a statistical tool used to determine the relationship between multiple independent and dependent variables. The model simultaneously analyses the choice of cooking energy while allowing for non-zero covariance among the available energy options (Megbowon et al., 2018). This is important as most households use multiple types of energy for heating and cooking. The variables used in the model are described in Table 3.1.

Table 3.1. Description of the variables used in the model

Variable	Description
Dependent Variable	
Sources of household energy	
Firewood	1 if a household is using Firewood; 0 otherwise
Charcoal	1 if a household is using Charcoal; 0 otherwise
Kerosene	1 if a household is using Kerosene; 0 otherwise
Agro-residue	1 if a household is using Agro-residue; 0 otherwise
LPG	1 if a household is using LPG; 0 otherwise
Electricity	1 if a household is using Electricity; 0 otherwise
Independent Variable	
Age	This is a continuous variable of respondents' age in years
Gender	The gender of the respondent; 1 if Female, 0 if male
Household Income	1 if low-income; 0 otherwise
Marital Status	1 if married; 0 otherwise
Size of Household	Number of individuals in the household, 1 if 5 or more; 0 otherwise
Occupation of head	1 if self-employed or fully employed in a public or private sector; 0 otherwise
Education of head	1 if senior high school and above; 0 otherwise
Education of Respondent	1 if senior high school and above; 0 otherwise

The multivariate probit regression model is expressed in Equation 3.3 (Twumasi et al., 2021).

$$Y_i^* = \beta_i X' + U_i \qquad (3.3)$$

Where Y_i^* ($Y_1^* \ldots\ldots Y_n^*$) are the dependent variables. X is the vector of the explanatory variables (independent variable) that may influence the choice of energy by the various households; β_i ($\beta_1 \, to \, \beta_n$) are the vector of the parameters of the control variables; U_i ($U_1 \, to \, U_n$) are the random errors.

3.5 Statistical analysis

Descriptive statistics in the form of proportions and frequencies using a linearized method of variance estimation were used in the analysis. A multivariate-probit regression model was employed to estimate the impact of various household factors on energy choices. Pearson chi-square test was employed to determine the relationship between the primary energy sources and the reasons for selection. The data were analyzed using Stata SE version 17.0 software.

3.6 Results

3.6.1 Descriptive analysis of variables

3.6.1.1 Household characteristics

The result of the various household factors is presented in Table 3.2. The result shows that 63% of the respondents are between the ages of 21 and 40. The result further revealed 87.5% of the respondents to be females based on which 78% are married. The findings also showed that most households (62.7%) have large family sizes (five or more members) and are predominantly (68.2%) low-income households. Similarly, the heads of the households are mainly (55.3%) self-employed largely engaged in farming and small-scale businesses. In terms of the educational qualification of the household heads and respondents, the result depicts a higher proportion (29.3%) of the household heads to be senior secondary school certificate (SSCE) and bachelor's degree (B.Sc.) holders (23.4%). However, these were more common among urban households, as heads of rural households are either uneducated or are holders of primary or junior secondary certificates (JSCE). In the case of the respondents, most of them are SSCE holders (39.2%).

Table 3.2. Descriptive statistics for the proportion of household variables

Variable	Options	Proportion	Std. Err.	[95%_Conf. Interval]	
Age of respondent	< 20	0.043	0.017	0.018	0.098
	21-30	0.353	0.048	0.256	0.463
	31-40	0.282	0.032	0.217	0.358
	41-50	0.166	0.030	0.110	0.244
	>50	0.156	0.037	0.091	0.255
Gender	Male	0.125	0.081	0.028	0.415
	Female	0.875	0.081	0.585	0.972
Marital Status	Married	0.780	0.042	0.676	0.857
	Divorced	0.028	0.012	0.011	0.068
	Single	0.117	0.046	0.048	0.258
	Widow(er)	0.075	0.024	0.037	0.148
Size of household	Single	0.033	0.026	0.006	0.167
	2	0.087	0.022	0.050	0.149
	3	0.095	0.020	0.060	0.148
	4	0.158	0.015	0.127	0.194
	5 or more	0.627	0.059	0.494	0.744
Occupation of head	Farming	0.090	0.013	0.065	0.124
	Civil Servant	0.320	0.033	0.251	0.397
	Self-employed	0.553	0.049	0.443	0.658
	Part-time Job	0.037	0.016	0.014	0.096
Household Income	Low	0.682	0.050	0.564	0.780
	Middle to High	0.318	0.050	0.220	0.436
Education of Head	None	0.075	0.031	0.029	0.182
	Primary	0.097	0.030	0.047	0.187
	JSCE	0.053	0.011	0.034	0.082
	SSCE	0.293	0.025	0.241	0.351
	Diploma	0.131	0.016	0.100	0.169
	HND	0.065	0.017	0.036	0.117
	B.Sc.	0.234	0.041	0.155	0.336
	M.Sc.	0.044	0.008	0.030	0.064
	Ph.D.	0.009	0.007	0.002	0.045
Education of Resp.	None	0.122	0.049	0.048	0.277
	Primary	0.144	0.027	0.094	0.215
	JSCE	0.107	0.017	0.073	0.152
	SSCE	0.392	0.037	0.313	0.476
	Diploma	0.147	0.030	0.092	0.228
	HND	0.019	0.008	0.008	0.045
	B.Sc.	0.066	0.010	0.047	0.092
	M.Sc.	0.003	0.003	0.000	0.028

3.6.1.2 Energy use

The data on energy use were analyzed based on the usage of cookstoves and cooking fuel/energy in the various households. The findings in this category are presented in Tables 3.3 to 3.8, and Figures 3.2 to 3.5. While Table 3.3 presents the summary of the energy use, Tables 3.4 to 3.8 show the association between the energy source and the variables (daily energy use, purchase frequency, and reasons for selection). With p-values < 0.05, it shows that there is significant evidence of association between the primary energy sources and the variables. As presented in Table 3.3, more than half (57.5%) of the households use their cookstoves within a range of 5-7 hours per day. This includes the time spent using the cookstoves for other applications different from cooking such as water heating. This further corroborates the findings of Kabir et al. (2018) which reports an average weekly cooking time of 25.48 hours among households in northern Nigeria. Most households (63.3%) use 1 to 5 kg of fuel daily. This is mainly among charcoal and fuelwood users (Table 3.4). For energy purchase frequency, charcoal, and fuelwood users were noted as households that purchase fuel daily with about 39.6% of households recorded. Out of this, 71.9% are users of charcoal while 23.5% are fuelwood users (Table 3.5). On the other hand, households purchasing fuel monthly are mainly the users of LGP (39%) and charcoal (24.5%) as cooking energy sources. However, only 8.5% of households purchase fuel weekly. Regarding the knowledge of the environmental and health impact of the energy types, almost all the households (92.2%) affirmed being aware of the effects of unsustainable and poor use of cooking energy and cookstoves on the environment and their health.

Table 3.3. Descriptive statistics for proportion of stove and fuel variables

Variable	Options	Proportion	Std. Err.	[95%_Conf. Interval]	
Daily Stove Use (h)	< 2	0.003	0.003	0.000	0.023
	2-4	0.122	0.042	0.056	0.248
	5-7	0.575	0.046	0.473	0.671
	8-10	0.198	0.050	0.111	0.327
	11-13	0.095	0.022	0.056	0.156
	>13	0.007	0.005	0.002	0.031
Daily Fuel Use (kg)	<1	0.310	0.024	0.266	0.358
	1-5	0.633	0.025	0.583	0.680
	6-10	0.036	0.010	0.022	0.061
	11-15	0.013	0.006	0.005	0.031
	16-20	0.003	0.003	0.000	0.018
	21-25	0.003	0.003	0.000	0.018
	26-30	0.003	0.003	0.000	0.018
Fuel Purchase Freq.	Daily	0.396	0.054	0.286	0.518
	Weekly	0.085	0.023	0.047	0.150
	Monthly	0.518	0.046	0.419	0.616
Awareness of potential health hazard	Yes	0.922	0.042	0.767	0.977
	No	0.077	0.042	0.023	0.233

Table 3.4. Distribution of daily energy use based on primary energy sources

Daily energy use	Primary energy source					
	FW	**CH**	**KE**	**AR**	**LPG**	**Total**
<1kg	14.00	22.00	0.00	1.00	73.00	110.00
	12.73	20.00	0.00	0.91	66.36	100.00
1-5kg	80.00	140.00	4.00	0.00	10.00	234.00
	34.19	59.83	1.71	0.00	4.27	100.00
6-10kg	12.00	1.00	0.00	0.00	0.00	13.00
	92.31	7.69	0.00	0.00	0.00	100.00
11-15kg	2.00	0.00	0.00	0.00	0.00	2.00
	100.00	0.00	0.00	0.00	0.00	100.00
16 - 20kg	0.00	1.00	0.00	0.00	0.00	1.00
	0.00	100.00	0.00	0.00	0.00	100.00
21 – 25 kg	0.00	1.00	0.00	0.00	0.00	1.00
	0.00	100.00	0.00	0.00	0.00	100.00
26-30kg	0.00	1.00	0.00	0.00	0.00	1.00
	0.00	100.00	0.00	0.00	0.00	100.00
Total	108.00	166.00	4.00	1.00	83.00	362.00
	29.83	45.86	1.10	0.28	22.93	100.00

[1] First row has *frequencies* and second row has *row percentages*, [2] Pearson chi2(24) = 201.0779 Pr = 0.000, Cramér's V = 0.3726, [3] FW (fuelwood), CH (Charcoal), KE (Kerosene), AR (agro-residue), LPG (liquefied petroleum gas)

Table 3.5. Distribution of energy purchase frequency based on primary energy sources

Energy purchase frequency	Primary energy						
	FW	**CH**	**KE**	**AR**	**LPG**	**EL**	**Total**
Daily	36.00	110.00	1.00	1.00	1.00	4.00	153.00
	23.53	71.90	0.65	0.65	0.65	2.61	100.00
Weekly	24.00	5.00	0.00	0.00	3.00	1.00	33.00
	72.73	15.15	0.00	0.00	9.09	3.03	100.00
Monthly	47.00	49.00	3.00	0.00	78.00	23.00	200.00
	23.50	24.50	1.50	0.00	39.00	11.50	100.00
other	1.00	2.00	0.00	0.00	1.00	9.00	13.00
	7.69	15.38	0.00	0.00	7.69	69.23	100.00
Total	108.00	166.00	4.00	1.00	83.00	37.00	399.00
	27.07	41.60	1.00	0.25	20.80	9.27	100.00

[1] First row has *frequencies* and second row has *row percentages*, [2] Pearson chi2(15) = 212.2395 Pr = 0.000, Cramér's V = 0.4211, [3] FW (fuelwood), CH (Charcoal), KE (Kerosene), AR (agro-residue), LPG (liquefied petroleum gas), EL (electricity)

In Figure 3.2 the various cooking energy types used in the households are presented. From the result, charcoal is the most used cooking energy option with 31.02% of the households followed by LPG with 19.52%, and fuelwood with 17.96%. However, in Figure 3.3 only the primary cooking energy used in the households was considered. Here, the results revealed charcoal and fuelwood as the most used cooking energy with 41.60% and 27.07% of the households, respectively. The reasons the respondents gave for selection are presented in Figure 3.4. These were based on availability (35.22%), and cost (33.60%) especially for the users of charcoal and firewood, and energy efficiency (assessed based on cooking time) (30.53%) majorly selected by households using LPG. The daily cooking energy consumption level is largely between 1 to 5 kg. However, it was observed that about 69.75% of the households that use less than a kilogram of fuel per day are LPG users, whereas 31.1% are households that use charcoal and fuelwood. Similarly, 67.5% of households that use 1-5 kg of fuel daily are charcoal users while 32.1% are firewood users. The results of cookstove types are shown in Figure 3.5. Most households use traditional charcoal cookstoves (32.70%). This conforms with the findings of Aziz et al. (2022), and further confirms the assertion of Oyeniran & Isola (2023) which noted that a considerable proportion of the population in Nigeria are users of traditional fuels and cookstoves.

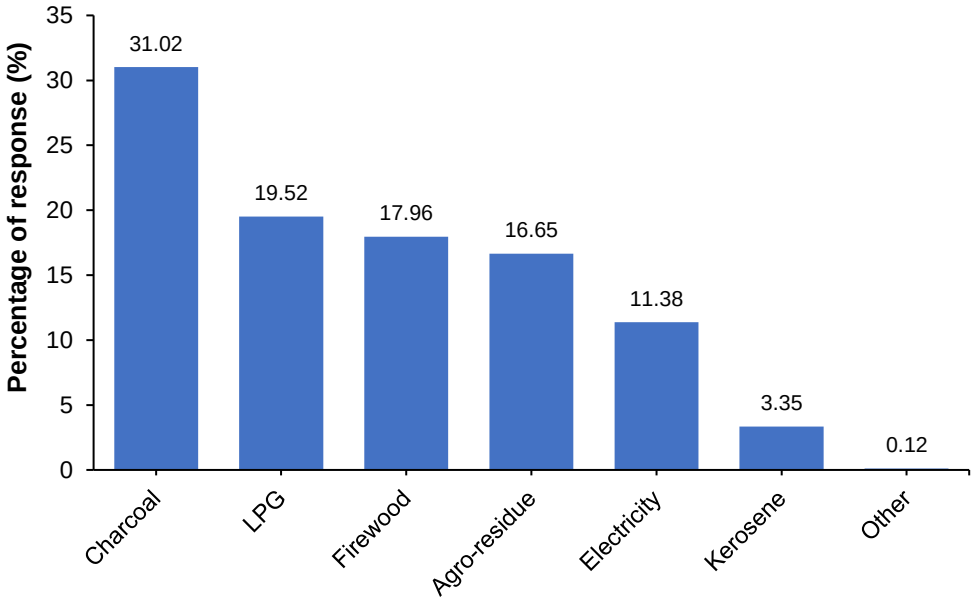

Figure 3.2. Sources of household energy

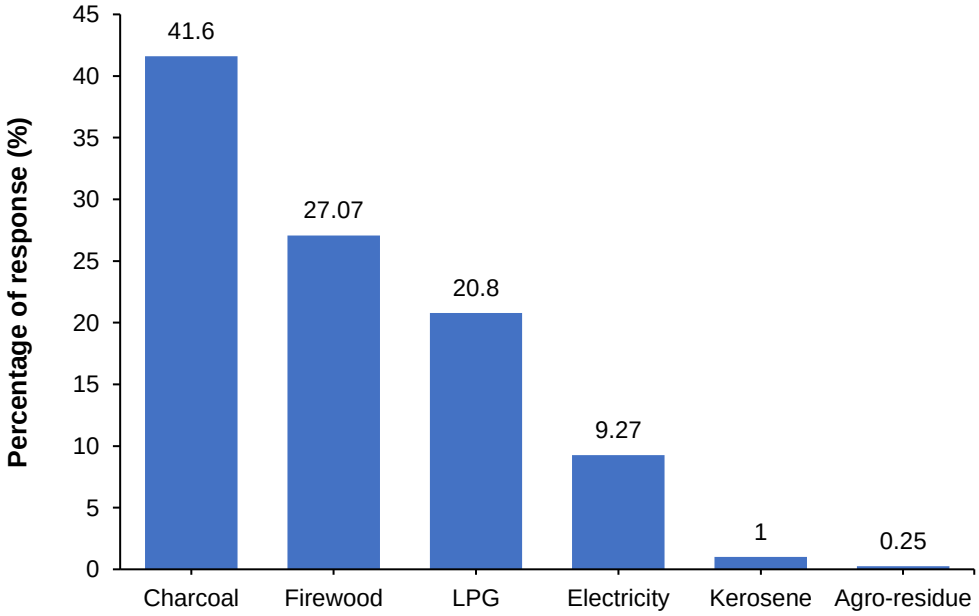

Figure 3.3. Primary sources of household energy

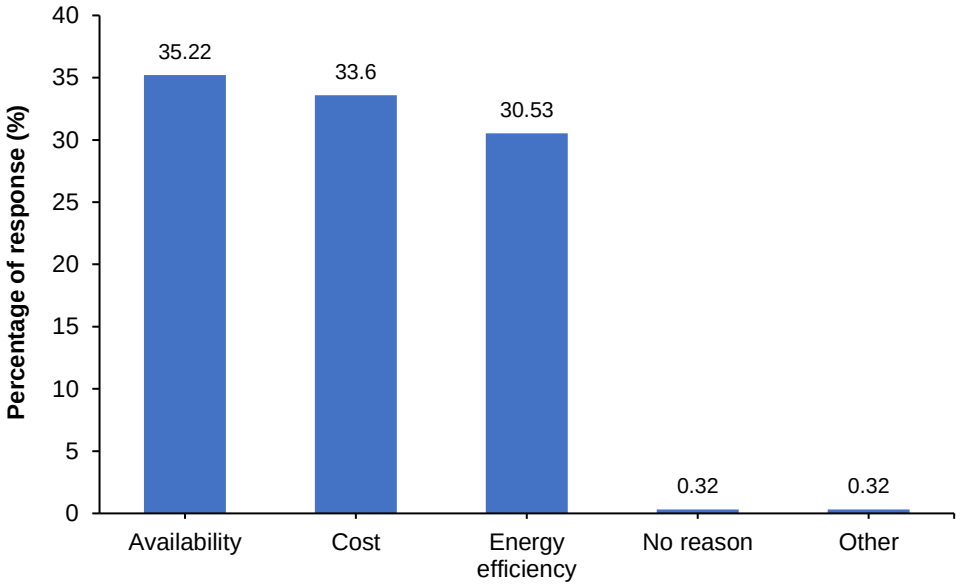

Figure 3.4. Various reasons for selecting a particular type of energy

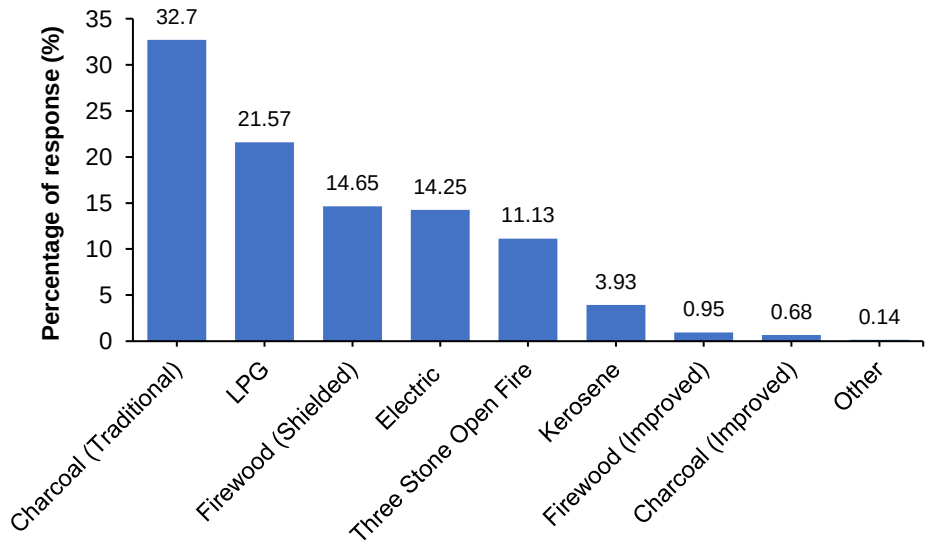

Figure 3.5. Cookstove types

In Tables 3.6 to 3.8, the frequencies and percentages of respondents that select their energy choices are presented based on reasons for selection (i.e., availability, cost, and energy efficiency). The probability level obtained (i.e., p-value < 0.05) shows that there is significant evidence of an association between the primary energy sources (row) and the reasons for selection (column). The majority of the respondents that choose an energy option based on availability (Table 3.6) and cost (Table 3.7) are the users of charcoal and fuelwood,

with 42.40% charcoal users and 34.56% fuelwood users in terms of availability, and 49.28% charcoal users and 40.58% fuelwood users in terms of cost. However, respondents who select their energy option based on efficiency (Table 3.8) are predominantly the users of LPG (38.62%).

Table 3.6. Distribution of energy choice based on availability

Availability	**Primary energy**						
	FW	**CH**	**KE**	**AR**	**LPG**	**EL**	**Total**
0	33.00	74.00	4.00	0.00	52.00	19.00	182.00
	18.13	40.66	2.20	0.00	28.57	10.44	100.00
1	75.00	92.00	0.00	1.00	31.00	18.00	217.00
	34.56	42.40	0.00	0.46	14.29	8.29	100.00
Total	108.00	166.00	4.00	1.00	83.00	37.00	399.00
	27.07	41.60	1.00	0.25	20.80	9.27	100.00

[1] First row has *frequencies* and second row has *row percentages*, [2] Pearson chi2(5) = 25.7534, Pr = 0.000, Cramér's V = 0.2541, [3] FW (fuelwood), CH (Charcoal), KE (Kerosene), AR (agro-residue), LPG (liquefied petroleum gas), EL (electricity)

Table 3.7. Distribution of energy choice based on availability

Cost	**Primary energy**						
	FW	**CH**	**KE**	**AR**	**LPG**	**EL**	**Total**
0	24.00	64.00	4.00	1.00	78.00	21.00	192.00
	12.50	33.33	2.08	0.52	40.63	10.94	100.00
1	84.00	102.00	0.00	0.00	5.00	16.00	207.00
	40.58	49.28	0.00	0.00	2.42	7.73	100.00
Total	108.00	166.00	4.00	1.00	83.00	37.00	399.00
	27.07	41.60	1.00	0.25	20.80	9.27	100.00

[1] First row has *frequencies* and second row has *row percentages*, [2] Pearson chi2(5) = 111.5063 Pr = 0.000, Cramér's V = 0.5286, [3] FW (fuelwood), CH (Charcoal), KE (Kerosene), AR (agro-residue), LPG (liquefied petroleum gas), EL (electricity)

Table 3.8. Distribution of energy choice based on efficiency

Energy efficiency	Primary energy						
	FW	**CH**	**KE**	**AR**	**LPG**	**EL**	**Total**
0	69.00	112.00	0.00	1.00	10.00	17.00	209.00
	33.01	53.59	0.00	0.48	4.78	8.13	100.00
1	39.00	54.00	4.00	0.00	73.00	20.00	190.00
	20.53	28.42	2.11	0.00	38.42	10.53	100.00
Total	108.00	166.00	4.00	1.00	83.00	37.00	399.00
	27.07	41.60	1.00	0.25	20.80	9.27	100.00

[1] First row has *frequencies* and second row has *row percentages*, [2] Pearson chi2(5) = 80.9397 Pr = 0.000, Cramér's V = 0.4504, FW (fuelwood), CH (Charcoal), KE (Kerosene), AR (agro-residue), LPG (liquefied petroleum gas), EL (electricity)

3.6.2 Multivariate probit regression model results

Multivariate probit regression analysis was conducted to understand the factors influencing household cooking energy choice. The dependent variable in this analysis represents the sources of cooking and heating energy in the households. The independent variables are household size, marital status of the respondent, education of the head of the household, education of the respondent, gender of respondent, occupation of the head, household income, and age of the respondent.

3.6.2.1 Model fit statistics

Table 3.9 presents the model fit statistics of the multivariate probit regression. A Wald chi2 value of 302.99 indicates a significant relationship between the independent variables and the outcome categories. On the other hand, the Prob > chi2 is 0.000, which is less than the conventional significance level of 0.05. This suggests strong evidence against the null hypothesis (there is no relationship between the independent variables and the outcome categories).

Table 3.9. Model fit statistics

Wald chi2(48)	Log-likelihood	chi2(15)	Prob > chi2
302.99	-1105.98	89.833	0.0000

Similarly, the log-likelihood of −1105.98 typically depicts a better fit. While it is essential to compare this value to other models or variations of the current model, it suggests that the model provides a reasonable fit to the data. Therefore, it can be concluded that the multivariate probit regression model is statistically significant in explaining the variation in the choice of primary cooking energy in the study area.

3.6.2.2 Multivariate probit regression results of variables influencing the choice of energy

Table 3.10 shows the results of the multivariate probit regression analysis. The model's findings showed that the household income coefficient is positive and significant for firewood, charcoal, and agro-residue, and negative and significant for electricity and LPG. This indicates that low-income households (base reference) are likely to use firewood, charcoal, and agro-residue and are less likely to use LPG and electricity. This is consistent with the energy ladder theory which points out that the level of household income highly influences the use of clean energy and also agrees with the findings of Oyeniran & Isola (2023) and Yang & Wang (2023), where household income was found to be a major factor influencing the choice of cooking energy.

Table 3.10. Multivariate probit regression results

Variable	Firewood	Charcoal	Kerosene	Agro-residue	LPG	Electricity
	Coefficient (P>|z|)	Coefficient (P>|z|)	Coefficient (P>|z|)	Coefficient (P>|z|)	Coefficient (P>|z|)	Coefficient (P>|z|)
Constant	-0.792	-1.221	-1.337	-0.364	0.800	0.499
	(0.039) ***	(0.001) ***	(0.014) ***	(0.313)	(0.030) ***	(0.216)
Income	0.770	0.865	0.289	0.351	-1.272	-0.804
	(0.000) ***	(0.000) ***	(0.303)	(0.022) ***	(0.000) ***	(0.000) ***
Marital Status	0.002	0.387	-0.237	-0.132	0.203	-0.149
	(0.990)	(0.020) ***	(0.348)	(0.412)	(0.239)	(0.415)
Household Size	0.236	0.138	-0.637	0.028	-0.384	0.048
	(0.149)	(0.354)	(0.009) ***	(0.847)	(0.011) ***	(0.770)
Age	0.029	0.007	0.016	0.000	-0.003	-0.020
	(0.000) ***	(0.147)	(0.034) ***	(0.997)	(0.567)	(0.001) ***
Gender	-1.058	0.147	-0.810	-0.313	-0.570	-0.289
	(0.000) ***	(0.522)	(0.002) ***	(0.145)	(0.008) ***	(0.265)
Occupation	-0.785	0.371	-0.410	0.201	0.146	0.267
	(0.000) ***	(0.067)	(0.203)	(0.302)	(0.485)	(0.270)
Education of head	0.082	0.309	0.380	-0.349	0.661	-0.412
	(0.701)	(0.160)	(0.291)	(0.081)	(0.003) ***	(0.110)
Education of cook	0.233	-0.282	0.225	0.163	-0.141	0.654
	(0.214)	(0.144)	(0.476)	(0.365)	(0.447)	(0.004) ***

Notes: p-values are in parentheses, *** means the P-value is significant at 0.05

Marital status is another factor that significantly influences household energy choice. A positive and significant coefficient was observed for charcoal implying that married households have a higher probability of using charcoal than other energy sources compared to other households. Similarly, the likelihood of using firewood and LPG is also high as a positive coefficient was noted. However, married households are less likely to use kerosene, electricity, and agro-residue than other households. The coefficient of household size is negative and significant for kerosene and LPG implying that households with large family

sizes (5 or more members) are less likely to use kerosene and LPG. Zhu et al. (2022) also observed that the use of LPG is low in large family households. Conversely, the model revealed a higher probability of using solid fuels especially firewood and charcoal in this category of households. This is consistent with the findings of Oyeniran & Isola (2023) and may be influenced by the fact that large pot sizes fit the firewood and charcoal cookstoves better than the electric stoves and LPG. The age coefficients revealed how different age groups influence household cooking energy choices. A positive and significant coefficient was recorded for firewood and kerosene, while a negative and significant coefficient was obtained for electricity. This shows that as the age of the household cooks increases, the use of firewood and kerosene for cooking and heating will significantly increase, while electricity use will significantly reduce. However, the coefficient of gender is negative and significant for kerosene, LPG, and firewood, which indicates that households with female cooks are less likely to use the mentioned energy sources than males. However, females are more likely to use charcoal.

The occupation of the head of household is an important factor in the choice of cooking energy as it is one of the indicators of household income. A negative and significant coefficient was observed for firewood showing that households whose heads are employed (either self-employed or in public service) are less likely to use firewood. This is because such households have a source of income which is an indicator for using other better and cleaner energy options. The level of education of the head of household is positive and significant for LPG depicting that households whose heads have at least a senior high school certificate are more likely to opt for LPG and less likely to use agricultural residues. This further confirms that such categories of households are aware of the negative effects of traditional fuels and open fires. Thus, they are more likely to go for clean energy options like electricity, depicting their interest in curtailing polluting fuels. This aligns with the findings of Bofah et al. (2022). However, in the case of the education level of respondents who are in charge of cooking, a different outcome was observed, as electricity has a positive and significant coefficient showing that the more educated, they are, the more they opt for electricity. LPG and electricity were obtained from both showing that education level is key in using clean energy for cooking. This is in agreement with the findings of Twumasi et al. (2021).

3.7 Discussion

Between 2016 and 2019, firewood and kerosene were the most used cooking energy options in Nigeria, while charcoal was among the least (Oyeniran & Isola, 2023). However, due to the increased cost of kerosene, coupled with the fact that most of the households are low-income earners, households now rely on charcoal and firewood to meet their cooking energy needs. Further observation from the survey revealed that because most households have large family sizes, they find it easier and more affordable to use charcoal and fuelwood for cooking. Thus, cleaner options such as LPG and electricity are not just unaffordable; models that accommodate large pot sizes are still not widely available in the local markets.

Predictions from the multivariate probit model also indicate that larger family sizes are more likely to use firewood and charcoal, which corroborates the findings of Oyeniran & Isola (2023). With sufficient evidence from the model fitness parameters, the stated prediction is highly certain to occur. Hence, considering the population growth of Nigeria, which is persistently rising, it depicts the potential of having more users of traditional solid fuels in the future. Thus, if measures are not taken to address this potential problem, then there is a likelihood of experiencing an increase in the rate of deforestation in the coming years making the country more vulnerable to climate change. Therefore, for a swift transition to the use of clean energy, governments, non-governmental organizations (NGOs), and/or private organizations must provide interventions that will improve the accessibility and affordability of clean energy, especially to low-income households. Overall, the findings from this study confirmed that the energy use pattern in the study area conforms better with the fuel stacking theory than the energy ladder theory as traditional energy is often used alongside modern energy. This is consistent with the findings of Baiyegunhi & Hassan (2014).

However, the major limitation of this study is that it only focused on six LGAs out of the 23 LGAs of Kaduna state, Nigeria. Future studies can explore a larger sample size to cover the entire state and if possible, the whole country. Secondly, the study could not ask questions on household income. This was assessed based on the enumerator's perception following the type of household and energy choice. Although the study assessed the presence of bio-based fuels such as briquettes and biogas, they were not included as variables in the modeling because none of the households used these energy sources. Future

studies can model these bio-based options to explore why they are still not in use in most households despite the progress recorded in scientific research.

3.8 Conclusion

This study assessed household cooking energy use and the various demographic and socio-economic factors influencing their choices. The outcome of the descriptive analysis revealed charcoal and fuelwood as the most used cooking energy in Kaduna State, Nigeria. Their cost and availability mainly influenced the choice of the stated energy options. The findings from the multivariate probit regression suggest that the independent variables significantly impact the outcome categories (energy sources).

Furthermore, the study found that although traditional cooking energy options such as charcoal and fuelwood are the most used cooking energy in the study area, cleaner options such as electricity and LPG were present in most households in the urban parts of the State. Therefore, the energy use pattern in the study area conforms better with the fuel stacking theory than the energy ladder theory. These findings can be crucial for policymakers and organizations promoting clean and sustainable energy production and use, climate change mitigation, and the reduction of indoor air pollution. Similarly, it would serve as a guide in tracking the advances in cooking energy consumption and its related impact towards achieving carbon neutrality or net zero emissions.

CHAPTER 4 : ASSESS THE PROPERTIES OF THE WOOD SPECIES USED AS ENERGY SOURCES IN THE STUDY AREA

fuels

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Article

Physical and Thermochemical Properties of Selected Wood Species in Nigeria: A Fuel Suitability and Pelleting Potential Assessment

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Abstract

Scientific studies on the impact of wood species on solid fuel production, performance, and sustainability are grossly inadequate. Knowledge of this is imperative as the number of users of solid fuels is increasing rapidly, especially in Africa. On this note, it is necessary to explore measures to improve its efficiency and sustainability as an energy source. This study investigates some properties of selected wood species used as an energy source in Nigeria and their pelleting potential. Nine samples were characterized and assessed for suitability of pelleting following four wood pellet quality standards. The properties investigated are physical (moisture content and density) and thermochemical (calorific value, ash content, volatile matter, fixed carbon, and ultimate properties (carbon, nitrogen, hydrogen, oxygen, sulfur, arsenic, cadmium, and lead)). These were selected because they are among the most important pellet parameters contained in the quality standards. The findings revealed a net calorific value between 10.61 $MJ.kg^{-1}$ for *Tectona grandis* (Teak) and 18.44 $MJ.kg^{-1}$ for *Eucalyptus cam.* (Red gum). The ash content, volatile matter, and fixed carbon contents range between 2.1 and 24.4%, 65.94 and 87.77%, and 3.51 and 18.63%, respectively. *Anogeissus leiocarpus* (African birch) was found to be the species with the best rating score in terms of fuel properties, while *Vitellaria paradoxa* (Shea) was the lowest. However, in terms of conformity with the four wood pellet standards, *Khaya senegalensis* (African mahogany), *Parkia biglobosa* (African locust bean), and *Eucalyptus cam.* (Red gum), having presented density, calorific value, sulfur, arsenic, cadmium, and lead within the limits of the wood pellet quality standards, were considered the best wood species in terms of fuel suitability and pelleting potential. The findings therefore suggest that not all wood species are suitable as fuel. Thus, for species that do not meet the standard wood pellet

requirements, alternatives such as biomass blends, additives, or process adjustments can be employed to adapt the quality to the standards or by using the fuels in improved cookstoves.

Keywords: wood; pellets; energy; physical properties; thermochemical properties; standards

4.1 Introduction

Woody biomass is one of the most used forms of biomass globally. Its use as fuel is increasing rapidly around the globe. About one-third of the world population, equivalent to 2.6 billion people, rely primarily on fuelwood to meet their energy needs (Schilmann et al., 2021). This is more predominant in Africa where over 80% of the population relies on different forms of wood to meet their energy needs (Boafo-mensah et al., 2020). Based on this, the impacts of deforestation and climate change have increased in recent years. In Africa, about 3.4 million hectares of forest land is lost per year (FAO, 2010). Nigeria is among the top 10 countries globally with the highest rate of forest loss, as 5.0% (410,000 hectares) of forest land is lost per annum (FAO, 2016). This figure may be exacerbated further as Nigeria is also the second-highest charcoal-producing nation in the world with an annual average production capacity of 4,828,689.00 tons as of 2022 (FAO, 2023). Similarly, the country's major consumer of wood is the fuelwood sector, which as of 2015 accounted for almost 87% of the total wood extracted (FAO, 2016). More worrisome is that the production process is devoid of sustainable mechanisms such as constant tree planting to account for the deforested ones. Apart from the environmental impacts recorded through deforestation in Nigeria, the gross domestic product GDP accrued from forest ecosystem services, which was valued at about NGN 1 million per hectare in 2015 (1,000,000 NGN/ha) has been drastically reduced due to deforestation (UNEP, 2017). To minimize the rate of deforestation in Nigeria, UNEP (2017) has recommended policy formulation involving tree planting through agroforestry, carbon trading, and the payment of incentives for forest management.

For solutions involving the production and use of alternative energy to curtail the unsustainable use of forests for fuel, several studies have worked enormously on various aspects. Some of these include the processing of lignocellulosic biomass into fuels such as briquettes (Akogun et al., 2022; Yunusa et al., 2023), pellets (Narra et al., 2011), and biogas

(Pal et al., 2022), among others. The appropriate use of fuel, especially at low moisture content in improved cookstoves, is another approach that can considerably reduce the gaseous emissions encountered from incomplete combustion. In this vein, studies including Barbour et al. (2021) and Yunusa et al. (2022) have developed improved biomass cookstoves to reduce fuel use and gaseous emissions. This has been proven as an effective approach to reducing the use of fuelwood and charcoal, with the potential of improved performance if the cookstoves are powered by pellets made from non-woody biomass (Yunusa et al., 2023). Despite numerous advances, the production and use of solid fuel (charcoal and fuelwood) continue to exacerbate. The use of polluting fuels including fuelwood and charcoal was projected to continue with more than one (1) billion people in sub-Saharan Africa by 2025 (Stoner et al., 2021). Thus, it becomes imperative to explore measures involving policy regulations that will improve sustainability in the use of wood. These may include limiting charcoal and fuelwood production to certain wood species or, more importantly, pelletizing the wood shavings and the residues into a more compact and durable form. To succeed in the mentioned steps, it is pertinent to study the properties of the wood species conventionally used as energy sources to recommend the most energy-efficient and cleaner option and to have a basis for comparison with alternative biomass feedstocks.

A couple of studies conducted on the characterization of selected wood species in Africa are presented in Table 4.1. This ranges from the study of Ogunsola et al. (2018) in Nigeria where species predominantly found in the southwestern part of Nigeria were characterized. Others include the study of Lubwama et al. (2023) in Uganda, Ndecky et al. (2022) in Senegal, Charis et al. (2020) in Botswana, Mitchual et al. (2014a) in Ghana, and Okoro et al. (2022) in South Africa**,** among others. Most of the analyzed properties (calorific value, ash content, and nitrogen and sulfur content) of the wood species conform with the European Norm ENplus (EPC, 2015), as set by the European Pellet Council, the German Institute for Standardization (DIN 51731/DINplus) (Hiegl et al., 2009), the Austrian standard (ÖNORM M7135) (Hiegl et al., 2009), and the International Organization for Standardization (ISO 17225-2, 2021) for wood pellets. Although some of the reported studies did not consider toxic gases such as N and S, *Afr. mesquite*, one of the species studied by Okoro et al. (2022) in South Africa, was found to have properties within the acceptable limits of ENplus (EPC, 2015), DIN 51731/DINplus (Hiegl et al., 2009), ÖNORM M7135 (Hiegl et al., 2009), and ISO 17225-2 (2021). However, in the same study, despite having good calorific value and

acceptable nitrogen (N) and sulfur (S) levels in the *Jacaranda* species, the ash content was above the required limits. A similar scenario was observed in the study of (Ogunsola et al., 2018) for the *M. excelsa* species, where a high calorific value was recorded but with ash content above the acceptable limit. This suggests that when selecting fuel woods by species, calorific value alone is insufficient to determine the best species (Mitchual et al., 2014a).

Table 4.1. A review of selected wood species in Africa and their conformity with international wood pellet standards.

Specie	Country	MC (%)	AC (% db)	VM (% db)	FC (% db)	GHV MJ.kg^{-1}	N (%)	S (%)	Ref.
M. excelsa	Nigeria	9.00	4.62	82.41	3.97	20.20	-	-	(Ogunsola et al., 2018)
M. altissima	Nigeria	13.00	2.01	80.93	4.06	21.50	-	-	(Ogunsola et al., 2018)
D. cinerea	Uganda	16.57	0.60	62.49	20.34	16.71	-	-	(Lubwama et al., 2023)
C. molle	Uganda	17.61	1.15	63.93	17.30	15.61	-	-	(Lubwama et al., 2023)
Senegal wood	Senegal	-	-	-	-	17.27	-	-	(Ndecky et al., 2022)
Acacia tortilis	Botswana	3.72	3.90	76.51	19.59	17.27	1.23	-	(Charis et al., 2020)
Pine	Zimbabwe	6.50	0.83	79.16	20.00	17.57	0.04	-	(Charis et al., 2020)
Jacaranda	S. Africa	9.12	2.21	57.91	30.76	18.43	0.18	0.00	(Okoro et al., 2022)
Afr. mesquite	S. Africa	9.61	0.10	43.29	47.11	20.72	0.26	0.01	(Okoro et al., 2022)
C. pentandra	Ghana	-	4.72	82.43	-	20.33	0.48	0.05	(Mitchual et al., 2014a)
T. scleroxylon	Ghana	-	2.01	80.97	-	21.60	0.56	0.09	(Mitchual et al., 2014a)
O. africana	Ethiopia	5.91	0.99	70.71	22.39	-	-	-	(Desta & Ambaye, 2020)
A. nilotica	Ethiopia	7.00	1.97	71.50	19.50	-	-	-	(Desta & Ambaye, 2020)
ENplus A1		≤10	≤0.7	-	-	≥16.56	≤0.3	≤0.04	(EPC, 2015)
ENplus A2		≤10	≤1.2	-	-	-	≤0.5	≤0.05	(EPC, 2015)
ENplus B		≤10	≤2.0	-	-	-	≤1.0	≤0.05	(EPC, 2015)
DIN 51731/DINplus		≤10–12	≤1.5	-	-	≥17.5–19.5	≤0.3	≤0.08	(Hiegl et al., 2009)
ÖNORM M7135		≤10	≤0.5	-	-	≥18	≤0.3	≤0.04	(Hiegl et al., 2009)
ISO 17225-2		≤10	0.7–2.0	-	-	≥16.56	≤0.3	≤0.05	(ISO 17225-2, 2021)

Although several studies have been carried out on wood characterization, there is no adequate explanation of how species types affect charcoal or fuelwood production, performance, and sustainability. This may be because of the greater interest in valorizing lignocellulosic biomass into new forms of energy rather than conventional solid fuels (fuelwood and charcoal). In this vein, studies focus more on using agricultural residues in developing biofuels, such as briquettes, pellets, biogas, etc., to reduce the pressure on fuelwood and charcoal to reduce deforestation. Nonetheless, knowledge of the effect of

wood species on fuel production is imperative as the users of charcoal and fuelwood are increasing rapidly. Thus, the findings in this study would serve as a guide in selecting the most energy-efficient wood and those with the best potential to be pelleted to augment the rapid deterioration of forests for fuelwood and charcoal production. Similarly, the findings will be a basis for comparing the potentiality of using alternative biomass feedstocks as energy sources. Analyzing the wood's proximate parameters with and without bark is an aspect that validates the influence of wood bark during combustion. This is equally missing in previous studies. Another novelty of this study is that it assessed the conformity of selected wood species from other African countries and those of this study with international wood pellet standards. Thus, the objective of this study is to evaluate the selected physical and thermochemical properties of some wood species used in fuelwood and charcoal production in Nigeria to determine the best in terms of fuel-related properties and the best in terms of compliance with ENplus (EPC, 2015), DIN 51731/DINplus (Hiegl et al., 2009), ÖNORM M7135 (Hiegl et al., 2009), and ISO 17225-2 (2021) standards.

4.2 Materials and Methods

4.2.1 Sample Collection and Preparation

About 20 species were broadly identified. However, only the nine (9) most commonly used species in fuelwood and charcoal production in Kaduna State, Nigeria, were selected for this study. The samples were collected from the Savannah Forestry Research Institute of Nigeria, Zaria Kaduna State (latitude 11°10′ N and longitude 7°37′ E). Of the nine (9) species collected, four (4) are mainly used in charcoal production, viz. *Vitellaria paradoxa* (Shea), *Mangifera indica* (Mango), *Anogeissus leiocarpa* (African birch), and *Tectona grandis* (Teak), four (4) for fuelwood, viz. *Eucalyptus cam.* (Red gum), *Parkia biglobosa* (African locust bean), *Albizia lebbeck* (Siris), and *Azadirachta indica* (Neem), and one (1) for both, viz. *Khaya senegalensis* (African mahogany).

The samples were sundried for two days, shredded into smaller sizes, and heated for 30 minutes at 105 °C in an oven to remove the core layer moisture. The dried samples were manually ground with a mortar and pestle. The ground samples were further sieved through a 1 mm mesh size for characterization. The overall study flowchart is presented in Figure 4.1.

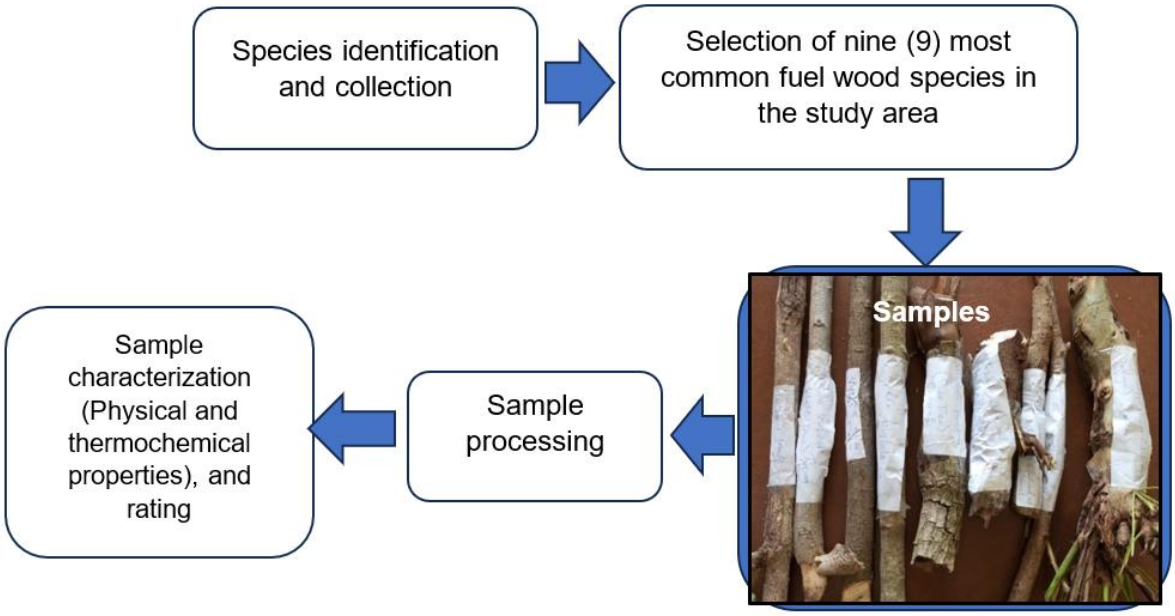

Figure 4.1. Study flowchart.

4.2.2 Sample Characterization

The samples were characterized based on physical (moisture content, volume, and density) and thermochemical properties (calorific value, proximate, and ultimate parameters).

4.2.2.1 Physical Properties

Three parameters, viz. moisture content, volume, and density were determined. The moisture content was determined following the method described in ASTM D3173-87 (1996). Because the samples are irregularly shaped, the volume and density were determined using the water displacement method. The weights of the samples were taken using a digital scale balance (model: OPH-T3001, Optima Scale, Rancho Cucamonga, CA, USA) with an accuracy of 0.1 g. The individual volume was obtained as the difference in volume after immersing each sample into a 500 mL volume of water in a transparent cylinder. Hence, the density was computed as the ratio of the mass and volume.

4.2.2.2 Thermochemical Properties

a. Gross Calorific Value (GHV) and Net Calorific Value (NHV)

The gross calorific value was determined using a bomb calorimeter (model: 6100, Parr Instrument Company, Moline, IL, USA) following the method described in ASTM D5865-10a (2010). The value indicates the energy content of the samples per unit mass ($MJ.kg^{-1}$) (Musabbikhah et al., 2019). Thus, the higher the value, the better the thermal performance of the wood species.

The net calorific value was estimated from the gross calorific value using Equation (4.1), as given by Ebeling & Jenkins (1985):

$$NHV = (1 - MC)\left[GHV - \lambda\left(\frac{MC}{1-MC}\right) + (0.09H)\right] \qquad (4.1)$$

where MC is the moisture content of the wood sample on a wet basis (decimal), H is the hydrogen concentration, percent by weight dry basis, and λ is the latent energy of vaporization of water ($MJ.kg^{-1}$) (2.26 $MJ.kg^{-1}$).

b. Proximate Analysis

Proximate analysis was performed to determine the volatile matter content, ash content, and fixed carbon contained in the wood samples. Unlike the physical analysis, the proximate analysis was analyzed with bark (WB) and without bark (WoB). This was to understand the differences between wood samples based on ash content and volatile matter with and without bark.

i. Volatile Matter

The sample's volatile matter was determined using the modified procedure described in ASTM D3175-07 (2007) for all sparking fuels. One gram of each sample was weighed into a crucible, covered with a lid, and gradually heated to 650 °C for six minutes in a furnace (BIOB Muffle furnace, Biobase, Jinan, China), after which the samples were heated further at 930 °C for another six minutes. The percentage of volatile matter in each sample was determined with Equation (4.2) (Mitchual et al., 2014a).

$$Percentage\ volatile\ matter\ (\%) = \frac{A-B}{A} \times 100 \qquad (4.2)$$

where A is the weight of the oven-dried sample and B is the weight of the sample after heating in the furnace.

ii. Ash Content

The ash content was estimated by heating 1 g of the sample in a furnace (BIOB Muffle furnace, Biobase, Jinan, China) for four hours, starting at room temperature, rising to 500 °C in the first hour, and heating to 700 °C in the second hour. After the first two hours, the sample was heated continuously at 700 °C for an additional two hours as per ASTM D3174-02 (2002). The percentage of ash content was determined using Equation (4.3) (Mitchual et al., 2014a).

$$Ash\ content\ (\%) = \frac{M_{ash}}{M_{oven-dry}} \times 100 \qquad (4.3)$$

where M_{ash} is the mass of the ash and $M_{oven-dry}$ is the mass of the oven-dried sample.

iii. Fixed Carbon

The fixed carbon (*FC*) was estimated by subtracting the value of the volatile matter (*VM*) and ash content from 100%, as given in Equation (4.4) (Mansaray & Ghaly, 1997):

$$\%\ FC = [100 - (\%\ Ash + \%\ VM)] \qquad (4.4)$$

c. Ultimate Analysis

The ultimate analysis was restricted to carbon, nitrogen, sulfur, hydrogen, oxygen, and three heavy metals (cadmium, lead, and arsenic). The nitrogen content was determined using the micro-Kjeldahl method using the micro-Kjeldahl digestion distillation apparatus, the sulfur content was determined using the aluminum block method in a Tecator (Model 40 digestor, Tecator AB, Sweden), and the heavy metals were determined through the perchloric acid digestion method using the Tecator (Model 40 digestor, Tecator AB, Sweden). However, the contents of carbon, hydrogen, and oxygen were estimated from the result of proximate analysis with an accuracy of ±2% using Equations (4.5)–(4.7) (TT et al., 2022).

$$Carbon\ (\%) = 0.635\text{FC} + 0.460\text{VM} - 0.095\ \text{AC} \qquad (4.5)$$

$$Hydrogen\ (\%) = 0.059\text{FC} + 0.060\text{VM} + 0.010\text{AC} \qquad (4.6)$$

$$Oxygen\ (\%) = 0.340\text{FC} + 0.469\text{VM} - 0.023\text{AC} \qquad (4.7)$$

where *FC* = fixed carbon, *AC* = ash matter, and *VM* = volatile matter.

4.2.3 Rating of the Properties of the Wood Species

To determine the most suitable species and vice versa, the samples were rated between 1 and 9, with 1 indicating the best and 9 being the worst. The method employed in the rating was based on the average scores of each tested property (Mitchual et al., 2014a). The rating scores were allocated based on the role of each tested property in solid fuels (i.e., either required or not required for efficient and clean combustion). For example, species with the highest calorific value, carbon, and fixed carbon content were allocated a rating score of 1 because they are essential properties required for effective fuel performance. However, in the case of ash, sulfur, nitrogen, arsenic, lead, and cadmium content, species with the lowest content were allocated the best rating score because they contribute to toxic gas emissions, which are not required in fuels. Overall, species with the lowest average rating score were considered the best in terms of suitability for use as fuel. However, the species whose physical and thermochemical properties meet the four wood pellet standards are considered the best for pelleting.

4.3 Results and Discussion

4.3.1 Physical Properties

The results of the physical properties are presented in Table 4.2. The moisture content of the samples ranges between 4.08% and 7%. This indicates that the samples were properly dried and within the optimum range of moisture required for wood pellets as set by ENplus (EPC, 2015), DIN 51731/DINplus (Hiegl et al., 2009), ÖNORM M7135 (Hiegl et al., 2009), and ISO 17225-2 (2021).

Table 4.2. Physical Properties.

Sample	MC % (wb)	Density (kg/m^3)
Teak	6.00	928.69
Mango	4.00	915.69
African mahogany	5.00	977.50
African locust bean	7.00	910.00
African birch	4.00	930.77
Red gum	4.00	901.00
Shea	6.00	398.00
Siris	5.80	947.50
Neem	4.08	674.75
ENplus A1, A2, B	≤10	≥600–750
DIN 51731	≤12	1000–1400
DINplus	≤10	1120
ÖNORM M7135	≤10	1120
ISO 17225-2	≤10	≥600

The density ranges between 398.00 kg/m^3 for Shea and 977.50 kg/m^3 for African mahogany. Although the obtained values are below the DIN 51731/DINplus (Hiegl et al., 2009) and ÖNORM M7135 (Hiegl et al., 2009) standards for wood pellets, all the samples except Shea conform with the density requirements of wood pellets for ENplus (EPC, 2015) and ISO 17225-2 (2021). This shows that the species (except Shea) meet the required threshold density for wood pellets. Density is an important parameter in wood pellet production as it simulates the strength of the pellets during transportation and storage. Similarly, density also influences the thermal performance of the pellets as low-density fuels have higher burning rates and specific fuel consumption. In contrast, very-high-density fuels are associated with incomplete combustion and high emissions. However, pellets with high density do not always imply better durability or strength (Kaliyan & Morey, 2009). Therefore, the set threshold values reported in the standards are perceived to be optimum, and for a wood species to be suitable, the density must be within the range and not too low or high. The variation in density by species shows that they will react differently during combustion. This is because density significantly influences the gasification process of fuels (Sakthivadivel & Iniyan, 2020). Similarly, the sample densities are consistent with the findings of Desta & Ambaye (2020) (553 kg/m^3 to 914 kg/m^3) for selected wood species in Ethiopia and higher than the findings (409.22 kg/m^3 to 764.11 kg/m^3) of Mitchual et al. (2014a) for selected wood species in Ghana. However, the densities of these species are below the density (1250.0 ± 26.2 kg/m^2) of *grenadilla,* a wood species common in the tropical part of Africa (Alkadri et al., 2020).

4.3.2 Thermochemical Properties

4.3.2.1 Calorific Value

Figure 4.2 shows the result of the calorific value of the samples. Because the calorific value indicates the estimated energy content per unit mass in the wood species, it is considered one of the most important parameters for assessing the suitability of the various species as fuel. Hence, the higher the calorific value, the better the thermal performance of the resulting wood pellets during combustion. The gross calorific value of the samples is between 10.92 MJ.kg^{-1} for Teak and 18.85 MJ.kg^{-1} for African mahogany, while the net calorific value is between 10.61 MJ.kg^{-1} for Teak and 18.44 MJ.kg^{-1} for Red gum. The net calorific values recorded in African mahogany, African locust bean, African birch, and Red gum are in agreement with ENplus (EPC, 2015) and ISO 17225-2 (2021) standards. Similarly, the

samples above, except African birch, also conform with DIN 51731/DIN plus (Hiegl et al., 2009) and ÖNORM M7135 (Hiegl et al., 2009) requirements for wood pellets.

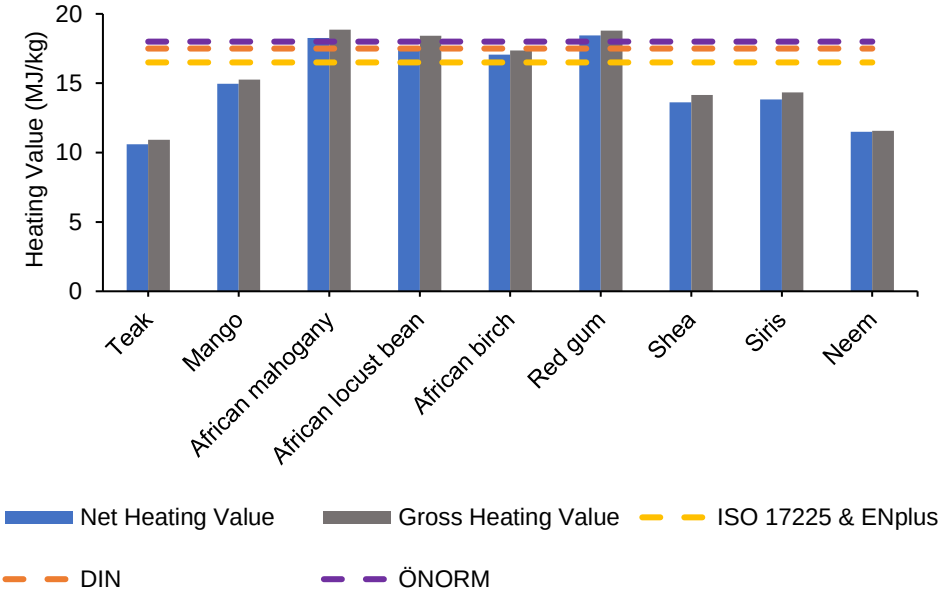

Figure 4.2. Calorific value of selected wood species

These species, therefore, have better potential to be transformed into pellets as they would yield higher thermal efficiency. However, it is pertinent to note that due to the hygroscopic nature of wood, it can easily absorb moisture during handling and storage, affecting the net calorific value. Species with higher calorific values were observed to have higher fixed carbon. Thus, the fixed carbon content of biomass directly influences the calorific value (Lubwama et al., 2023). The values obtained are consistent with the calorific values of some native wood species in Africa (Charis et al., 2020; Lubwama et al., 2023; Ndecky et al., 2022). While moisture content significantly influences the energy content of fuels (Mierzwa-Hersztek et al., 2019), this fact is inconsistent with all the samples in this study, possibly due to the moisture loss during pretreatment. Although calorific value is an important parameter, it is not sufficient in selecting wood species with the best pelleting potential (Mitchual et al., 2014a). Therefore, other parameters such as ash, carbon content, and elemental constituents must be examined accordingly.

4.3.2.2 Proximate Analysis

The results of the proximate analysis are presented in Table 4.3. The ash content, volatile matter, and fixed carbon range between 4.6 and 24.4%, 65.94 and 87.77%, and 3.51 and 13.25% for the samples analyzed with bark and between 2.1 and 21.3%, 73.98 and 85.99%, and 4.72 and 18.63% for the samples analyzed without bark.

Table 4.3. Proximate analysis

Sample	AC (% db)	VM (% db)	FC (% db)
Shea (WoB)	6.50	78.19	15.31
Shea (WB)	15.40	81.09	3.51
Mango (WoB)	21.30	73.98	4.72
Mango (WB)	24.40	65.94	9.66
Siris (WoB)	2.90	80.46	16.64
Siris (WB)	7.40	79.35	13.25
Neem (WoB)	2.10	79.27	18.63
Neem (WB)	6.00	84.76	9.24
African birch (WoB)	3.40	78.74	17.86
African birch (WB)	4.60	87.77	7.63
African locust bean (WoB)	9.50	75.24	15.26
African locust bean (WB)	10.80	79.49	9.71
Red gum (WoB)	5.30	78.31	16.39
Red gum (WB)	9.30	82.66	8.04
Teak (WoB)	3.30	81.16	15.54
Teak (WB)	6.00	86.85	7.15
African locust bean (WoB)	7.40	85.99	6.61
African locust bean (WB)	13.20	74.91	11.89

The ash content was observed to vary with the presence of bark as the samples without bark depict lower ash levels compared with those with bark (Figure 4.3). This shows that, irrespective of the wood species, ash content increases with an increase in the quantity of bark. Moreover, because the content of ash depicts the slagging nature of the wood during combustion, the lower the ash content, the better the heating value (Thabuot et al., 2015). Overall, an ash content of less than 4% is generally preferred as it reduces slagging potential (EN 1860-2, 2005; Nagarajan & Prakash, 2021). However, when the woods have been carbonized into charcoal, an ash content of up to 8% is acceptable (EN 1860-2, 2005). While ash content can go relatively high in other solid fuels, a very low ash content (0.5–2.0%) is required for wood pellets. This implies that wood species having ash content above the stated range are not suitable for pelleting. If they must be used, then pretreatment measures such as carbonization or the use of additives or blends could be employed to reduce the ash content. Overall, Neem, Siris, Teak, and African birch, all without bark, yielded the best ash contents of 2.1%, 2.9%, 3.3%, and 3.4%, respectively.

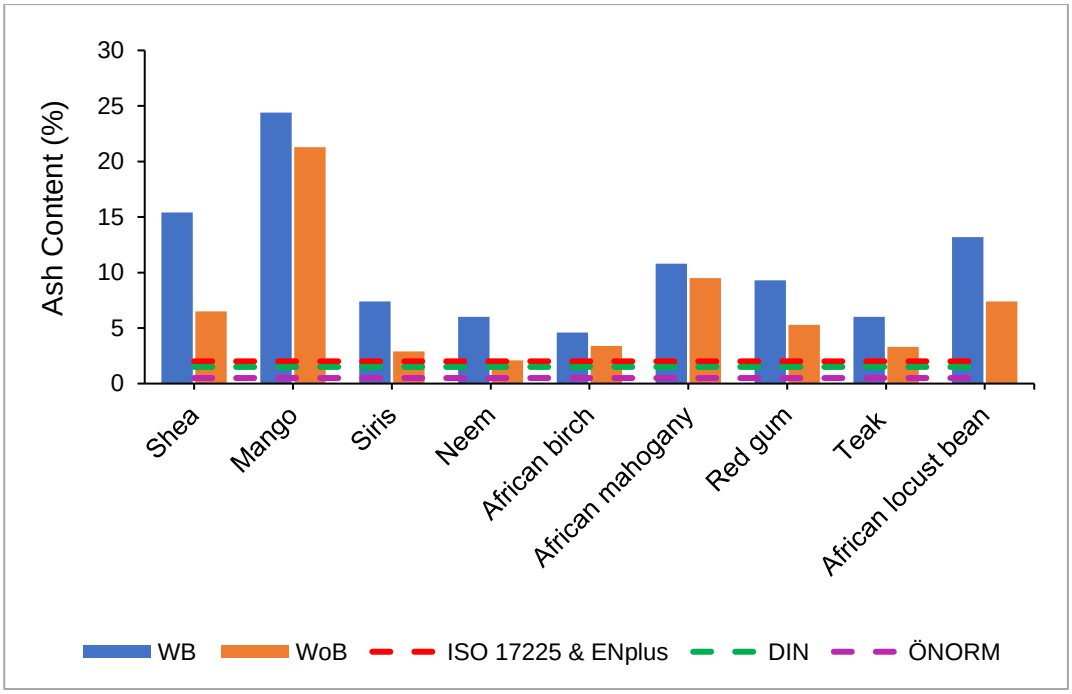

Figure 4.3. Variation in ash content in the nine wood species with and without bark

However, in the case of volatile matter, all the species except Mango, Siris, and African locust bean depict higher values of volatile matter in samples with bark. Higher volatile matter shows the fuel ignitability and combustion potential (Lubwama et al., 2023). In contrast, all samples without bark except Mango and African locust bean depict higher values of fixed carbon. Thus, since volatile matter is a measure of the quantity of fuel that combusts into gas when subjected to temperatures of 400 °C to 500 °C or more (Sunnu et al., 2021) and fixed carbon is the remnant of combustible fuel after the volatile matter, moisture, and ash content have been removed (Sarkar, 2015), it implies that fixed carbon is more essential in fuels. Thus, wood species without bark that present higher fixed carbon values in most samples are perceived to be more efficient as fuel with better pelleting potential than samples with bark.

In terms of conformity with the ash content limit of the wood pellet standards, only Neem (WoB) is at par with the ENplus B (EPC, 2015) and ISO 17225-2 (2021) standards, as none of the samples meet ENplus A1 and A2 (EPC, 2015), DIN 51731/DINplus, and Austria ÖNORM M7135 (Hiegl et al., 2009) standard. Hence, using blends and additives becomes imperative to reduce the ash contents.

Table 4.4 shows the results of the ultimate analysis. Here, major elemental constituents like carbon, oxygen, and hydrogen are higher in African birch (44.78%, 43.65%, and 5.76%, respectively), Neem (44.29%, 42.76%, and 5.69%, respectively), Siris (44.21%, 41.55%, and 5.62%, respectively), and Teak (43.92%, 43.03%, and 5.69%, respectively). This shows that the mentioned samples will have better combustion efficiency when used as fuel or pelleted. On the other hand, minor constituents such as nitrogen and sulfur depict the extent of nitrogen- and sulfur-based emissions during combustion.

Table 4.4. Ultimate analysis.

Sample	C (%)	N (%)	S (%)	H (%)	O (%)
African birch	44.780	1.820	0.0115	5.760	43.650
African locust bean	40.750	2.380	0.0108	5.330	38.870
Teak	43.920	1.540	0.0124	5.690	43.030
Red gum	42.250	2.240	0.0089	5.530	41.290
African locust bean	41.700	2.660	0.0031	5.450	40.330
Siris	44.210	3.780	0.0034	5.620	41.550
Mango	34.150	1.680	0.0088	4.770	33.650
Shea	38.070	1.820	0.0070	5.230	38.870
Neem	44.290	2.520	0.0104	5.690	42.760
ENplus A1	-	≤0.3	≤0.04	-	-
ENplus A2	-	≤0.5	≤0.05	-	-
ENplus B	-	≤1.0	≤0.05	-	-
DIN 51731/DINplus	-	≤0.3	≤0.08	-	-
ÖNORM M7135	-	≤0.3	≤0.04	-	-
ISO 17225-2	-	≤0.3	≤0.05	-	-

4.3.3. Rating of the Properties of the Wood Species

Table 4.5 presents a summary of the results of the fuel properties arranged in order of rank, while the ratings of the fuel properties for the nine wood species are presented in Table 4.6. The species were rated between 1 and 9, with 1 indicating the best and 9 being the worst. The overall rating was defined as the average rating of the properties of each wood species (Mitchual et al., 2014a). Based on the result, African birch revealed the best fuel properties with an average rating score of 3, while Shea, on the other hand, revealed the worst properties with an average rating score of 6.38.

Table 4.5. Summary of the results of physical and thermochemical properties of the wood species in order of rank

Properties	Rating								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Density (kg/m^3)	977.500	947.500	930.770	928.690	915.690	910.000	901.000	674.750	398.000
NHV (MJ/kg)	18.440	18.260	17.420	17.060	14.960	13.840	13.620	11.490	10.610
Ash (%)	2.100	2.900	3.300	3.400	5.300	6.500	7.400	9.500	21.300
VM (WB) (%)	87.770	86.850	84.760	82.660	81.090	79.490	79.350	74.910	65.940
FC (%)	13.250	11.890	9.710	9.660	9.240	8.040	7.630	7.150	3.510
Carbon (%)	44.780	44.290	44.210	43.920	42.250	41.700	40.750	38.070	34.150
Nitrogen (%)	1.540	1.680	1.820	2.240	2.380	2.520	2.660	3.780	-
Sulfur (%)	0.003	0.003	0.007	0.009	0.009	0.010	0.011	0.012	0.012
Hydrogen (%)	5.760	5.690	5.620	5.530	5.450	5.330	5.230	4.770	-
Oxygen (%)	43.650	43.030	42.760	41.550	41.290	40.330	38.870	33.650	-
As (Mg/kg)	0.204	0.229	0.230	0.413	0.543	0.628	0.632	0.711	0.845
Cd (Mg/kg)	0.001	0.002	0.004	0.006	-	-	-	-	-
Pb (Mg/kg)	0.026	0.030	0.032	0.034	0.056	0.095	0.144	0.147	0.214

Table 4.6. Rating of the physical and thermochemical properties of the wood species.

1 = Best 9 = Worst

Property	Species								
	Teak	**Mango**	**African mahogany**	**African locust bean**	**African birch**	**Red gum**	**Shea**	**Siris**	**Neem**
Density	4	5	1	6	3	7	9	2	8
CV	9	5	1	3	4	2	7	6	8
Ash	3	9	6	7	1	5	8	4	2
VM	2	9	6	8	1	4	5	7	3
FC	8	4	3	2	7	6	9	1	5
Carbon	4	9	7	6	1	5	8	3	2
Nitrogen	1	2	7	5	3	4	3	8	6
Sulfur	9	4	1	7	8	5	3	2	6
Hydrogen	2	8	5	6	1	4	7	3	2
Oxygen	2	8	6	7	1	5	7	4	3
As	2	6	7	3	1	4	9	8	5
Cd	2	4	3	1	2	4	1	3	1
Pb	2	9	4	1	6	5	7	3	8
Average rating	**3.85**	**6.31**	**4.38**	**4.77**	**3**	**4.62**	**6.38**	**4.15**	**4.54**

Note: CV = calorific value, VM = volatile matter, FC = fixed carbon.

However, in terms of conformity with the four wood pellets standards (Table 4.7), African mahogany, African locust bean, and Red gum, having presented moisture content, density, calorific value, sulfur content, arsenic, cadmium, and lead within the set limits of ENplus (EPC, 2015), DIN 51731/DINplus (Hiegl et al., 2009), ÖNORM M7135 (Hiegl et al., 2009), and ISO 17225-2 (2021), are therefore considered the best wood species. However, it is imperative to note that African mahogany is classified as a vulnerable species according to the International Union for Conservation of Nature (IUCN), and thus possesses a very high risk of extinction. Therefore, measures must be put in place to ensure sustainable utilization. Although African birch had the best rating score, its calorific value (17.35 $MJ.kg^{-1}$) is below the DIN 51731/DINplus (Hiegl et al., 2009) and ÖNORM M7135 (Hiegl et al., 2009) standards.

Table 4.7. Summary of wood species' compliance with evaluated standards.

Standards	Species								
	Teak	**Mango**	**African mahogany**	**African locust bean**	**African birch**	**Red gum**	**Shea**	**Siris**	**Neem**
ENplus A1, A2, B	MM	MM	MM	MM	MM	MM	FM	MM	MM
DIN 51731/DINplus	FM	FM	MM	MM	FM	MM	FM	FM	FM
ÖNORM M7135	FM	FM	MM	MM	FM	MM	FM	FM	FM
ISO 17225-2	MM	MM	MM	MM	MM	MM	FM	MM	MM

Note: MM = most properties meet the standard, FM = few properties meet the standard.

4.3.3 Improving the Properties of Non-Suitable Wood Species

As discovered in previous sections, some wood species were more suitable as fuel than others. Thus, this study is not oblivious that, in certain environments, the non-suitable species might be the only woods available or probably the more sustainable. In these cases, additives, blends, and combinations of two or more species are recommended to augment the low properties. This is more typical if the wood residues or shavings are to be pelleted. Here, biomass residues such as groundnut shells, sawdust, or leaf litter waste may be used as blends to enhance the physical and thermal properties of the pellets (Rajput et al., 2020). Similarly, bio-additives such as alkali lignin, glycerol, and L-proline can also be used (Azargohar et al., 2019). Chemical additives such as adenylate kinase 2 (AK2) (Emami et al., 2014), crude glycerin and paraffin also showed good results in wood pellet production (Xia et al., 2019). Other additives reported in the literature include lignosulphonate, dolomite, starches, potato flour and peel, and some lubricating and vegetable oils (Tarasov

et al., 2013). These additives have excellent thermal properties that when mixed with non-suitable biomass or wood species reduce the ash fusion and improve the calorific values. However, a careful selection of the type of additive and the use of the appropriate biomass is imperative in attaining wood pellets with desired physical and thermal characteristics (Tarasov et al., 2013). For example, the addition of AK2 as an additive in pelleting barley and oat straw was observed to improve density and durability but increased the level of ash (Emami et al., 2014).

In the case of combining or co-pelleting two or more species, it is equally important to check both properties carefully to ensure the resulting mixture yields an improved output. For example, a biomass with very low ash content may be mixed with another with high ash content to reduce the resulting ash content of the mixture (Rajput et al., 2020). A 0.5% content of motor oil and vegetable oil was observed to have increased calorific value, while a 0.5% content of wheat starch as an additive significantly reduced ash formation by 200% (Tarasov et al., 2013). Similarly, adding 20 wt% sawdust or 20% groundnut shell reduces ash content by 8.6% to 10.44% (Rajput et al., 2020).

If the following recommendations as sourced from previous findings are applied, the properties of some unsuitable species could be improved and meet the designated standards:

(a) Using 5% lignin and 10% proline additives was found to improve density significantly, reduce ash content (AC) by 0.04%, and increase gross calorific value (GHV) by 0.2 $MJ.kg^{-1}$ (Abedi et al., 2018).

(b) The calorific values may be improved using lignin additives. Based on this, the original content of lignin in the species can be added to the percentage of additives to obtain the total lignin (L). Thus, the gross calorific value (*GHV*) can be determined from Equation (8) (Demirbaş, 2001).

$$GHV\ (MJ/kg) = 0.0893\ \mathrm{L} + 16.9742 \quad (4.8)$$

Since the lignin content of the samples was not determined, values from previous studies were considered. The lignin content of the shea tree is about 35.7 ± 0.2% (Olabisi et al., 2023), and it is 23.75% for Mango tree (Sharma & Mohanty, 2021), 25.67% for Siris (Sultana et al., 2021), 13.58% for Neem (Manimaran et al., 2018), and 35.4% for Teak (Lourenço et al., 2015). Following this, the five (5) species with calorific values below the standard minimum can be improved by adding 5% content of lignin as an additive and recomputing the calorific value following Equation (4.8) (Table 4.8).

Table 4.8. Improved calorific value of species with low calorific values.

Wood Sample	L (%)	L + 5%A	GHV ($MJ.kg^{-1}$)	Improved GHV ($MJ.kg^{-1}$)
Shea	35.70	40.70	14.16	20.61
Mango	23.75	28.75	15.25	19.54
Siris	25.67	30.67	14.33	19.71
Neem	13.58	18.58	11.57	18.63
Teak	35.40	40.40	14.16	20.58

Note: L = lignin, A = additive.

Similarly, the ash contents and gaseous emissions would be drastically reduced if the wood barks were shaved out before pelleting or direct use as fuel. This is more peculiar to Siris (WoB) and Neem (WoB), which recorded lower ash contents of 2.9% and 2.1%, respectively.

If the above assertions are followed, Teak, Siris, and Neem, with their calorific values improved to the standard limit and other parameters (density, sulfur, arsenic, cadmium, and lead) within the minimum limit of ENplus (EPC, 2015), DIN 51731/DINplus (Hiegl et al., 2009), ÖNORM M7135 (Hiegl et al., 2009), and ISO 17225-2 (2021), would be equally suitable for use as fuel.

4.3.4 Research Limitations, Practical Implications, and Future Perspectives

While this study has assessed the suitability of the wood species as fuel based on their physical and thermochemical properties, this paper has not practically measured the use of blends and additives to determine the improvement in ash content and calorific values. Thus, only a theoretical approach was used to predict the improvement. In this vein, future research could evaluate the effect of various blends and additives on species found particularly unsuitable in this study to track the influence and compare the outputs with the theoretical method for validation. Although the samples were pretreated before characterization, no measure was employed to eliminate contaminants embedded in the samples. This might have influenced the output of the experiments, especially the ash and nitrogen content. Future research could include the removal of toxic contaminants to simulate the actual properties of the species.

4.4 Conclusions

Selected physical and thermochemical properties of nine wood species used in charcoal and fuelwood production in Nigeria were evaluated. This was to assess their suitability as fuel and their pelleting potential based on four wood pellet standards. A proximate analysis was carried out on the samples with and without bark to determine the influence of wood bark on thermal performance. The findings revealed a net calorific value between 10.61 $MJ.kg^{-1}$ for *Tectona grandis* (Teak) and 18.44 $MJ.kg^{-1}$ for *Eucalyptus cam.* (red gum). The ash content, volatile matter, and fixed carbon range between 2.1 and 24.4%, 65.94 and 87.77%, and 3.51 and 18.63%, respectively. Overall, it can be inferred from the study that wood samples without bark have lower ash content and higher fixed carbon content compared to samples with bark. Thus, they have better thermal and combustion performance than samples with bark.

Regarding suitability as fuel based on the physical and thermal properties, the findings showed *Anogeissus leiocarpus* (African birch) to contain the best fuel properties. However, in terms of conformity with the four wood pellet standards, *Khaya senegalensis* (African mahogany), *Parkia biglobosa* (African locust bean), and *Eucalyptus cam.* (red gum), having presented moisture content, density, calorific value, sulfur content, arsenic, cadmium, and lead within the set limits of ENplus, DIN 51731/DINplus, ÖNORM M7135, and ISO 17225-2, are therefore considered the best wood species with the highest pelleting potential. However, it is imperative to note that *Khaya senegalensis* (African mahogany) is classified as a vulnerable species according to the International Union for Conservation of Nature (IUCN), and thus possesses a very high risk of extinction. Thus, strict measures must be considered to ensure its sustainable utilization. The findings further revealed that not all wood species are suitable as fuel. Therefore, it is important to set policies to curtail the indiscriminate cutting of trees for fuel to help mitigate climate change and improve energy efficiency. However, in environments where non-suitable species are the dominant or available woods, biomass blends or additives could be employed to adapt the quality to the ISO commercialization standards. In the same context, using improved cookstoves is another measure to minimize fuel use and toxic gas emissions during combustion.

CHAPTER 5 : DETERMINE THE EFFECT OF THE BINDER TYPE ON THE QUALITY METRICS OF RICE HUSK BRIQUETTES

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ORIGINAL ARTICLE

Optimizing selected quality metrics of rice husk briquettes: a response surface methodology approach

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Abstract

Rice husk is among the most generated biomass residues in developing countries. If this abundant resource is effectively valorized into fuel briquettes, the rate of deforestation and energy deficit in the region would be substantially reduced. This paper employed process-based modeling to optimize the quality metrics of briquettes made from rice husk, and to improve its efficiency and sustainability as an energy source. Using a low-pressure technique, two novel bio-binders (locust bean pulp and sweet potato peel) were assessed alongside cassava starch. The experiment was designed using Box Behnken Design (BBD) in Design Expert 13 and Response Surface Methodology (RSM) was employed in optimizing the process metrics and response variables. A confirmatory test was used to validate the optimal conditions. From the experimental results obtained, the compressed density is between 0.495 g/cm^3 and 0.691 g/cm^3, while the impact resistance is between 12.5% and 100%. The optimum process metrics predicted by the model are a 15% binder ratio, 1 mm particle size rice husk, 0.5 min dwell time, and cassava starch binder. The optimal predicted responses are 0.71 g/cm^3 compressed density and 84.8% impact resistance. The differences between the experimented and predicted values were statistically insignificant at a 95% confidence interval. Thus, the study affirms that rice husk briquettes suitable for domestic application can be sustainably produced under the above optimum conditions. The above findings can be a reference in future studies and applications involving briquette production.

Keywords: Rice husk, briquette, energy, optimization, RSM

5.1 Introduction

Over one-third of the global population lives in energy poverty (UN-ECOSOC, 2022). This is mainly because many people cannot afford or access clean energy. With this, the dependence on solid fuels, especially fuelwood and charcoal has increased rapidly in recent years resulting in a higher rate of deforestation (Yunusa et al., 2024). About 10 million ha of forest is lost annually between 2015 and 2020, of which, if not halted, about 3.6 gigatonnes of carbon dioxide equivalent ($GtCO_2$) will be released into the atmosphere between 2020 and 2050 (FAO, 2022). On this basis, a sustainable solution that would help decrease deforestation and improve energy security is pertinent.

Biomass, being a renewable energy resource abundantly available across the globe (Liu et al., 2018), has a substantial potential for energy production using various valorization techniques (Nikhom et al., 2024). Rice husk is one major biomass produced globally because rice is a significant dietary staple (Jyothsna et al., 2024). Globally, it has an estimated energy potential of about 16 EJ/a (Baetge & Kaltschmitt, 2018). Nigeria is the largest producer of rice in Africa. The country's production capacity increased from 4.0 million tons in 2018 to 8.4 million tons in 2021 (FAO, 2021). In every kilogram of milled paddy, about 0.28 kg of rice husk is generated (Siddika et al., 2021). On this basis, about 2.4 million tons of rice husk is produced annually in Nigeria. However, there is still no definite strategy for managing or recycling the generated waste (Japhet et al., 2020). They are commonly landfilled or burned, contributing to the emission of greenhouse gases. Thus, transforming these biomass residues into energy is a means of achieving carbon neutrality and mitigating climate change (Wang et al., 2024).

One major technique employed in harnessing energy from biomass in most developing countries is through briquette production. This involves the compression of raw biomass into a solid, uniformly stable, and more compact form (Sugebo, 2022). The process improves the density and energy content of the biomass (Simões et al., 2024). Although the technology was primarily developed to solve the problem of excess waste generation, it is now majorly focused on energy production (Njezic et al., 2014). As a solid fuel with good energy content, it is suitable for powering improved cookstoves and reducing fuel consumption (Yunusa et al., 2023). This aligns with the waste management principle that ensures the reusing, reducing, recycling, and recovering of waste materials (Brunerová et

al., 2024). The progress in briquette production has been quite slow owing to the high capital cost of setting up a briquetting plant or having a high-pressure machine (Brunerová et al., 2024). On this basis, low-pressure technologies were developed to save cost and promote the use of biomass residues in place of continuous deforestation for fuel. However, another challenging aspect of using the low-pressured press has been the selection of an appropriate and affordable binder. Binding materials are essential in briquetting as they enhance bonding and contribute to both the briquette's physical and combustion performance, especially in low-pressured briquetting. Over the years, starchy binders generated from edible products such as cassava, flour, corn, wheat, potato, etc., have been the most used binders in briquetting (Zhang et al., 2018). They are, however, expensive and have low water resistance (Zhang et al., 2018). Another form of binders is the inorganic binders which are grossly used for their hydrophobic and strength properties (Kpalo et al., 2020a). However, they produce high ash content (Obi et al., 2022). Hence, studies have now focused on developing novel, affordable, and more sustainable binders (Muazu & Stegemann, 2017). This paper evaluated two novel binders (sweet potato peel gelatinized with locust bean solution, and locust bean pulp) alongside cassava starch.

Several studies have examined the properties of briquettes under varying process parameters. This includes Brunerová et al. (2024) where a low-pressured (<5 MPa) technology was employed in densifying four biomass residues using wastepaper pulp as a binder. The developed briquettes have densities between 179.69 and 227.53 kg/m^3 at varying mixing ratios. Magnago et al. (2020b) produced briquettes from the blends of citrus peels and rice husks using grounded Irish potato peel as a binder. The briquettes have densities between 0.35 and 0.46 g/cm^3, ash content between 3.9 % and 4.9 %, and gross calorific value between 14.6 and 17.2 MJ/kg. Yank et al. (2016) developed briquettes from rice husk and bran using three binders (cassava wastewater, rice dust, and okra stem gum). The results show that the briquettes produced with cassava starch wastewater had the highest density of 471.3 kg m^{-3}. In contrast, those made from rice dust had the highest durability of 91.9% and compressive strength of 2.54 kN. Similarly, Sunnu et al. (2021) produced and characterized charred briquettes from rice husk, maize cobs, palm kernel shells, and sawdust at variable process parameters. The briquette made with palm kernel shell with 0.60 mm particle sizes, densified at 30 MPa had the best performance with an ash content of 2.7% and relaxed density of 753 kg/m^3.

Similarly, some recent studies that explored optimization include Oladosu et al. (2023) where the optimum thermal parameters of briquettes produced from the flamboyant pod and corn cob bonded with cassava starch were determined. An optimum ignition time, boiling time, and burning rate of 185 sec, 930 sec, and 0.032 g/s, respectively, were recorded. In a different approach, Nganko et al. (2024) observed that a binder ratio, pressure and dwell time of 10%, 75 kPa, and 7.49 min are optimum for producing carbonized sawdust briquettes. For lignite powder, Guo et al. (2020) reported an optimum compression pressure, binder ratio, water, and drying time of 19.70 MPa, 0.52%, 21.61%, and 5.65 h, respectively. For briquettes made from urban wood waste and poultry litter, a 1:1 mixing ratio and 194 sec dwell time were found to be optimum, yielding HHV of 22.75 MJ/kg and a density of 1180.4 kg/m^3 (Marreiro et al., 2024). Overall, previous studies reported an optimum binder and compression pressure of <5-15% and 6.86 – 122.7 MPa for different biomass materials (Yunusa et al., 2023).

While studies have explored the production and analysis of briquettes from several biomass (Yunusa et al., 2023), there are limited studies on briquette production using uncarbonized rice husk at low pressure (≤ 5 MPa). This stems from some perceptions that rice husk is unsuitable for briquette production due to its high ash and silica content. This belief has over the years reduced the potential of this abundant resource, especially in developing countries. With this, only a few studies utilized rice husk in briquette production. These were largely employed as co-feedstock with other biomass as in the studies of Yank et al. (2016) and Magnago et al. (2020b), or in carbonized form (Lubwama & Yiga, 2018; Suryaningsih et al., 2018), or using a higher compression pressure which is generally expensive. Thus, this paper aims to develop briquettes from uncarbonized rice husk at low pressure and optimize the process and quality variables to improve its efficiency. In addition to providing the optimum conditions, another novelty of the paper is that it assessed the potential of some biomass materials as novel binders in briquette production. This will serve as a way of saving costs, thereby making it affordable and accessible to low-income households. Overall, the data obtained from this paper will guide the sustainable and efficient utilization of rice husk as an energy source.

5.2 Materials and Methods

5.2.1 Materials

A two-stage rice husk was selected as the primary feedstock while three lignocellulosic biomass materials (sweet potato peel, locust bean pulp, and husk) were selected as binding material. The selected binders were evaluated alongside cassava starch which is one of the most used binders in briquette production (Yunusa et al., 2023). The selection of sweet potato peel, locust bean pulp, and husk was based on availability within the study area, projected performance (as evident from the preliminary evaluation), and because they have not been previously used in briquette production (novelty).

The materials used are as follows:

a. ***Rice husk***: this is the major outturn after milling paddy rice. Depending on the type of milling employed (i.e., one-stage or two-stage), rice husk comes in two forms, one-stage and two-stage. The rice husk used in this study is a two-stage rice husk. This type of rice husk is obtained from two-stage milling. Two-stage milling involves the removal of the rice husk and bran separately (Dhankhar, 2014).

b. ***Sweet potato peel:*** sweet potato **(***Ipomoea batatas* L.) peel is the bark obtained after peeling off the potato. Although it has some nutritional value, it is largely considered a waste material. Sweet potato is largely available in Nigeria as it is among the major crops cultivated (Awoyale et al., 2021).

c. ***Locust bean pulp and husk:*** Locust bean pulp and husks are obtained from the fruit of the African locust bean (*Parkia biglobosa)* tree. This is a perennial tree of leguminous origin that belongs to the sub-family *mimosoideae,* and family *leguminosae* (now family *fabaceae*) (Simonyan, 2012). It is a native African tree predominant in nineteen African countries including Nigeria (Auta et al., 2015). This resource is largely available in Nigeria, especially in the Northern part of the country. A matured African locust bean tree yields more than a tone of fruits (Akande et al., 2010). In Nigeria, the seeds of the fruit are commonly processed into a local seasoning referred to as *'Dawa Dawa'*, while the pulp and husk have limited applications (Olujobi, 2012), therefore they end up as waste or as animal fodder.

A pictorial view of these materials is presented in Figure 5.3. Rice husks weighing 40 kg were obtained from a rice mill in Kaduna State, Nigeria (latitude 11˚12′1.8″ N and longitude 7˚33′23.2″ E). The binding feedstocks viz: sweet potato peel (PPL), locust bean husk (LBH), and locust bean pulp (LBP) were sourced from Samaru (latitude 11˚10′5.65824″ N and longitude 7˚39′25.88832″ E), and Sabon Gari, Zaria, Kaduna State, Nigeria (latitude 11˚6′37.1826″ N and longitude 7˚43′40.48392″ E, and latitude 11˚6′28.54044″ N and longitude 7˚43′47.84988″ E), respectively. The control binder (cassava starch) was purchased from the market.

5.2.1.1 Material preparation

The samples were screened for foreign materials and kept in medium-density polyethylene (MDPE) plastic to avoid moisture absorption. The rice husk was not dried further as it was well dried (MC = 4.8%). However, due to its recalcitrant nature resulting from its high silica and ash content, it was milled to smaller particle sizes of ≤ 2000 microns (2 mm) using a hammer mill (Model HR600, Henan, China) fitted with a 2 mm screen mesh and powered by a 5.22 kW diesel engine output. Milling the sample gives it better mixing and binding uniformity (Miao et al., 2019). Because PPL was obtained in fresh form, it was washed and sun-dried at an average temperature and relative humidity of 29 ℃ and 65% for 5 days. The temperature and relative humidity were measured using a smart sensor (Model AR837, Dongguan Wanchuang Electronic Products, China) with an accuracy of ± 1℃ for temperature measurements and ± 1% for relative humidity measurements. The dried sample was then grounded using an electric milling machine (Model 9z-23, Zhengzhou Shuliy Machinery Company, Ltd., China). LBH was also sun-dried at an average temperature and relative humidity of 29 ℃ and 65% for 2 days and milled using a hammer mill (Model HR600, Henan, China) fitted with a 2 mm screen and powered by a 5.22 kW diesel engine output. Subsequently, the milled sample was sieved through a 1mm standard sieve (Shaoxing Hengyu Instrument Company, China) to obtain particles ≤ 1mm. LBP was manually mixed to homogenize the lumps and eventually sieved through a 1mm sieve to obtain particles ≤ 1mm.

5.2.1.2 Material characterization

The feedstocks were characterized to determine the gross calorific values, volatile matter, ash content, fixed carbon, and elemental constituents like carbon, nitrogen, sulfur, hydrogen, and oxygen. The gross calorific value was determined using a Bomb Calorimeter (Model: 6100, Parr Instrument Company, USA) with a class precision of 0.1 – 0.2%, following the

method described in ASTM D5865-10a (2010). The moisture content was estimated using Equation 5.1 following the procedure described in ASTM D3173-87 (1996). Samples were heated in an oven (Model: DHG – 7090A, England) with a temperature control precision of ± 1℃.

$$MC\ (\%)\ wb = \frac{W_i - W_f}{W_i} \times 100 \qquad (5.1)$$

where MC (%) wb is moisture content (web basis), W_i is the initial weight of the sample (g) and W_f is the final weight of the sample (g)

The volatile matter was determined by heating the samples in a furnace (Model SX-5-12 Box-Resistance, Huanghua Faithful Instrument Co., LTD, China) with a maximum allowable temperature of 1200 ℃, based on the modified procedure described in ASTM D3175 (2011) for all sparking fuels. The percentage of volatile matter in each sample was estimated using Equations 5.2 and 5.3 (ASTM D3175, 2011).

$$weight\ loss\ (\%) = \frac{A - B}{A} \times 100 \qquad (5.2)$$

$$Volatile\ matter\ (\%) = C - D \qquad (5.3)$$

where C is the weight loss (%), and D is the moisture content (%).

where A is the weight of the oven-dried sample (g) and B is the weight of the sample (g) after heating in the furnace

The ash content was determined as per ASTM D3174-02 (2002) by heating in a furnace (Model SX-5-12 Box-Resistance, Huanghua Faithful Instrument Co., LTD, China) with a maximum allowable temperature of 1200 ℃, and the percentage ash content was estimated using Equation 5.3 (Mitchual et al., 2014a).

$$Ash\ content\ (\%) = {M_{ash}}\Big/{M_{oven-dry}} \times 100 \qquad (5.3)$$

where, M_{ash} is the mass of the ash (g) and $M_{oven-dry}$ is the mass of the oven-dried sample (g).

The fixed carbon (FC) was estimated by subtracting the value of moisture content, volatile matter (VM), and ash content from 100% as given in Equation 5.4 (Nganko et al., 2024).

$$\%\ FC = [100 - (\%MC + \%\ Ash + \%\ VM)] \qquad (5.4)$$

The nitrogen content was determined using the Micro-Kjeldahl method with a Micro-Kjeldahl digestion distillation apparatus. The sulfur content was determined using the aluminum block method in a Tecator (Model 40 digestor, Tecator AB, Sweden). The carbon, hydrogen, and oxygen contents were determined from the result of proximate analysis with an accuracy of ±2% using Equations 5.5 to 5.7 (TT et al., 2022).

$$Carbon\ (\%) = 0.635\text{FC} + 0.460\text{VM} - 0.095\ \text{AC} \quad (5.5)$$

$$Hydrogen\ (\%) = 0.059\text{FC} + 0.060\text{VM} + 0.010\text{AC} \quad (5.6)$$

$$Oxygen\ (\%) = 0.340\text{FC} + 0.469\text{VM} - 0.023\text{AC} \quad (5.7)$$

where FC is Fixed Carbon, AC is Ash Matter, and VM is Volatile Matter

5.2.2 Experimental design

The experiment was designed using Box Behnken Design (BBD) with three numerical factors (each set at three levels), one categorical factor, and three replicated central points. Box-Behnken Design (BBD) was selected because apart from being among the two most popular RSM designs (i.e., Central Composite Design CCD and BBD), it is flexible and easy to obtain as it does not require a test for axial points. Thus, the issue of extreme experimental boundaries is addressed. As depicted in Table 5.1, the numerical factors considered are binder content (5%, 10%, and 15%), particle size (1 mm, 1.5 mm, and 2 mm), and dwell time (0.5, 1, and 1.5 minutes). The categorical factor considered is binder type {Cassava starch (CSS), potato peel gelatinized with locust bean extract (PPL), and locust bean pulp (LBP)}. Fifteen randomized order runs were generated (Table 5.3) using the Design Expert Software (version 13, Stat-Ease Inc., MN, USA). Two responses (compressed density and impact resistance) were considered, and Response Surface Methodology (RSM) modeling was employed in optimizing the production. The experimental process flowchart is presented in Fig. 5.1.

Table 5.1. Actual and coded factors for experimental design

Factors	Code	Variation Levels		
		Low (−1)	Medium (0)	High (+1)
Binder ratio (%)	A	5	10	15
Particle size (mm)	B	1	1.5	2
Dwell time (min)	C	0.5	1	1.5
Binder Type	D	PPL	CSS	LBP

The number of experiments in three-level factorial BBD was calculated using Equation 5.8 (Kipngetich et al., 2022).

$$N = 2k(k-1) + cp \qquad (5.8)$$

where cp is the number of central points, k is the number of factors, and N is the number of experiments.

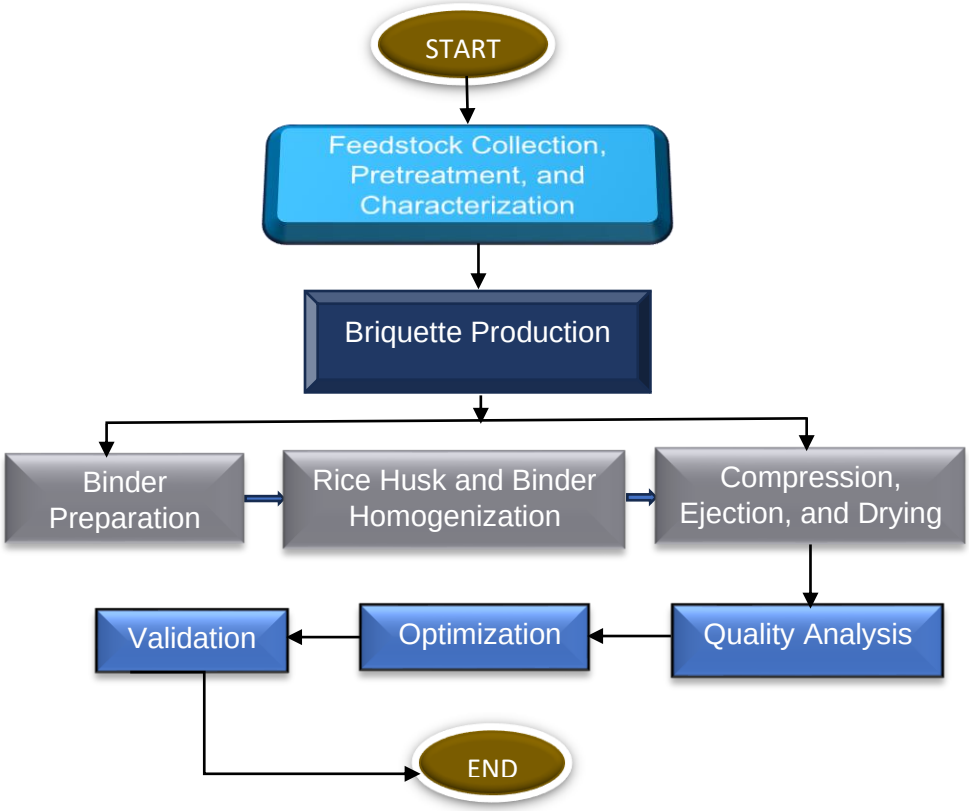

Figure 5.1. Experimental process flowchart

5.2.3 Binder preparation

a. Binder PPL

Binder PPL is a combination of potato peel and LBH solution. The binder was prepared by mixing 300 g of raw LBH with 8 liters of water at room temperature. The mixture was then boiled continuously with an electric stove until the reddish surface was observed to have turned pale yielding a reddish-brown solution. The raw potato peel was mixed with 100 ml of water at room temperature until it dissolved into a paste without clogs. The paste was then added to 500 ml of boiled water and stirred continuously for about 5 minutes to gelatinize using an electric stove.

b. Binder LBP and CSS

In preparing binder LBP and CSS, the raw samples were dissolved into a paste using 100 ml of water at room temperature. 500 ml boiled water was added to the paste and mixed continuously for 5 minutes to gelatinize appropriately.

5.2.4 Briquette production

The briquettes were produced with a low-pressure hydraulic piston press with four cylindrical molds of 8 cm diameter and height of 16 cm. The press has a total weight of 100 kg and is made of galvanized and stainless-steel metal. The rice husk was manually mixed with the binder for 10 minutes to homogenize appropriately in producing the briquettes. Because the water ratio was not considered a variable, a predetermined constant volume of 140 ml befitting to all the mixing ratios was added and mixed to improve homogenization and ease compression further. 200 g of the sample mixture was fed per mold and compressed at an average room temperature of 28 ℃ and pressure of 4.5 MPa using a 5-ton hydraulic jack. Being a four-cylinder machine, 4 briquette samples were produced per run in triplicate and were sun-dried for a week. The dried samples were kept at room temperature for 23 days to obtain a total relaxation period of 30 days before evaluation. Fig. 5.2 shows the pictorial view of the briquetting press.

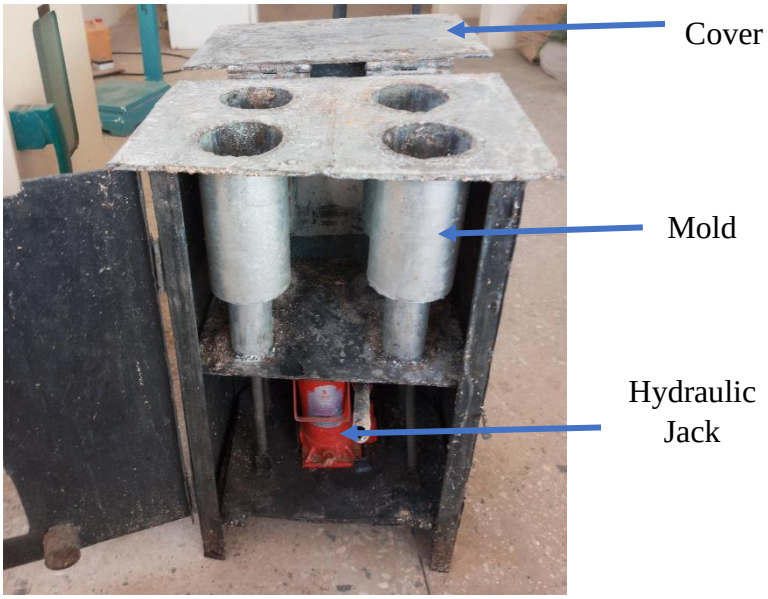

Figure 5.2. Briquette production press

Fig. 5.3 shows the pictorial view of the raw and preprocessed feedstocks, and the briquettes produced from each combination. As depicted, the primary feedstock is a stage two rice husk (Fig. 5.3a), which was milled to ≤ 2 mm (Fig. 5.3b) to improve interparticle bonding. Other feedstocks are the binding feedstocks, which include the cassava starch as received (Fig. 5.3c), LBH as received (Fig. 5.3d.), preprocessed LBH (Fig. 5.3e), PPL as received (Fig. 5.3f), preprocessed PPL (Fig. 5.3g), and LBP as received (Fig. 5.3h). While briquettes were produced from rice husks and CCS (Fig. 5.3i), PPL was combined with LBH extract to form a single binder used for producing PPL briquettes (Fig. 5.3j), and the third binder is LBP which yielded the LBP briquettes (Fig. 5.3k)

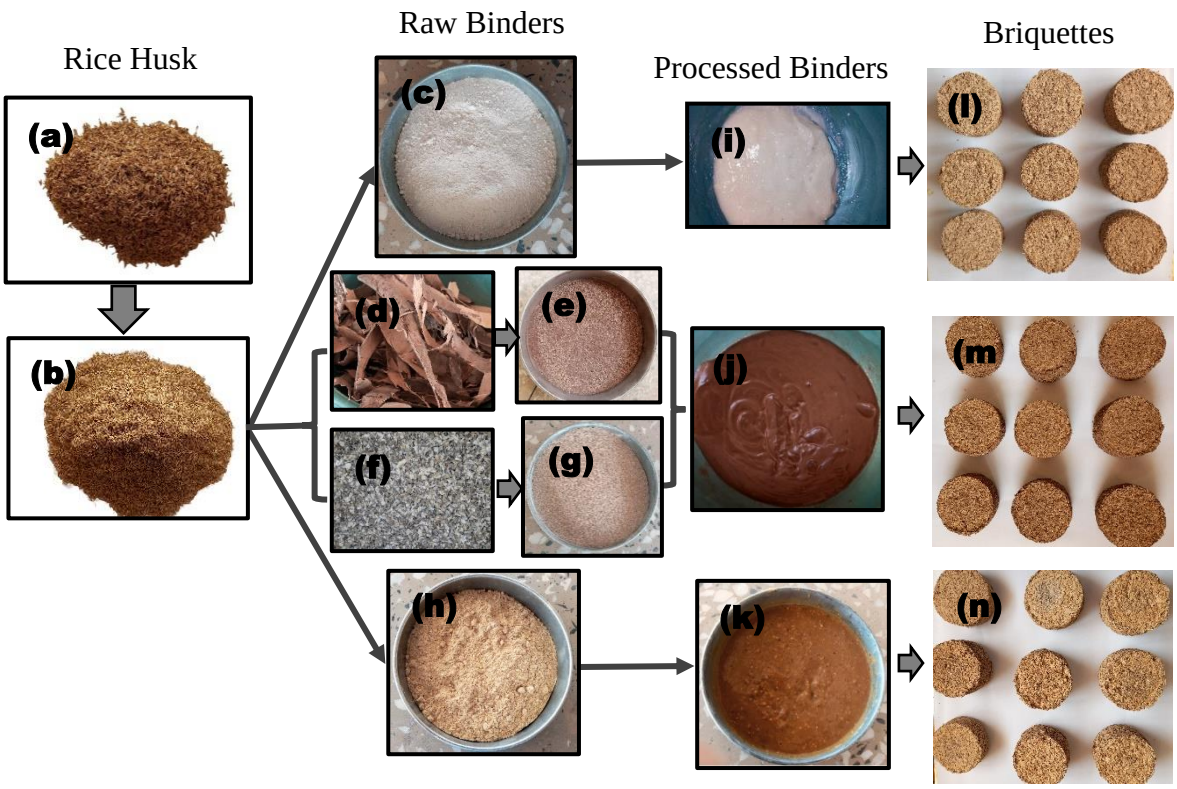

Figure 5.3. Feedstocks and developed briquettes. (a) rice husk, (b) milled rice husk, (c) raw CSS (d) raw LBH (e) raw milled LBH (f) raw PPL (g) raw milled PPL (h) raw LBP (i) CSS binder (j) PPL binder (k) LBP binder (l) CSS briquettes (m) PPL briquettes (n) LBP briquettes

5.2.5 Quality evaluation

The briquettes were tested for compressed density and impact resistance

5.2.5.1 Compressed density

The compressed density was determined following ASTM D2395-17 (2017). This is the ratio of the mass of the briquettes to the corresponding volume after ejection from the mold as given in Equation 5.9 (Gendek et al., 2018). The volume was determined by directly measuring the diameter and length in two perpendicular directions (±0.01 mm) using a digital vernier caliper and the mass (±0.1 g) was determined by weighing the samples on a digital scale balance (Model: OPH-T3001, Optima Scale, USA).

$$\rho = \frac{m}{\pi/4 \cdot d^2 l} \qquad (5.9)$$

where ρ is the density (g/cm^3), m is the mass of the briquette (g), d is the averaged diameter (cm) and l is the averaged length (cm).

5.2.5.2 Impact resistance

The briquette impact resistance test is regarded as the overall best diagnostic of briquette quality (Richards, 1990). The impact resistance test was carried out as per ASTM D440 - 86 (2002). The samples were dropped from a height of 2 m onto a steel plate. After shattering, the samples were separated based on sized proportions, and only pieces that weighed 5% or more of the initial weight of the briquette were considered in the IRI estimation (Mitchual et al., 2014b). The impact resistance index (IRI) was estimated using Equation 5.10 (Richards, 1990).

$$IRI = \frac{N}{n} \times 100 \qquad (5.10)$$

where N is the number of drops and n is the number of pieces that weighed 5% or more of the initial weight of the briquette after N drops.

5.2.6 Uncertainty analysis

Uncertainty analysis measures an instrument's error or result, the analysis judges the fitness of the values obtained and estimates the parameters' accuracy. The uncertainties from this work's known physical values were calculated using Equation 5.11 (Barik & Murugan, 2016).

$$U_r = (B_r^2 + P_r^2)^{1/2} \qquad (5.11)$$

Where U_r is the uncertainty of the parameter at a 5% significant level, B_r is the systematic uncertainty, and P_r is the random uncertainty. B_r and P_r were determined from Equations 5.12 and 5.13, respectively.

$$B_r = \left[\sum_{i=1}^{n_5} \left(\frac{1}{r}\frac{\partial r}{\partial X_i} B_i\right)^2\right]^{1/2} r \qquad (5.12)$$

$$P_r = \left[\sum_{i=1}^{n_5} \left(\frac{1}{r}\frac{\partial r}{\partial X_i} p_i\right)^2\right]^{1/2} r \qquad (5.13)$$

Where r is the parameter that depends on the variable X_i, Bi is the systematically measured error in r, and pi is the measurement-level uncertainty in r. To ensure the repeatability of the experiments, the overall experimental uncertainty (σ_k) percentage was calculated using Equation 5.14.

$$\sigma_k = [(U_{r1})^2 + (U_{r2})^2 + \cdots + (U_{rn})^2]^{1/2} \qquad (5.14)$$

5.2.7 Statistical analysis and performance optimization

The experimental data were analyzed using analysis of variance (ANOVA) in Design Expert Software (version 13, Stat-Ease Inc., MN, USA). A second-order polynomial equation (Equation 5.15) was employed to predict the response variables as a function of the independent variables and the various interactions. Response surface methodology (RSM) was used in optimizing the process parameters and response variables (Dalha et al., 2024).

$$y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j \qquad (5.15)$$

Where y denotes the response variable, $x_{,i}$ and x_j are the input variables, k is the number of factors, β_o is the intercept, β_i is the first-order model coefficient, β_{ii} is the quadratic coefficient, and β_{ij} is the linear model coefficient for the interaction between variables i and j.

5.3 Results and Discussion

5.3.1 Accuracy and Uncertainty of Instruments

The accuracies and uncertainty of the measurement instruments used in the evaluation phase are presented in Table 5.2. The values range between ±0.03% for the vernier caliper (diameter measurement) to ±2.26% for the smart sensor (relative humidity measurement). An overall uncertainty of ± 3.56 % was obtained. With an uncertainty of less than ±10%, the results obtained from the various instruments are reliable. This agrees with the findings of Barik & Murugan (2016) who obtained an overall uncertainty of ± 2.20%.

Table 5.2. Accuracy and uncertainty of instruments and parameters

Instrument	Parameter	Accuracy	Uncertainty (%)
Smart sensor	Ambient temperature	±1.0℃	±1.73
Smart sensor	Relative humidity	±1.0%	±2.26
Digital scale balance	Weight	±0.1 g	±2.13
Vernier caliper	Length	±0.01 mm	±0.09
Vernier caliper	Diameter	±0.01 mm	±0.03
Overall experimental uncertainty			**± 3.56**

5.3.2 Feedstocks characterization

The results of the feedstock analysis are presented in Table 5.3. The calorific value of rice husk is 21.78 MJ/kg, consistent with the values (14.2 -20.5 MJ/kg) reported by Asamoah et al. (2016) for rice husks/straws. The obtained value also meets the European Norm (ENplus) limit of 16.56 MJ/kg and exceeds the typical range (14.7 - 16.6 MJ/kg) reported in ISO 17225-1 (2020), showing that the rice husks have adequate energy content for use as fuel. However, it is important to state that the calorific value is reasonably high. This could be due to the very low moisture content of the rice husk (4.8%), and possibly due to the presence of additives/impurities as they are usually landfilled or kept in an open space in the source (rice mills). Because the calorific value is an estimate of the energy content present per unit mass of the sample, it is one of the most important properties in assessing the suitability of biomass as fuel (Yunusa et al., 2024). The binding feedstocks also have good calorific values between 21.26 MJ/kg for PPL and 34.48 MJ/kg for LBP. With all the feedstocks having good calorific value, it indicates that the resultant briquettes would have good energy densities (Muazu & Stegemann, 2017).

Table 5.3. Result of proximate and ultimate analysis

Sample	Moisture Content (%)	Volatile Matter (%)	Ash Content (%)	Fixed Carbon (%)	HHV (MJ/kg)	C (%)	N (%)	O (%)	H (%)	S (%)
RH	4.80	78.00	12.90	4.30	21.78	39.59	1.33	40.00	5.35	0.32
LBP	6.70	63.18	5.35	24.77	34.48	47.37	0.56	43.10	5.66	7.17
LBH	10.00	55.56	13.25	24.19	32.45	42.88	1.33	36.97	5.18	7.70
PPL	6.70	84.20	5.50	3.70	21.26	43.64	1.12	43.74	5.72	0.47
ISO 17225-1 (2020)	-	-	13.00 to 23.00	-	14.70 to 16.60	38.00 to 43.00	0.10 to 0.80	35.00 to 47.00	4.30 to 5.10	0.02 to 0.10

[b] RH = rice husk, LBP= locust bean pulp, LBH = Locust bean husk, PPL= sweet potato peel. [C] the quoted values of ISO 17225-1 are specifically for the primary biomass (rice husk)

Similarly, high values of volatile matter were recorded (62.56% – 90.9%) indicating the potential of having good ignitability and combustion efficiency (Lubwama et al., 2023). The content of volatile matter obtained agrees with the range (71.4% –88.3%) reported for food waste, sawdust, coconut shell, husk, and fiber intended for briquette production (Nikiema et al., 2022). Although the level of ash in the primary feedstock (rice husk) is above the

required limit (<4%) for briquette production (Nagarajan & Prakash, 2021), the value obtained (12.9%) conforms with the typical range of ash content in rice husks (13% – 23%) reported in ISO 17225-1 (2020). This is one major limitation in producing briquettes from rice husk (Lubwama & Yiga, 2018). The content of ash in a fuel shows its slagging potential during combustion, therefore, the lower the ash content, the lower the slagging and fouling behavior and the better the heating value (Nagarajan & Prakash, 2021). On this basis, applying thermal pretreatment techniques such as hydrothermal carbonization (Wang et al., 2020), or the use of chemical additives such as $Ca(H_2PO_4)_2$ (Wang et al., 2018), or organic additives such as guar gums (Espuelas et al., 2020), and lignin (Abedi et al., 2018) may reduce the ash level.

With carbon content between 39.59% and 47.37%, oxygen between 36.97% and 43.74%, and hydrogen between 5.18% and 5.72% it shows that the major elemental constituents needed for combustion are adequately present in the feedstocks. The contents of carbon, oxygen, hydrogen, and sulfur obtained in rice husk agree with the reported range in ISO 17225-1 (2020) (Table 5.4). Apart from the sulfur content of LBP and LBH, other minor elemental constituents (nitrogen and sulfur) are low in the feedstocks, showing lesser potential to emit nitrogen and sulfur when combusted. It is important to note that the lower the nitrogen and sulfur content, the cleaner the fuel during combustion (Mitchual et al., 2014a).

5.3.3 Experimental design inputs and responses

The experimental design input variables and responses are presented in Table 5.4. The values of compressed density (CD) range between 0.5 g/cm^3 for LBP and 0.69 g/cm^3 for PPL with close values for the three binder types, while the impact resistance ranges between 12.5 % and 100% with CSS binder having the highest. Although rice husk is a low-density (96-160 kg/m^3) biomass with low lignin reactivity (Kumar et al., 2012), densifying it into fuel briquettes improved its density significantly. The compressed density obtained is consistent with the assertion of Mitchual et al. (2013) which observed that the density of briquette made from a low-pressured hydraulic piston press is usually < 1000 kg/m^3. Similarly, the results obtained are higher than those of Anggraeni et al. (2021) for briquettes made from rice husk and sawdust blend at 0.36 MPa.

Overall, because the bulk density of rice husk is low, it must be subjected to longer dwell time and higher pressure to consolidate appropriately into higher-quality composites (Kariuki et al., 2020; Yunusa & Wakili, 2023). In addition, the durability of low-temperature and pressure briquettes is highly dependent on the binder content (Yank et al., 2016). Nonetheless, this is not always consistent when other influential interacting factors are involved. For example, Falemara et al. (2018) observed that biomass type influences the density of briquettes better than the binder content, as higher binder ratios of 20% and 25% yield lower densities. Similarly, Fadele et al. (2021) observed selected samples densified with low binder content to possess better quality than those with high binder content. Thus, the overall quality of briquettes depends on other interacting factors such as the type of biomass and binder, particle size, and compression pressure, among others.

Table 5.4. Experimental design inputs and responses

Std Run	A: BR (%)	B: PS (mm)	C: DT (min)	Responses					
				CD (g/cm^3)			IRI (%)		
				CCS	LBP	PPL	CCS	LBP	PPL
1	5	1	1	0.67	0.64	0.51	12.50	14.29	16.67
2	15	1	1	0.68	0.56	0.69	100.00	50.00	50.0
3	5	2	1	0.59	0.50	0.56	12.50	12.50	33.33
4	15	2	1	0.65	0.57	0.61	100.00	50.00	50.0
5	5	1.5	0.5	0.56	0.57	0.69	33.33	50.00	33.33
6	15	1.5	0.5	0.62	0.66	0.66	33.33	25.00	50.00
7	5	1.5	1.5	0.61	0.67	0.65	12.50	33.33	50.00
8	15	1.5	1.5	0.63	0.60	0.67	50.00	66.67	14.29
9	10	1	0.5	0.55	0.62	0.63	33.33	20.00	50.00
10	10	2	0.5	0.58	0.56	0.53	50.00	50.00	14.30
11	10	1	1.5	0.61	0.67	0.64	33.33	25.00	16.67
12	10	2	1.5	0.59	0.59	0.54	14.29	14.29	16.67
13	10	1.5	1	0.67	0.59	0.64	20.00	25.00	16.67
14	10	1.5	1	0.68	0.58	0.61	50.00	25.00	20.00
15	10	1.5	1	0.66	0.59	0.60	14.29	25.00	25.00

[c] BR = binder ratio, PS = particle size, DT = dwell time CCS = cassava starch, PPL= sweet potato peel, LBP= locust bean pulp

As depicted in Table 5.4, there is no significant difference among the compressed densities based on binder type. The density of briquettes bonded with LBP binder is lower possibly due to the binder's coarse texture even when gelatinized. However because CSS is pure starch and PPL contains a significant amount of starch, they have better gel stability and viscosity following the high content of amylose and amylopectin (Muazu & Stegemann,

2017). Thus, both surface and core layer particles are adequately bonded resulting in better density. In terms of particle size, the density was observed to be higher when the particle size was low (1mm). Similarly, Miao et al. (2019) report that smaller particle sizes yield briquettes with better quality and thermal performance.

This equally applies to impact resistance but is more evident with CSS briquettes, because contrary to the quality metrics obtained immediately after ejection from the mold as in compressed density, sometimes the briquette's morphology changes drastically after attaining the relaxed (dried) period. Although density is an essential briquette quality parameter, it does not necessarily imply better durability or strength of the briquette (Sakthivadivel & Iniyan, 2020). Thus, as shown in Fig. 5.4, there is a weak positive correlation between the compressed density and the impact resistance index. In addition, low-pressured machines are susceptible to less precision. Hence, it is sometimes difficult to establish or examine the precise influence of the process factors.

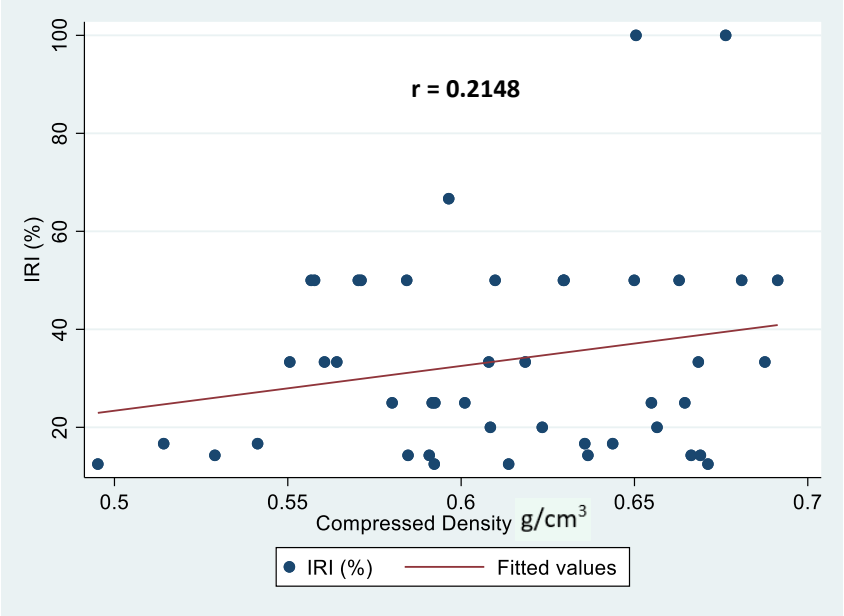

Figure 5.4. Correlation plot of impact resistance index (IRI) and compressed density

5.3.4 Analysis of variance (ANOVA) and regression model equations

Table 5.5 presents the fit statistics parameters of the response variables. The r-squared values (0.90 and 0.87) are in reasonable agreement with the adjusted r-squared values (0.80 and 0.76) as the differences between both are less than 0.2. Furthermore, adequate precision in both responses is desirable as they are greater than 4. This further depicts the adequacy of the model in navigating the design space.

Table 5.5. Response model fit summary output for compressed density and impact resistance

Indicators	R^2	Adjusted R^2	Predicted Precision
Compressed density	0.90	0.80	14.00
Impact resistance	0.87	0.76	12.50

The predicted vs actual plots of compressed density and impact resistance are shown in Fig. 5.5. The data points are closely aligned to the line depicting a strong correlation between the predicted and actual values. These further prove the fitness of the model prediction in navigating subsequent design space.

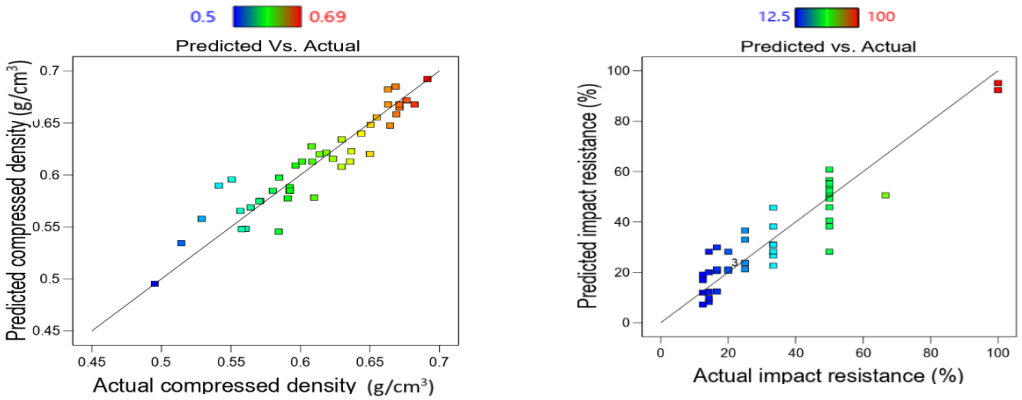

Figure 5.5. Predicted vs. actual plots of compressed density and impact resistance

Tables 5.6 and 5.7 show the results of the analysis of the variance. The results depict the model's significance level and the lack of fit relative to pure error. In both results, the models have very low p-values (< 0.0001), showing that there is only a 0.01% chance that large F-values (11.32 and 7.83) could occur due to noise. This yielded a significant model and insignificant lack of fit, proving minimal variation between the design points and their predicted values.

Table 5.6. Analysis of variance result for compressed density

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0888	16	0.0056	11.32	< 0.0001*	significant
A-Binder Ratio	0.0081	1	0.0081	16.44	0.0004*	
B-Particle Size	0.0150	1	0.0150	30.66	< 0.0001*	
C-Dwell Time	0.0049	1	0.0049	10.00	0.0038*	
D-Binder Type	0.0060	2	0.0030	6.12	0.0064*	
AB	0.0005	1	0.0005	1.09	0.3066	
AC	0.0067	1	0.0067	13.70	0.0010*	
AD	0.0076	2	0.0038	7.74	0.0022*	
B^2	0.0064	1	0.0064	12.99	0.0013*	
ABD	0.0102	2	0.0051	10.45	0.0004*	
ACD	0.0018	2	0.0009	1.80	0.1839	
C^2D	0.0204	2	0.0102	20.76	< 0.0001*	
Residual	0.0132	27	0.0005			
Lack of Fit	0.0123	21	0.0006	3.71	0.0550	not significant
Pure Error	0.0009	6	0.0002			

* Means significant at $p < 0.05$

Table 5.7. Analysis of variance result for impact resistance

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	16739.77	20	836.99	7.83	< 0.0001*	significant
A-Binder Ratio	4401.04	1	4401.04	41.19	< 0.0001*	
B-Particle Size	0.6431	1	0.6431	0.0060	0.9388	
C-Dwell Time	380.77	1	380.77	3.56	0.0712	
D-Binder Type	454.48	2	227.24	2.13	0.1411	
AB	18.45	1	18.45	0.1727	0.6814	
AD	2194.50	2	1097.25	10.27	0.0006*	
BC	138.14	1	138.14	1.29	0.2667	
A^2	2001.19	1	2001.19	18.73	0.0002*	
B^2	170.11	1	170.11	1.59	0.2191	
ACD	1730.86	2	865.43	8.10	0.0021*	
BCD	914.03	2	457.02	4.28	0.0258*	
AB^2	3069.73	1	3069.73	28.73	< 0.0001*	
B^2D	687.14	2	343.57	3.22	0.0579	
C^2D	556.22	2	278.11	2.60	0.0948	
Residual	2564.25	24	106.84			
Lack of Fit	1793.01	18	99.61	0.7749	0.6892	not significant
Pure Error	771.24	6	128.54			

* Means significant at $p < 0.05$

The regression equations of compressed density (ρ_c) and impact resistance (IRI) for the independent variables [binder ratio (A), particle size (B), dwell time (C), and binder type] are presented in Equations 5.12 and 5.13.

Compressed density

$$\rho_c = 0.6217 + 0.0216\text{A} - 0.0250\text{B} + 0.0160\text{C} + 0.037\text{D} + 0.0067\text{AB} - 0.0255\text{AC} + 0.0205\text{AD} - 0.0245B^2 - 0.032\text{ABD} + 0.0136\text{ACD} - 0.0463C^2D \quad (5.12)$$

Impact resistance

$$IRI = 24.38 + 2.23\text{A} - 0.1637\text{B} - 3.98\text{C} + 0.67\text{D} - 1.24\text{AB} + 3.35\text{AD} - 3.39\text{BC} + 13.40A^2 + 3.91B^2 - 10.97\text{ACD} + 6.78\text{BCD} + 22.62\ \text{A}B^2 + 8.61B^2\text{D} - 7.61C^2\text{D} \quad (5.13)$$

5.3.5 Response Surface Analysis

5.3.5.1 Compressed density

Figs. 5.6 and 5.7 show the 3D model graphs of the various interactions between the independent variables and compressed density. The color region in the plots indicates the change in performance from the lowest (blue) to the highest (red). In Fig. 5.6 the effect of interaction between particle size and binder ratio is shown when dwell time is held constant for 1 min. As depicted, compressed density increased steadily as particle size decreased from 2 mm to 1 mm and as binder content increased from 5% to 15% in the three briquette types. This is because as the rice husk particle size decreases, the surface area increases, which enhances the interparticle bond during homogenization and compression. Kipngetich et al. (2022) also affirmed that the density of briquettes increases as particle size decreases and that binder content influences the briquette's density. A similar observation was reported by Ndindeng et al. (2015) for briquettes made from carbonized rice husks. Although the maximum compressed density was noted at PPL briquettes, the difference between CSS and LBP briquettes in terms of the interaction between particle size and binder ratio was insignificant.

The effect of the interaction between dwell time and binder ratio on compressed density yielded a non-linear effect (Fig. 5.7). In this case, the highest compressed density in the PPL briquette was achieved when the dwell time was at the mid-level and the binder ratio was at the maximum. This could imply a good interaction between the rice husk particles and PPL during densification, thereby retaining more content internally. In addition, having a good density in PPL could be due to its combination with LBH extract which improved the binder's jelly form. However, the highest density was recorded when dwell time and binder

content were 0.5 min and 15%, respectively for the CSS briquette. Whereas a different pattern was observed for LBP. This shows that the effect of dwell time and binder content on the briquette's density differs with the type of binder. Compressed density was observed to increase in most of the briquette types as the binder ratio increased. A similar trend was reported by Sanjika & Chipula (2021) for briquettes of water hyacinth using a paper pulp binder. This is more typical in low-pressured briquetting where higher percentages of binder are required for adequate consolidation (Yunusa et al., 2023). Ajimotokan et al. (2019b) also observed that compressed density increases as particle size decreases. This indicates that dwell time positively influences compressed density when reacting with small particle sizes rather than when reacting with different binder content. However, it is important to note that the effect of dwell time on briquette quality depends on the type of biomass, binder, and the compression method.

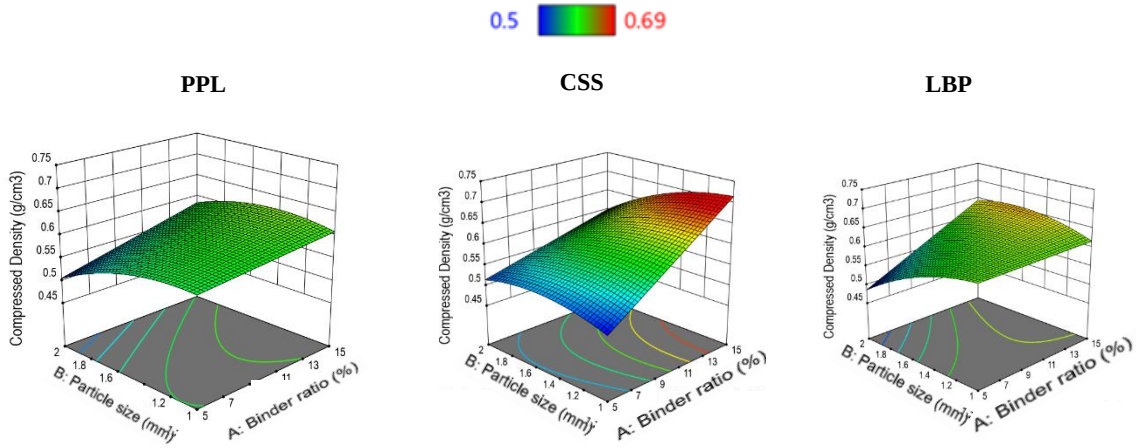

Figure 5.6. Effect of interaction between particle size and binder ratio on compressed density

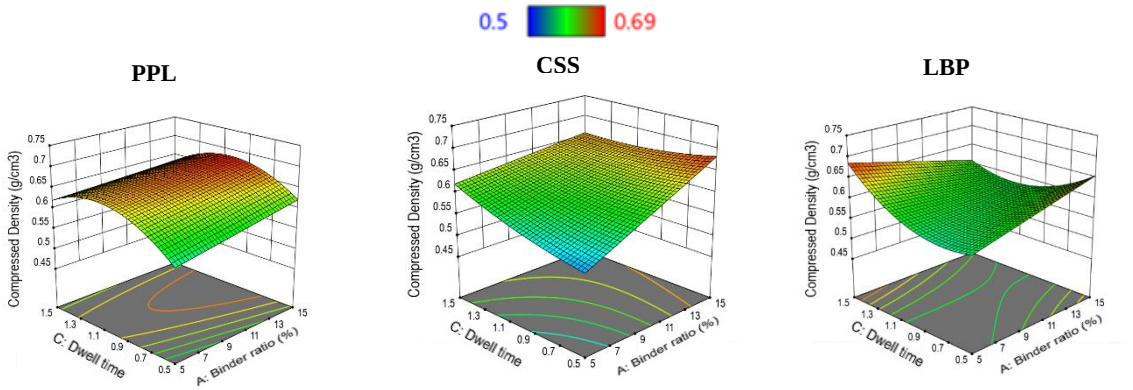

Figure 5.7. Effect of interaction between dwell time and binder ratio on compressed density

5.3.5.2 Impact resistance

The 3D model graphs of impact resistance are presented in Figs. 5.8 and 5.9. In Fig. 5.8, the impact resistance was observed to increase as the binder content increased and particle size decreased in the PPL briquette. TT et al. (2022) also observed that impact resistance increases as particle size decreases. This implies that briquettes produced with small particle sizes have better strength and durability than those produced with large particle sizes. However, in CSS and LBP briquettes, the impact resistance decreased to a certain level within the particle size region of 1.4 to 2 mm and binder ratio of 5% to 11.5% before it increased to the peak maximum between 40% and 60% at 15% binder content region. Although not clearly shown in the two-way interaction, the experimental results show that CSS briquettes presented the highest impact resistance. This could be because cassava starch binder is more viscous and effective than PPL and LBP binders, based on which both the surface and core layer particles of the briquettes remain consolidated even after drying. Similarly, cassava starch contains amylose and amylopectin which enhances the briquette's resistance to heat and shear strength (Lubwama & Yiga, 2018). Although the general trend was not consistent, the highest impact resistance was noted at the point where the binder ratio was maximum in all the briquettes. With this, it becomes more evident that briquette's density and durability are two distinct quality parameters. In Fig. 5.9, impact resistance was low between 12.5% and 40% depicting a minimal influence from the interaction between dwell time and particle size. In this vein, it shows that the strength of the briquette is more evident when the binder interacts with another parameter than when it interacts with dwell time and particle size, inferring that binders are more essential in low-pressured briquette production. Overall, in low-pressure briquette production, the quality largely depends on the quality of the binding material (Zhang et al., 2018).

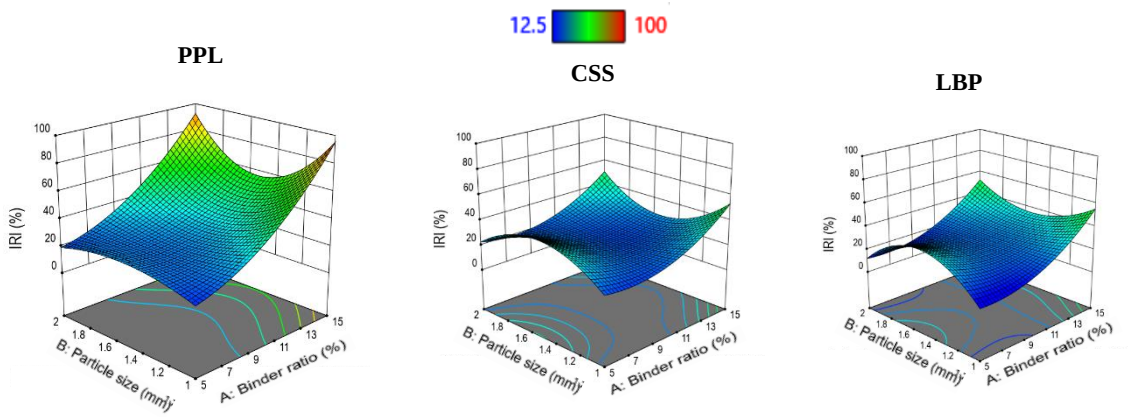

Figure 5.8. Effect of interaction between particle size and binder ratio on impact resistance

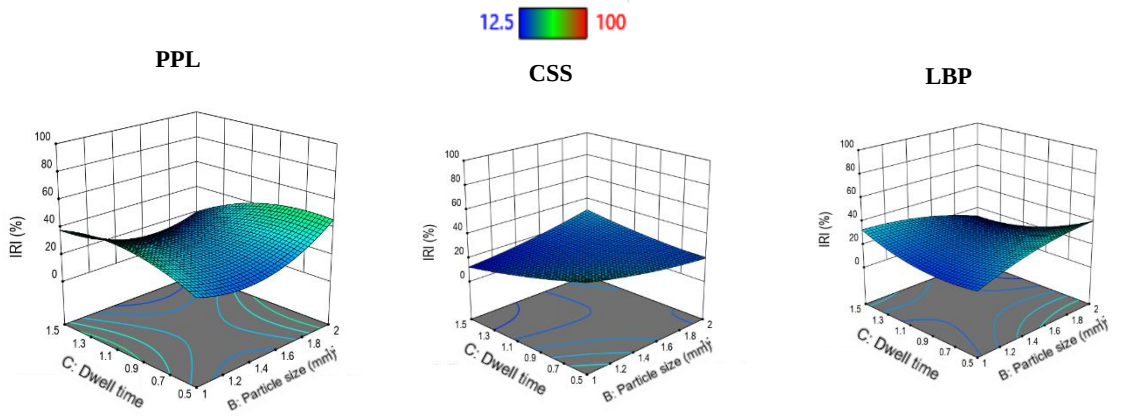

Figure 5.9. Effect of interaction between dwell time and particle size on impact resistance

5.3.6 Optimization and validation

The optimization criteria employed in this paper were targeted at maximizing the response variables while maintaining the process parameters at the design range. The optimum process parameters are a 15% binder ratio, 1 mm particle size, 0.5 min dwell time, and cassava starch binder. Fig. 5.10 shows the optimization plots of compressed density and impact resistance. The model predicted an optimal compressed density of 0.71 g/cm^3 and an impact resistance of 84.8%. The obtained values represent the ideal process conditions that will reduce capital, maintenance, and operational costs (Marreiro et al., 2024), and give the most efficient output. This is important as multiple solutions are obtained from the model. An overall desirability of 0.93 was obtained (Fig. 5.11). With desirability close to 1, it shows that the predicted values are close to the ideal value.

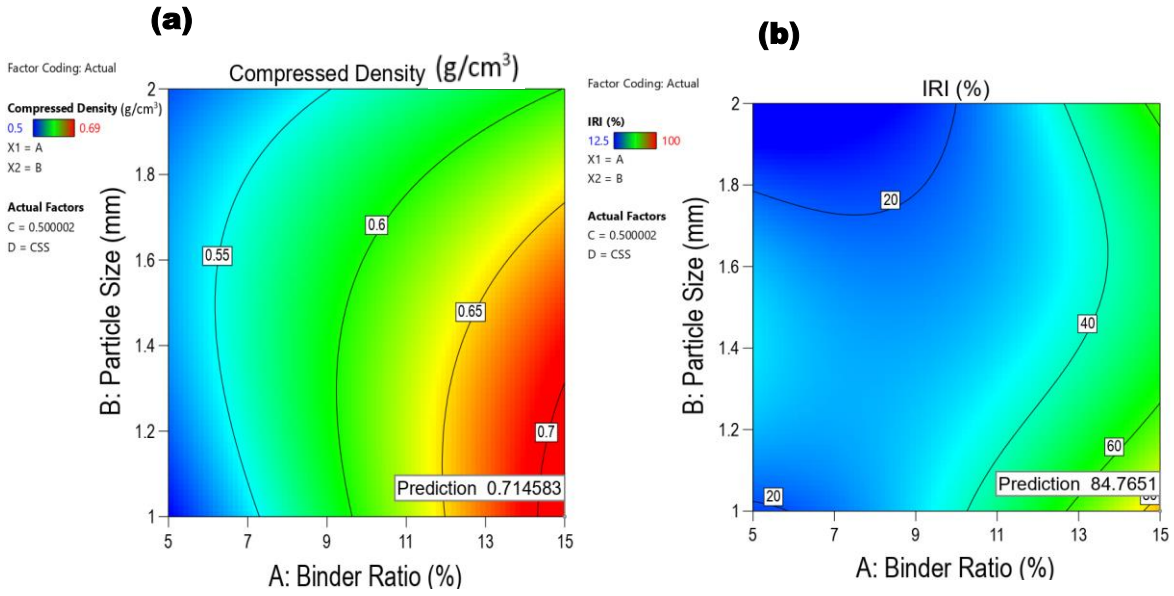

Figure 5.10. Contour plots showing the optimized points (a) compressed density (b) impact resistance

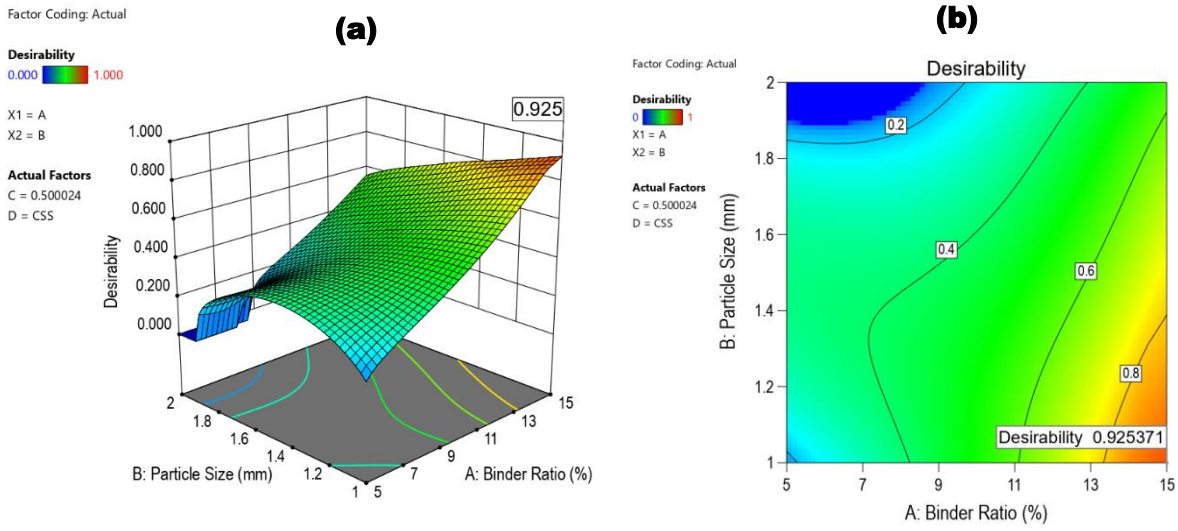

Figure 5.11. Overall desirability graph (a) 3D response surface plot (b) contour plot

A validation experiment was conducted to ascertain the veracity of the optimized parameters and responses, considering the optimal conditions obtained from the model. The average of three (3) solutions was considered for the validation (Table 5.9).

Table 5.9 shows the values obtained from the confirmatory experiment and those predicted by the model. With low percentage errors (<10%), the difference between the confirmatory experiment and the predicted responses was minimal. Thus, confirming the validity of the

optimization model. Further analysis using a t-test was employed to measure the deviation between the means (Table 5.10). With a p-value of 0.50 (>5%), it depicts that there is no significant difference between the experimented and predicted means.

Table 5.8. Experimented and predicted values

Variable	Experimental value	Predicted Value	Absolute Error (%)
Comp. Den. (g/cm^3)	0.582	0.715	
	0.699	0.714	
	0.699	0.714	
Average	*0.660*	*0.714*	*7.56*
Impact Resistance (%)	100.00	84.77	
	100.00	98.00	
	100.00	90.59	
Average	*100.00*	*91.12*	*9.7*

Table 5.9. Summary of t-test analysis

	Obs.	Mean1	Mean2	Dif.	St Err.	t value	p-value
EV - PV	2	50.33	45.92	4.42	4.47	1	0.50

5.4 Conclusion

Briquettes were developed from rice husk under low pressure (4.5 MPa) using novel biomass binders. While this was aimed at determining the optimal process conditions and quality response using RSM, it also assessed the potential of using locust bean pulp and sweet potato peel as binders in briquette production. This is essential as previous studies are focused on inorganic and starch-based binders. The paper finds that to produce briquettes with rice husks at low pressure, 15% binder, 1 mm particle size of rice husks, and 0.5 min residence time are optimum. With these optimal conditions, maximum predicted responses of 0.71 g/cm^3 compressed density and 84.8% impact resistance are achievable. The above prediction was validated experimentally and the differences between the experimented and predicted values were statistically insignificant at a 95% confidence interval. Similarly, the paper discovered that locust bean pulp and sweet potato peel can be used as binders in briquette production. However, more properties such as the starch, protein, and sugar content of the materials need to be explored.

In addition, the paper reveals that rice husk can be processed into briquettes without necessarily carbonizing or subjecting it to high pressure. This is critical for households relying heavily on fuelwood and spending a lot of time and resources sourcing or purchasing fuelwood and charcoal as it shows that a low-cost production method is feasible. Based on this, with the large quantity of rice husk generated in Nigeria, rice husk briquettes can be sustainably produced at low pressure to reduce overreliance on fuelwood and charcoal and augment the energy shortfall in the country. This would not only save costs and provide a waste management strategy but would equally mitigate climate change. Although the paper is focused primarily on improving household energy use, the optimal conditions can be scaled up and applied at an industrial scale to achieve improved quality and output capacity. In this case, a multi-criteria optimization could be employed. Industries relying on coal and wood such as the cement and rice processing industries, could switch to using high-density briquettes. Here, machines within the pressure range of 50 to 100 MPa could be employed with a low proportion of binder. The higher the pressure, the lesser the binding requirement.

Future research should explore the possibility of processing two-stage rice husk into briquettes at low to medium pressure without milling the husk. In this case, the energy expended in milling will be saved thereby reducing the cost of production. However, based on the pressure range, the ratio of binder may increase. Thus, evaluating distinctive design

criteria and parameters is pertinent. Co-densifying rice husks and charcoal dust is another aspect that could be explored to reduce the effect of silica and ash in rice husks without necessarily carbonizing the husks, thereby enhancing the quality and thermal performance of the resulting briquettes. While carbonization could improve the thermal properties, it will surely affect the cradle-to-grave life cycle. In this case, a comprehensive environmental life cycle assessment of rice husk briquette using different approaches is required to assess the impact of each process and determine the approach with the best quality and less environmental impact. Due to the nature of the briquette machine used in this paper (a constant pressure machine), the pressure level could not be varied. Thus, considering the pertinence of application pressure in briquette production, future studies could explore a broader pressure range through optimization to determine the optimum pressure for producing uncarbonized rice husk briquettes. This paper has evaluated selected biomass materials for briquette production based on the international wood pellet standard (ENplus). It has revealed new binders for briquette production and the optimum process and response level in employing the binders in producing rice husk briquettes. These findings could guide future research and developments relating to household and industrial energy use, deforestation control, climate change mitigation, waste management, and recycling. Similarly, policymakers and authorities advocating for net zero emission or carbon neutrality could find it worthwhile.

CHAPTER 6 : CHARACTERIZATION AND OPTIMIZATION OF RICE HUSK COMPOSITE BRIQUETTE MADE FROM THREE BINDER TYPES

Abstract

The processing of biomass into fuel briquettes is one of the sustainable measures widely advocated for reducing deforestation and meeting the energy needs of about 3 billion people living in energy poverty. Improving the efficiency and durability of these briquettes is essential for their effectiveness as an energy source. This paper explored rice husk briquettes' production, evaluation, and optimization using response surface methodology (RSM). The process variables considered are binder type and ratio, particle size, and dwell time, while the responses are relaxed density and compressive strength. The experiment was designed using Box Behnken Design (BBD). Briquettes were produced in a low-pressure (4.5 MPa) hydraulic piston press utilizing two novel biomass binders (locust bean pulp and sweet potato peel gelatinized with locust bean husks solution) compared to cassava starch as control. In addition to the optimized responses, the briquettes were characterized to assess the energy content, proximate, elemental constituents, and thermal and emission performances. The Fourier transform infrared spectroscopy (FTIR) test was employed to characterize the functional groups present in the briquettes. The results range from 0.196 g/cm^3 to 0.306 g/cm^3 for relaxed density and from 20 kN/m^2 to 410 kN/m^2 for compressive strength across varying process parameters. Under optimal conditions, 15% binder content, 0.5 min dwell time, and 1 mm particle size could yield briquettes with a relaxed density of 0.30 g/cm^3 and a good compressive strength. The model's predictions were validated through confirmatory experiments, with the differences between the predicted and actual values being statistically insignificant at a 95% confidence interval. These findings suggest that rice husk briquettes with an optimal quality for domestic use can be efficiently produced under low pressure, offering a viable solution for energy sustainability and environmental conservation.

Keywords: Rice husk, briquette, energy, optimization, Box Behnken Design (BBD), Response Surface Methodology (RSM)

6.1 Introduction

Energy is an imperative aspect of socioeconomic development (Balat, 2006). As a result of the population growth in most developing countries, the energy demand has outweighed the available energy resources and has persistently contributed to the rising cost of energy (Yunusa et al., 2024). With this, low-income earners find it difficult to access or afford the basic energy required for their primary needs. In contrast, the medium to high-income earners have overburdened fossil fuels and electricity, making it unsustainable. As a result, more than a third of the world's population relies on solid fuels to meet their energy needs (Schilmann et al., 2021). This has significantly increased the rate of deforestation, especially in Africa where fuelwood and charcoal use is intense (Yunusa et al., 2024). Similarly, about 3.4 million hectares of forest land are lost annually in Africa (FAO, 2010). Nigeria is among the top ten countries globally with the highest deforestation rate of 5.0 % (410,000 hectares) per annum (FAO, 2016). In the same vein, with an annual charcoal production capacity of 4,828,689.00 tons as of 2022, the country is the second-largest producer of charcoal in the world after Brazil (FAO, 2023). This highlights the country's vulnerability to continued deforestation and climate change. More alarming, is that there are no measures in place for replanting trees to account for deforested ones. Similarly, burning the fuels in open and traditional cookstoves produces toxic gases (Yunusa et al., 2023).

As part of measures to curtail deforestation and meet the energy needs of about 3 billion people living without access to clean and sustainable energy, producing energy from non-woody biomass has been largely encouraged (Park et al., 2023). This will serve as an alternative energy source and a source of income and livelihood (Saleh et al., 2020). Briquetting is one of the most advocated and practiced methods of harnessing energy from biomass (Yunusa et al., 2023). It involves densifying loosed biomass materials into a solid and more compact form. Through this process, the energy content and density of the biomass are improved, making it suitable as fuel and enhancing its storage and transportation potential. While the technology continues to diversify as a sustainable energy production method, its adoption and sustained use have been quite slow in Sub-Saharan Africa due to the high capital costs of setting up a commercial-scale production plant and its unavailability in local markets (Ndindeng et al., 2015). On this basis, small-scale or low-pressured (<5 MPa) production methods have emerged to minimize costs and save energy (Brunerová et al., 2024). With the low-pressure methods, households can now produce it themselves.

However, the low-pressure technique typically requires binders as there are no provisions for heating systems (Jekayinfa et al., 2024; Mwampamba et al., 2013). As a result, selecting the appropriate type and ratio of the binder has been one of the most challenging aspects of producing low-pressured briquettes over the years. Hence, studies on briquette production have now focused majorly on developing new and sustainable binders (Muazu & Stegemann, 2017). In this study, selected biomass materials were evaluated as potential binders in briquette production. In addition to the type of binder, choosing the appropriate feedstock is even more important. Because agricultural residues are the most abundant and easily accessible biomass, they have been the most commonly used feedstocks in briquette production (Yunusa et al., 2023).

Rice husk is one of the most abundant biomass feedstocks globally. In Nigeria, about 2.4 million tons are produced annually. However, there is still no adequate strategy in place for utilizing this mammoth biomass (Japhet et al., 2020). Typically, rice husks are burned or landfilled contributing to toxic gas emissions. With an energy content above the ENplus minimum for fuel production ($\geq$ 16.56 MJ/kg), rice husk is a good feedstock for briquette production (Yunusa et al., 2023b). Processing it into fuel briquettes improves its density and energy content, making it more compact and efficient as fuel. However, rice husk has a high ash content rich in silica (Kamari & Ghorbani, 2021), which affects its thermal efficiency during combustion. Due to these challenges, there are limited studies on rice husk briquette production. This includes but is not limited to the study of Yank et al. (2016), where rice husks and bran were co-densified using three binders (rice dust, cassava starch wastewater, and okra stem gum) at ratios ranging between 0 and 15%. The findings showed that briquettes densified with cassava starch wastewater had the highest density of 441.18 kg/m^3, while those bonded with rice dust had better durability of (91.9%) and compressive strength (2.54 kN) (Yank et al., 2016). In a different approach, rice husks were bonded with starch, tree resin, and wastepaper pulp at ratios of 1:1, 1:5, 1:6, and 1:7 under low pressure, where briquettes of tree resin were found to have the highest energy content (Lakshika et al., 2024). Rice husks were blended with citrus husks (orange, tangerine, and lemon) at varying ratios using a yellow potato peel binder, yielding briquettes of densities, ash content, and energy value of 0.35 to 0.46 g/cm^3, 3.9 to 4.9 %, and 14.6 to 17.2 MJ/kg, respectively (Magnago et al., 2020b). Suryaningsih et al. (2018) employed carbonized rice husks and 6% tapioca

starch, yielding briquettes with a calorific value of 3.126 cal/g and compressive strength of 2.02 kg/cm^2.

While this study acknowledges the shortcomings of rice husk, it focuses on its sustainability as an energy source, especially for low-income households that cannot afford or access better energy options. Following its abundance in Nigeria, it is perceived to be a sustainable feedstock for energy production. Hence, it was selected as the primary feedstock in this study. Processing rice husks into fuel briquettes would not only serve as an energy source and a waste management solution, but it would help reduce dependence on fuelwood and charcoal, thereby mitigating deforestation.

Recent studies on briquette production and process optimization include but are not limited to the study of Chukwuneke et al. (2021) where rice husk was blended with sawdust using starch and clay binder. Therein, 15% starch binder, 28% rice husk, and 9 MPa pressure were observed as optimum in achieving briquettes with an energy content of 5.69 kcal/g. Ndindeng et al. (2015) optimized the quality of briquettes made from rice husk and bran. The study noted an optimum pressure of 7.7 MPa, a dwell time of 30 sec, and a moisture content of 20%. In a different approach Ossei-Bremang et al. (2024), blended decanter cake and charred palm kernel shell using waste paper pulp and bentonite clay as binders. The study showed that to achieve an optimum density and energy content, an ideal process combination of 12.5 % binder proportion, 50 % biomass content, and 15 MPa compaction pressure is required when using cardboard pulp binder. For bentonite clay binder, a 5 % binder content, 50 % biomass content, and 12.5 MPa pressure are optimum (Ossei-Bremang et al., 2024). For the combination of wood waste and poultry litter, Marreiro et al. (2024) reported an optimum condition of 1:1 mixing ratio and 194 sec dwell time to achieve a briquette with a calorific value and density of 22.75 MJ/kg and 1180.4 kg/m^3, respectively. Guo et al. (2022) observed an optimal condition of 40 wt% of coal, 20 wt% moisture, 25 MPa compression pressure, and 12 h of drying time to achieve a maximum compressive and drop strength for briquettes made of waste coal. Oladosu et al. (2023) optimized the process parameters of producing briquettes from the flamboyant pod and corn cob using a cassava starch binder. The optimal values predicted to yield the best combustion performance are 30 wt% of the flamboyant pod, 51 wt% corn cob, and 17 wt% starch. Kipngetich et al. (2022) explored the optimal combustion parameters of carbonized rice husk briquettes. The optimal ignition time (249.08 s) and reaction thickness (102.43 mm) were achieved at 0.31 kg/m^2.s air-mass flux, 25% binder ratio, and 2.6 mm particle size, respectively. The

optimum peak bed temperature (1226.25 ℃) was recorded at 0.31 kg/m^2.s air-mass flux, 25% binder ratio, and 0.3 mm particle size. In terms of process parameters, a substantial number of literature reported optimum values between <5-15% for binder content and 6.86 – 122.7 MPa for compression pressure (Yunusa et al., 2023a).

Overall, there are limited studies on low-pressure briquette production from rice husk, as previous studies were largely focused on other forms of biomass. The few studies that explored rice husk in briquette production used it as a blend with other biomass such as the studies of Chukwuneke et al. (2021), Yank et al. (2016), and Magnago et al. (2020). Others, such as Lubwama & Yiga (2018) and Suryaningsih et al. (2018) used it in carbonized form, while some studies such as Saeed et al. (2021) employed a high-pressure which is not only energy-intensive but also expensive to set up. Although, Lakshika et al. (2024) used a low-pressure compression, a very high content of binder beyond the limit of ISO 17225-1 (2020) for briquette production (≤ 20%) was used. Similarly, studies that optimized rice husk briquette process and quality metrics are limited. Against this background, this paper aims to optimize the process condition and selected quality metrics of rice husk briquette production. In addition to employing rice husk in its uncarbonized form under low pressure, the paper's novelty lies in exploring the potential of some biomass materials as novel binders in briquette production with one of the binders prepared using the locust bean husk (LBH) extract. In addition, the study has determined the optimum process conditions for attaining the most efficient output utilizing this technology. In the same vein, quality metrics prediction models have been developed.

6.2 Materials and Methods

The flowchart followed in the study is presented in Fig. 6.1, which ranges from collecting the feedstocks to evaluating the model predictions.

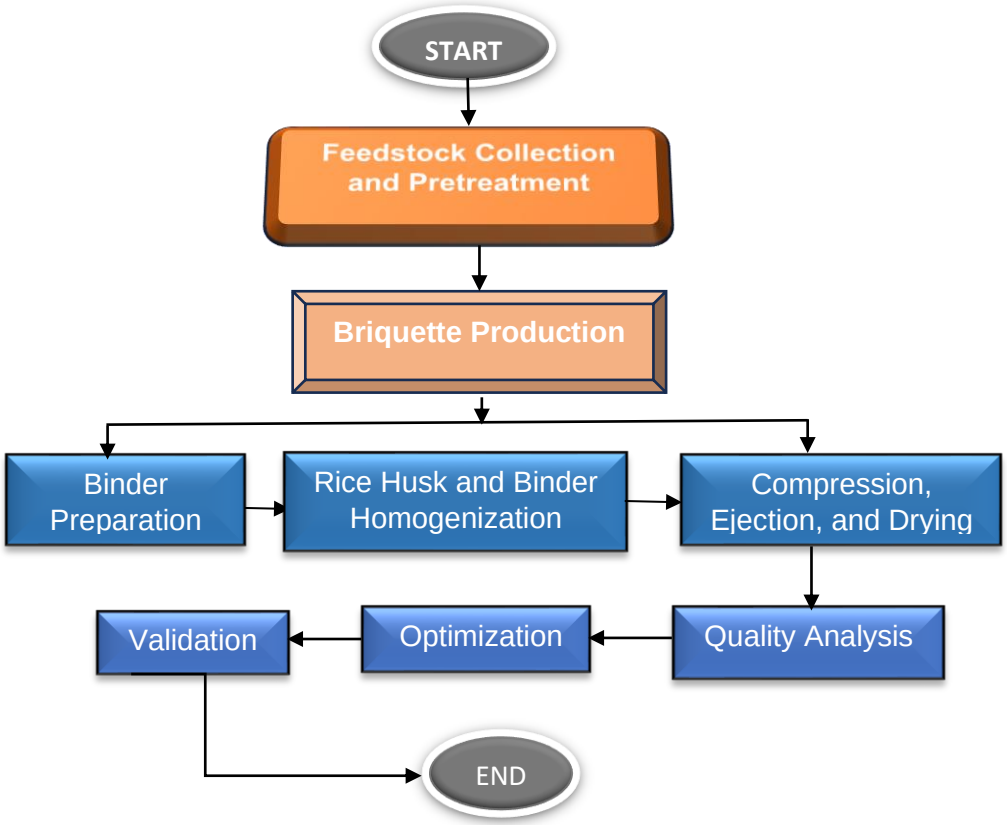

Figure 6.1. Experimental process flowchart (Yunusa et al., 2024)

6.2.1 Material preparation

The feedstocks which include rice husks and binding materials (sweet potato peel (PPL), locust bean husk (LBH), and locust bean pulp (LBP)) were sourced from Zaria, Kaduna State, Nigeria at latitude 11˚12′1.8″ N and longitude 7˚33′23.2″ E, latitude 11˚10′5.65824″ N and longitude 7˚39′25.88832″ E, and latitude 11˚6′37.1826″ N and longitude 7˚43′40.48392″ E, respectively. The control binder (cassava starch (CSS)) was purchased from the market. The binding biomass was selected based on availability, ease of handling, and part of efforts to develop new biomass binders. All feedstocks were kept in a closed container to avoid moisture absorption. The sweet potato peel was washed, sun-dried at an average temperature and relative humidity of 29 ℃ and 65% for 5 days, and ground in an

electric milling machine (Model 9z-23, Zhengzhou Shuliy Machinery Company, Ltd., China). Rice husks and sweet potato peel were milled to particle sizes of ≤ 2000 microns (2 mm) using a hammer mill (Model HR600, Henan, China) fitted with a 2 mm screen mesh. The milled sample was sieved through a 1 mm standard sieve (Shaoxing Hengyu Instrument Company, China) to obtain particles ≤ 1 mm. However, locust bean pulp was collected in a pre-processed form which does not require much processing. Thus, it was only mixed thoroughly to homogenize the lumps and then sieved through a 1 mm sieve to achieve particles ≤ 1 mm.

6.2.2 Briquette production

The production process began with binder preparation using the hot gelatinization method. The binder ratio was varied in three levels, i.e., 5%, 10%, and 15%, corresponding to 21 g, 42 g, and 64 g, respectively. The contents of the binder were maintained between 5 and 15% in compliance with the limit of ISO 17225-1 (2020), which requires that additives (binders) should not exceed 20%. The raw binder was mixed with 100 ml of water at room temperature to homogenize appropriately in each experimental trial. This was followed by adding 500 ml of boiled water and 5 minutes of manual mixing to gelatinize. The binder was then mixed with rice husks, and 140 ml of water at room temperature was added and manually mixed for about 10 minutes to homogenize appropriately. The quantity of rice husk in each run was added based on the percentage of binder in the designed ratios, i.e., 85% (360 g) rice husks to 15% binder, 90% (382 g) rice husks to 10% binder, and 95% (403 g) rice husks to 5% binder as shown in Table 6.2. 200 g of the mixture was fed into the mold of a manually operated hydraulic piston press, and densified per the residence time.

Table 6.1. Briquette production mixing ratios

S/N	Rice husk (%)	Binder (%)
1	85	15
2	90	10
3	95	5

The press consists of four cylindrical molds of 8 cm diameter and 16 cm height. The samples were compressed at room temperature and a constant pressure of 4.5 MPa using a 5-ton hydraulic jack. Four (4) samples were produced per compression and each run was replicated thrice. After ejection from the mold, the samples were sun-dried for 7 days. After drying, the samples were stored at room temperature for three weeks before evaluation. A pictorial view of the samples is shown in Figure 6.2.

Figure 6.2. Briquettes samples of (a) Locust bean pulp (LBP) binder, (b) Sweet potato peel (PPL) binder, (c) Cassava starch (CSS) binder

6.2.3 Experimental design

Box Behnken Design (BBD) was employed in designing the experiment, using three numerical factors, one categorical factor, and three replicated central points. The actual and coded factors are presented in Table 6.3. Fifteen (15) experimental runs were generated for each binder type using Design Expert 13. Two responses, relaxed density, and compressive strength were considered. Response Surface Methodology (RSM) modeling was employed to optimize the production.

Table 6.2. Actual and coded factors for experimental design

Factors	Code	Variation Levels		
		Low (-1)	Medium (0)	High (+1)
Binder ratio (%)	A	5	10	15
Particle size (mm)	B	1	1.5	2
Dwell time (min)	C	0.5	1	1.5
Binder Type	D	PPL	CSS	LBP

The number of experiments in three-level factorial design was estimated using Equation 6.1 (Kipngetich et al., 2022).

$$N = 2k(k-1) + cp \qquad (6.1)$$

where N is the number of experiments, cp is the number of central points, and k is the number of factors.

6.2.4 Briquette evaluation

6.2.4.1 Calorific value, proximate and ultimate analysis

The gross calorific value of the briquette was determined as per the method described in ASTM D5865-10a (2010), using a Bomb Calorimeter (Model: 6100, Parr Instrument Company, USA). The moisture content was determined following the method described in ASTM D3173-87 (1996) and it was estimated using Equation 6.2.

$$MC\ (\%)\ wb = \frac{W_i - W_f}{W_i} \times 100 \qquad (6.2)$$

where MC (%) wb is moisture content (web basis), W_i is the initial weight of the sample (g) and W_f is the final weight of the sample (g)

The volatile matter was determined based on the modified procedure described in ASTM D3175 (2011) for all sparking fuels and the percentage of the volatile matter was estimated as the difference between the percentage weight loss and moisture content as given in Equations 6.3 and 6.4 (ASTM D3175, 2011).

$$weight\ loss\ (\%) = \frac{A-B}{A} \times 100 \qquad (6.3)$$

$$Volatile\ matter\ (\%) = C - D \qquad (6.4)$$

where C is the weight loss (%), and D is the moisture content (%).

where A is the weight of the oven-dried sample (g) and B is the weight of the sample (g) after heating in the furnace

The ash content was determined following the procedure described in ASTM D3174-02 (2002), and the percentage of ash was estimated using Equation 6.5 (Mitchual et al., 2014a).

$$Ash\ content\ (\%) = {M_{ash}}/{M_{oven-dry}} \times 100 \qquad (6.5)$$

where, M_{ash} is the mass of the ash (g) and $M_{oven-dry}$ is the mass of the oven-dried sample (g).

The fixed carbon (FC) was determined using Equation 6.7 (Nganko et al., 2024).

$$\%\ FC = [100 - (\%MC + \%\ Ash + \%\ VM)] \qquad (6.6)$$

The carbon, hydrogen, and oxygen contents were determined from the result of proximate analysis with an accuracy of ±2% using Equations 6.7 to 6.9 (TT et al., 2022).

$$Carbon\ (\%) = 0.635\text{FC} + 0.460\text{VM} - 0.095\ \text{AC} \qquad (6.7)$$

$$Hydrogen\ (\%) = 0.059\text{FC} + 0.060\text{VM} + 0.010\text{AC} \qquad (6.8)$$

$$Oxygen\ (\%) = 0.340\text{FC} + 0.469\text{VM} - 0.023\text{AC} \qquad (6.9)$$

where FC is Fixed Carbon, AC is Ash Matter, and VM is Volatile Matter

6.2.4.2 Relaxed density

The relaxed density of the briquettes was determined 30 days after ejection from the mold (Kpalo et al., 2020b), by measuring the mass and volume following the method described in ISO 3131 (1975). The mass was determined by weighing the samples on a digital weighing balance (Model: OPH-T3001, Optima Scale, USA) with an accuracy of ± 0.1 g, and the volume was obtained by measuring the length and diameter in two perpendicular directions using a digital vernier caliper with an accuracy of ± 0.01 mm. Thus, the density was estimated as the ratio of the mass per unit volume as given in Equation 6.10 (Gendek et al., 2018).

$$\rho = \frac{m}{\pi/4 \cdot d^2 l} \qquad (6.10)$$

where ρ is the density (g/cm^3), m is the mass of the briquette (g), d is the averaged diameter (cm) and l is the averaged length (cm)

6.2.4.3 Compressive strength

The compressive strength is the maximum crushing force that briquettes can withstand before failure (Marreiro et al., 2021). This was determined using a universal test machine (SM1000-TecQuipment Ltd., Nottingham, UK) with a load cell capacity of 100 kN and a force measurement accuracy of ± 0.5% following the method described in ASTM D2166 (2006). Each sample briquette was placed between the plates as shown in Fig. 6.3 and subjected to uniform loading until failure. The peak load and nominal stress were automatically recorded every 0.5 seconds, with the maximum considered as the compressive strength.

Figure 6.3. Determination of compressive strength of a briquette sample using the universal test machine

6.2.4.4 Thermal and Emission Analysis

a. Thermal analysis

To simulate the thermal performance of the briquettes, laboratory analysis was conducted using the standard water boiling test (WBT) version 4.2.3 (PCIA & GACC, 2013). The parameters determined are the time taken to boil, burning rate, and specific fuel consumption. The experimental layout is presented in Table 6.3.

Table 6.3 Experimental layout for combustion analysis

Sample	Sample ID	Binder Ratio (%)	Particle size (mm)	Dwell Time (sec)
CSS	CSS1	5	1.5	30
	CSS2	10	1.5	30
	CSS3	15	1.5	30
LBP	LBP1	5	1.5	30
	LBP2	10	1.5	30
	LBP3	15	1.5	30
PPL	PPL1	5	1.5	30
	PPL2	10	1.5	30
	PPL3	15	1.5	30

The test was conducted in a laboratory with an average temperature and relative humidity of 33.9 ℃ and 32 %, respectively. It was carried out at a hot-start high-power phase with 150 g of each sample used in boiling 500 ml of water using an improved biomass cookstove. It commenced by determining the local boiling temperature (88 ℃). A Camry digital scale balance (model: EK5350, China) with an accuracy of 1g was used in weight measurements. A Smart Sensor (model: AR837, Hong Kong) was used to determine the temperature and relative humidity of the laboratory. A mercury-in-glass thermometer was employed to monitor the temperature rise to boiling. An infrared thermometer was used to verify the readings from the glass thermometer, especially before steaming. While the time taken to boil was recorded using a stopwatch, the burning rate, and specific fuel consumption were estimated using Equations 6.11 and 6.12 (PCIA & GACC, 2013).

$$r_{cb} = \frac{f_{cd}}{\Delta t_c} \qquad (6.11)$$

Where, r_{cb} = burning rate (g/min), f_{cd} = equivalent dry fuel consumed (g), Δt_c = time to the test (min)

$$SFC = \frac{f_{cd}}{W_{cr}} \qquad (6.12)$$

Where, SFC = specific fuel consumption (g/lit), W_{cr} = effective mass of water boiled (lit)

b. Emission analysis

The emission of gases was determined using an emission analyzer (model: NHA-506EN, Nanhua Instruments Co. LTD). Each sample was ignited in the cookstove and allowed for about 5 minutes, for the flame to be established. The cookstove was covered with a duct comprising a central gas outlet. The emission analyzer was warmed up for 10 minutes, and the probe was inserted into the chamber via the outlet and allowed for about a minute until the readings were observed to have reached their maximum. The gases considered are CO_2, CO, HC (n-hexane), and NO.

6.2.4.5 Fourier transform infrared spectroscopy (FTIR) analysis

Fourier transform infrared spectroscopy (FTIR) was conducted to identify the functional groups in the samples (Harussani et al., 2021). It is an analytical method of determining the briquette's organic structure (Akam et al., 2024). Through this, the bonding mechanism within the briquettes is known (Adeleke et al., 2021). The analysis was done with a Cary 630 spectrometer (Agilent Technologies Inc. USA). The spectra for each sample were collected in the range of 650 – 4000 cm^{-1} with a resolution of 8 cm^{-1}, sample scans of 32, and background scans of 16.

6.2.5 Statistical analysis and response equation

The data were analyzed statistically using analysis of variance (ANOVA) in Design Expert 13 (Stat-Ease Inc., MN, USA). The responses as a function of the independent variables were predicted using a second-order polynomial equation (Equation 6.13). Response surface methodology (RSM) was used to optimize the process parameters and responses.

$$y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j \qquad (6.13)$$

Where y represents the response variable (relaxed density and compressive strength), $x_{,i}$ and x_j are the input variables, k is the number of factors, β_o is the intercept, β_i is the first-order model coefficient, β_{ii} is the quadratic coefficient, and β_{ij} is the linear model coefficient for the interaction between variables i and j.

6.3 Results and Discussion

6.3.1 Calorific value, proximate, and ultimate analysis

6.3.1.1 Calorific value

The results of the calorific value are presented in Fig. 6.4. The calorific value shows the estimated energy content per unit mass of the briquette. The values range between 13.54 to 18.74 MJ/kg, with the CSS briquettes having the highest calorific value. The calorific values are in agreement with the values (9.5 - 16.6 MJ/kg) obtained by Lubwama & Yiga (2018) for briquettes developed from rice husk using cassava starch and clay binders and also conforms with the findings (9.66 -19.23 MJ/kg) of Ndindeng et al. (2015) for briquettes made from the blend of rice husk and bran. The values obtained for CSS and PPL also conform with the European Norm (ENplus) limit of 16.56 MJ/kg and meet the limit (14.5 MJ/kg) reported in ISO 17225-7 (2021). This shows that the briquettes have adequate energy densities (Muazu & Stegemann, 2017).

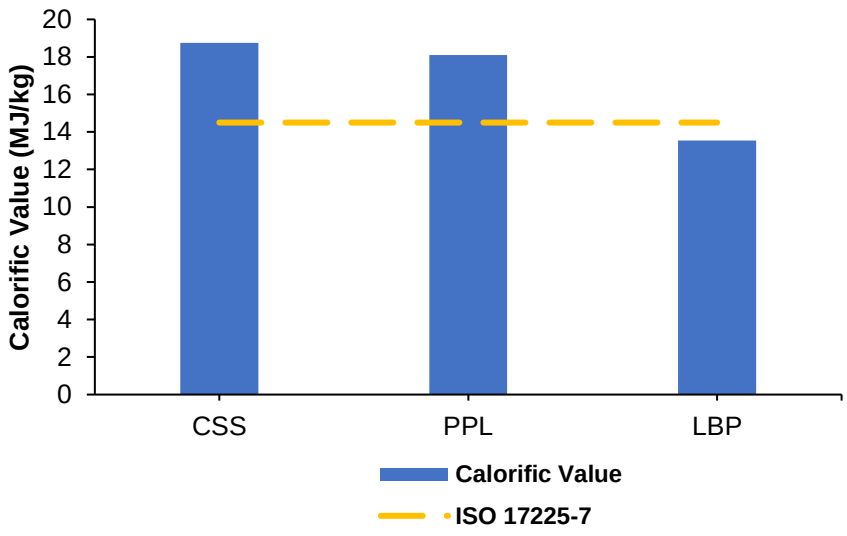

Figure 6.4. Calorific value

6.3.1.2 Proximate and Elemental Constituents

The results of the briquette's proximate and elemental constituents are presented in Table 6.4. The content of volatile matter ranges between 79.65% to 82.40%, consistent with the values (76.36% –89.18%) reported for briquettes made from rice husk using paper pulp, starch, and tree resin binders (Lakshika et al., 2024). High volatile matter content as obtained

in this study indicates good ignitability and combustion efficiency (Lubwama et al., 2023). The ash content is between 13.33% and 16.50%, with LBP having the highest content. This agrees with the findings of Lakshika et al. (2024) (7.11% – 16.20%), and lower than the values (17.64% to 68.8%) reported by Ndindeng et al. (2015) for briquettes produced from rice milling by-products. Overall, the ash content of uncarbonized rice husk briquette is usually high because rice husk is a recalcitrant biomass with a very high content between 13% and 23% as reported in ISO 17225-1 (2020). With a carbon content between 37.52% and 39.35%, oxygen between 38.29% and 39.79%, and hydrogen between 5.17% and 5.33%, the major elemental constituents needed for combustion are adequately present in the briquette. The content of carbon, oxygen, and hydrogen are in agreement with the reported range in Lakshika et al. (2024), and are relatively lower than the values reported in Chou et al. (2009).

Table 6.4. Proximate and major elemental constituents of the briquettes

	MC (%)	**Ash (%)**	**VM (%)**	**FC (%)**	**C (%)**	**H (%)**	**O (%)**
PPL	6.10	13.33	82.40	4.27	39.35	5.33	39.79
LBP	4.85	16.50	79.65	3.85	37.52	5.17	38.29
CSS	6.00	15.00	82.00	3.00	38.20	5.25	39.13

**Note:* PPL = Sweet potato peel briquette, LBP = Locust bean pulp briquette, CCS = cassava starch briquette

6.3.2 Analysis of variance, model diagnostics, and equations

The analysis of variance (ANOVA) results is presented in Tables 6.5 and 6.6. The results depict the model's significance and the lack of fit relative to pure error. For both responses, the model has very low p-values < 0.0001 (<0.05), indicating that there is only a 0.01% chance that large F-values (7.37 and 7.72) could occur due to noise. Additionally, the large p-values for the lack of fit (> 0.05) indicate that the model is significant and the lack of fit is insignificant.

Table 6.5. Analysis of variance result for relaxed density

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0150	17	0.0009	7.37	< 0.0001*	significant
A-Binder Ratio	0.0035	1	0.0035	28.80	< 0.0001*	
B-Particle Size	0.0039	1	0.0039	32.89	< 0.0001*	
C-Dwell Time	0.0001	1	0.0001	0.6105	0.4422	
D-Binder Type	0.0001	2	0.0000	0.2347	0.7926	
AB	0.0009	1	0.0009	7.90	0.0097*	
AC	0.0003	1	0.0003	2.60	0.1202	
AD	0.0007	2	0.0003	2.85	0.0772	
BC	0.0000	1	0.0000	0.1100	0.7431	
BD	0.0012	2	0.0006	4.98	0.0155*	
CD	0.0008	2	0.0004	3.36	0.0515	
A^2	5.324E-06	1	5.324E-06	0.0444	0.8349	
B^2	0.0022	1	0.0022	17.96	0.0003*	
C^2	0.0001	1	0.0001	0.6330	0.4341	
Residual	0.0029	24	0.0001			
Lack of Fit	0.0015	18	0.0001	0.3498	0.9610	not significant
Pure Error	0.0014	6	0.0002			

* Means significant at $p < 0.05$

Table 6.6. Analysis of variance result for compressive strength

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.1270	16	0.0079	7.72	< 0.0001*	significant
A-Binder Ratio	0.0284	1	0.0284	27.63	< 0.0001*	
B-Particle Size	0.0079	1	0.0079	7.65	0.0101*	
C-Dwell Time	0.0001	1	0.0001	0.0999	0.7543	
D-Binder Type	0.0462	2	0.0231	22.47	< 0.0001*	
AB	0.0001	1	0.0001	0.1067	0.7464	
AC	0.0002	1	0.0002	0.2317	0.6341	
AD	0.0091	2	0.0045	4.41	0.0220*	
BC	0.0019	1	0.0019	1.85	0.1856	
BD	0.0105	2	0.0053	5.13	0.0130*	
A^2	0.0121	1	0.0121	11.76	0.0020*	
B^2	0.0044	1	0.0044	4.28	0.0483*	
C^2	0.0003	1	0.0003	0.3342	0.5680	
A^2C	0.0050	1	0.0050	4.88	0.0359*	
Residual	0.0277	27	0.0010			
Lack of Fit	0.0257	21	0.0012	3.65	0.0571	not significant
Pure Error	0.0020	6	0.0003			

* Means significant at $p < 0.05$

Although the ANOVA results showed that the model used is statistically significant with an insignificant lack of fit, a transformation was recommended for compressive strength to improve the model's fitness and predictive capacity. As presented in the Box-Cox plot (Figure 6.5), the model recommended an inverse square root transformation. Hence, after

applying the transformation, the lambda value eventually changed to -5 from an initial value of 1 indicating a significant improvement in the model fitness.

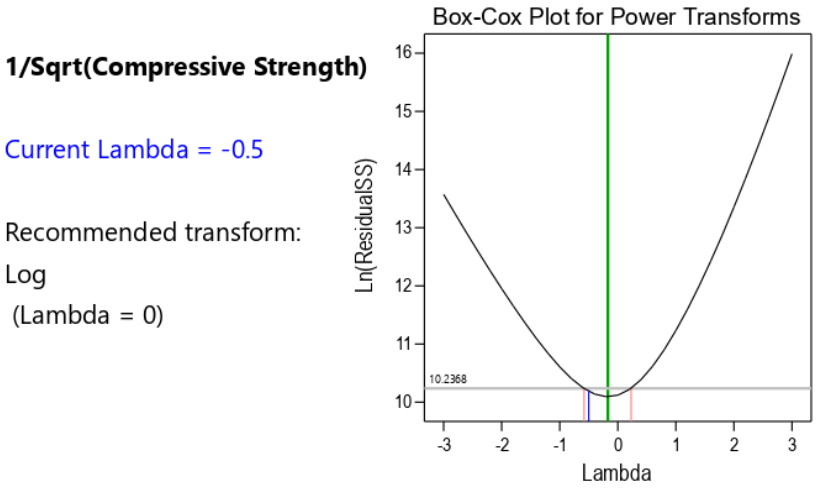

Figure 6.5. Box-cox plot for power transforms of compressive strength after transformation

Additional fit statistics parameters are presented in Table 6.7. Therein, the obtained r-squared values (0.84 and 0.82) are in reasonable agreement with the adjusted r-squared values (0.73 and 0.71) as the differences between both are less than 0.2. Furthermore, the values of adequate precision for all the responses are desirable, as they are all greater than 4, indicating the model's adequacy in navigating the design space.

Table 6.7. Response model fit summary output for relaxed density and compressive strength.

Indicators	R^2	Adjusted R^2	Predicted Precision
Relaxed density	0.84	0.73	9.63
Compressive strength	0.82	0.71	9.56

Based on the aforementioned, it means that there is little variation between the design or actual points and their predicted values (Fig. 6.6).

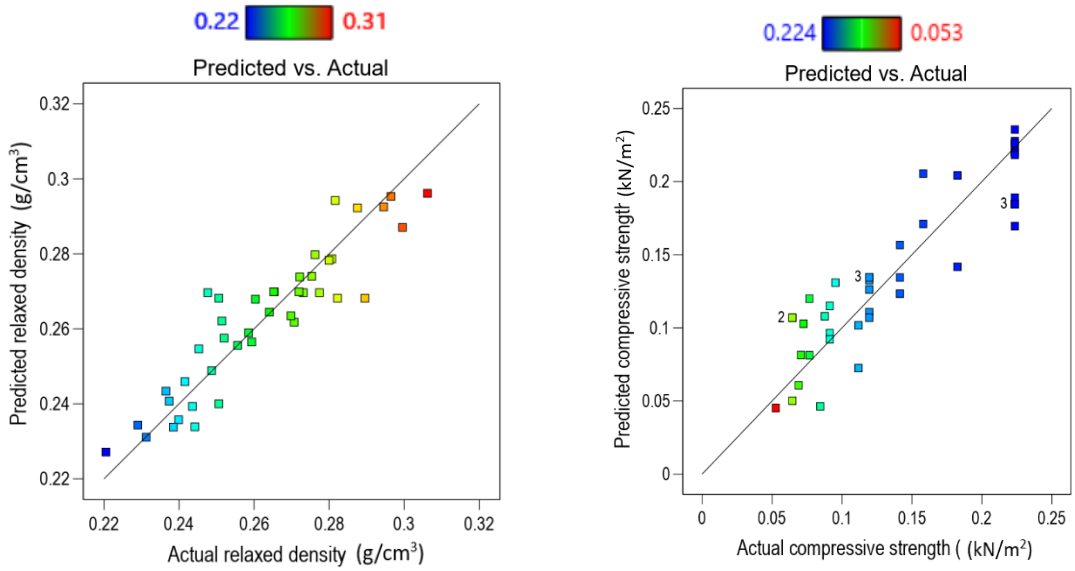

Figure 6.6. Predicted vs. actual plots of relaxed density and compressive strength

6.3.2.1 Model equations

The regression equations of relaxed density (ρ_r) and compressive strength (CS) for the independent variables [binder ratio (A), particle size (B), dwell time (C), and binder type] are presented in Equations 6.14 and 6.15, respectively.

a. Relaxed Density

$$\rho_r = 0.2692 + 0.0134\text{A} - 0.0146\text{B} - 0.0014\text{C} - 0.0007\text{D} - 0.0096\text{AB} - 0.0055\text{AC} + 0.0006\text{AD} + 0.0011\text{BC} + 0.0108\text{BD} + 0.0012\text{CD} + 0.0007A^2 - 0.0147B^2 + 0.0028C^2 \quad (6.14)$$

b. Compressive Strength

$$\frac{1}{\sqrt{CS}} = 0.1420 - 0.0353\text{A} + 0.0181\text{B} - 0.0157\text{C} + 0.0074\text{D} - 0.0030\text{AB} + 0.0067\text{AC} + 0.0063\text{AD} - 0.0126\text{BC} - 0.0192\text{BD} - 0.0325A^2 + 0.0203B^2 + 0.0057C^2 + 0.0299A^2C \quad (6.15)$$

6.3.3 Experimental design variables and quality parameters

The experimental design variables and responses are presented in Table 6.8. Each binder type was varied in fifteen (15) different experiments based on BBD. The response variables (relaxed density and compressive strength) were evaluated. The experimental data obtained were used in further modeling stages to determine the predicted values and optimal input and response variables. The values obtained range from 0.20 to 0.31 g/cm^3 for relaxed density and from 20 to 410 kN/m^2 for compressive strength, across varying process parameters (particle size, dwell time, binder type, and ratio). The findings are in agreement with those of Ajimotokan et al. (2019) for briquettes made from rice husks and corncob under low pressure where a relaxed density between 0.42 and 0.78 g/cm^3, and a compressive strength between 39 kN/m^2 and 111 kN/m^2 were recorded. Similarly, the compressive strength meets the minimum standard of 350 kN/m^2 required for briquettes intended for domestic application (Richards, 1990)

Table 6.8. Quality parameters as a function of input design variables

Std Run	A: BR (%)	B: PS (mm)	C: DT (min)	Responses					
				ρ_r (g/cm^3)			CS (kN/m^2)		
				CSS	LBP	PPL	CSS	LBP	PPL
1	5	1	1	0.24	0.26	0.24	20.00	50.00	80.00
2	15	1	1	0.31	0.26	0.28	110.00	140.00	210.00
3	5	2	1	0.23	0.22	0.25	20.00	30.00	50.00
4	15	2	1	0.26	0.24	0.24	190.00	120.00	70.00
5	5	1.5	0.5	0.25	0.25	0.26	40.00	30.00	200.00
6	15	1.5	0.5	0.29	0.28	0.30	170.00	360.00	240.00
7	5	1.5	1.5	0.20	0.27	0.27	20.00	50.00	120.00
8	15	1.5	1.5	0.30	0.28	0.26	50.00	410.00	120.00
9	10	1	0.5	0.25	0.30	0.28	20.00	70.00	130.00
10	10	2	0.5	0.24	0.24	0.22	20.00	20.00	20.00
11	10	1	1.5	0.27	0.28	0.25	20.00	170.00	80.00
12	10	2	1.5	0.26	0.23	0.24	40.00	20.00	70.00
13	10	1.5	1	0.27	0.27	0.25	20.00	70.00	70.00
14	10	1.5	1	0.25	0.27	0.28	20.00	70.00	240.00
15	10	1.5	1	0.28	0.27	0.29	20.00	70.00	240.00

* BR = binder ratio, PS = particle size, DT = dwell time CSS = cassava starch, PPL= sweet potato peel, LBP= locust bean pulp

6.3.3.1 Relaxed density

The results of the relaxed density are presented in Fig. 6.6. Although there was no significant difference between the three briquette types, CSS-bonded briquettes had the highest relaxed density. The obtained values are within the range of values previously reported for low-pressured briquettes (Kpalo et al., 2020b; Magnago et al., 2020b; Yank et al., 2016). These values are relatively low because rice husk is low-density biomass (96-160 kg/m^3) (Kumar et al., 2012), with low lignin reactivity. Therefore, rice husks require a longer densification period to consolidate properly into composites (Kariuki et al., 2020; Yunusa & Wakili, 2023). Additionally, the compression method employed in this study is a low-pressure (< 5MPa) type. Moreover, the density of briquettes produced with a hydraulic piston press is usually < 1000 kg/m^3 (Mitchual et al., 2013). This indicates that in addition to the type of feedstock and densification pressure, the type of machine or briquette press used also influences the quality performance.

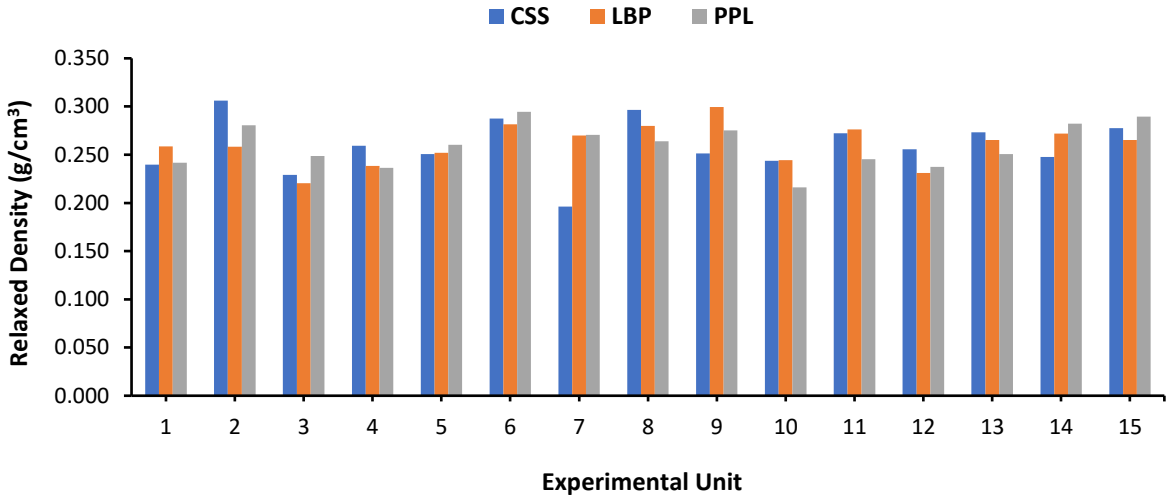

Figure 6.7. Experimental result of relaxed density

6.3.3.2 Compressive strength

The compressive strength test results are shown in Fig. 6.7. The highest compressive strength was obtained in LBP-bonded briquettes at 15% binder, 1.5 mm particle size, and 1.5 minutes dwell time. This was followed by briquettes made from the combination of 15% LBP binder, 1.5 mm particle size, and 0.5 min dwell time. This shows that the ratio of binder is instrumental in obtaining compressive strength. Thus, the higher the binder ratio, the better the compressive strength (Afra et al., 2021). However, this assertion may vary

depending on other interacting process factors such as the blend of feedstocks used (Ajimotokan et al., 2019a), material type, particle size, and compaction pressure (Ajimotokan et al., 2019a). The compressive strength values of LBP briquettes were significantly higher than those of PPL and CSS binders, indicating that the LBP binder could potentially perform better than CSS. Moreover, this superior performance of LBP may be attributed to its good textural density in raw and gelatinized forms, allowing it to be retained in the core layers even after densification and drying. However, the performance was not consistent throughout the experiments, as briquettes made with PPL also showed higher compressive strength in several runs. This inconsistency could be due to the low precision in manual densification making it difficult to accurately determine the influence of all the interacting factors.

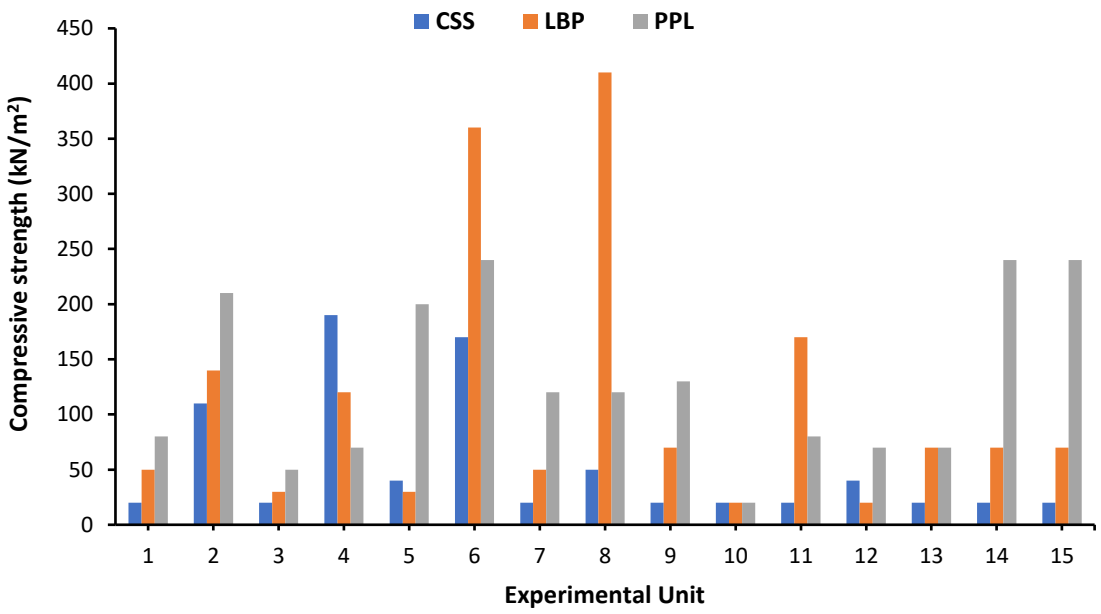

Figure 6.8. Experimental result of compressive strength

Though CSS-bonded briquettes exhibited better-relaxed density, their compressive strength was below that of LBP and PPL in most runs. This shows that relaxed density does not translate to the total strength of the briquette, as it mainly concerns the sample's mass per unit volume, not the interparticle bond and core layer strength. Magnago et al. (2020) also observed that the density of briquettes made from rice husks and citrus peel does not consistently change with compressive strength. Similarly, in the study of Yank et al. (2016), it was observed that the briquette of rice husks and bran with the greatest density does not

yield the highest compressive strength. Thus, compressive strength simulates the durability of the briquettes, indicating the total load a briquette can withstand during handling and storage (Obi et al., 2022). While the density of briquettes may occasionally influence the compressive strength, it is important to note that compressive strength is not necessarily influenced by density, as density alone cannot fully account for the effectiveness of bonding (Richards, 1990). This is evident in the correlation plot (Fig. 6.8), which shows a moderate positive correlation between the two responses, depicting that compressive strength is moderately influenced by relaxed density. Based on this, it can be observed in Fig. 6.7 that several samples yielded a low compressive strength despite having relatively good densities, with only a few meeting the minimum limit of >350 kN/m^2, as recommended by Richards (1990). To improve compressive strength significantly, employing pretreatment measures such as hydrothermal carbonization on the raw rice husks before densification is recommended (Liu et al., 2014).

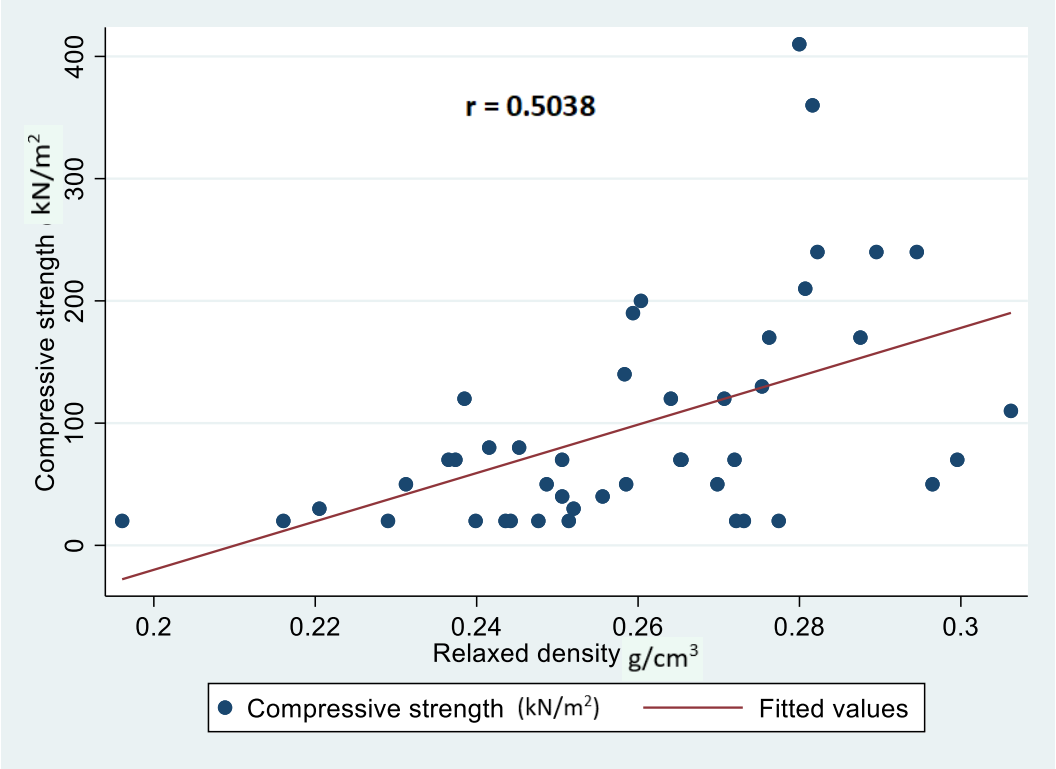

Figure 6.9. The correlation between compressive strength and relaxed density

6.3.4 Response Surface analysis

6.3.4.1 Relaxed density

The 3D surface response and contour plots of relaxed density are shown in Figs. 6.10 to 6.12. The color gradient illustrates the dynamics from lower relaxed density values (blue) through the medium values (green) to the region where relaxed density is highest (red). Relaxed density ranged between 0.22 and 0.31 g/cm^3 with the higher values predominantly observed in briquettes bonded with LBP binder. The maximum relaxed density was recorded in the LBP-bonded briquettes at the interaction between particle size and binder ratio when dwell time is held constant at 1 minute (Fig. 6.10a). This indicates that after attaining the thirty-day relaxation period, briquettes bonded with LBP binder have higher densities than those bonded with other binders, likely due to better gelatinization and improved binding of the core layer particles by the binder.

As shown in Figure 6.11, relaxed density increases as dwell time increases and particle size decreases. This confirmed the assertion of Miao et al. (2019) who reported that biomass with smaller particle sizes yields denser briquettes than those with larger sizes. Similarly, relaxed density increases as dwell time and binder ratio increases (Fig. 6.12). Because the dwell time is the period during which the mixture consolidates, the higher it is, the better the briquette density (Yunusa et al., 2023). Similarly, binder content is very instrumental in low-pressure briquetting, as it aids compaction and solidification. Thus, as observed, the higher the binder, the better the relaxed density. These findings are consistent with those of Magnago et al. (2020) and Onyango et al. (2020) that also observed briquettes with higher binder content to have higher relaxed densities. Although the highest relaxed density was achieved with LBP-bonded briquettes, there is no significant difference with briquettes made from PPL and CSS binders.

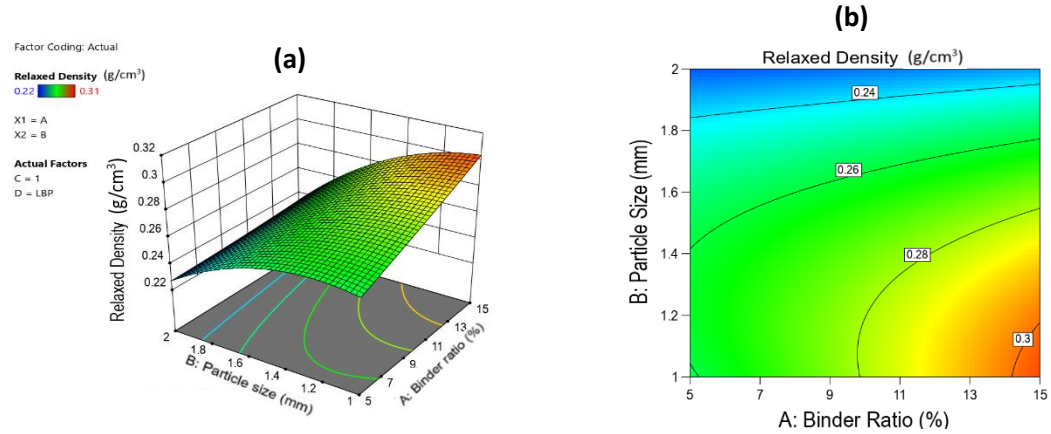

Figure 6.10. (a) 3D surface response, and (b) contour plots, for the effect of interaction between BR and PS on relaxed density

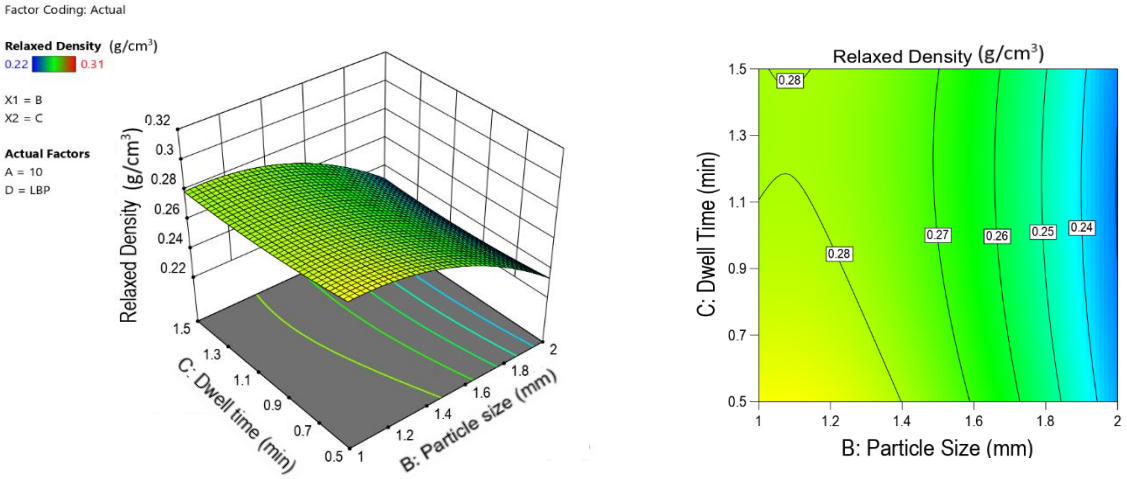

Figure 6.11. (a) 3D surface response, and (b) contour plots, for the effect of interaction between PS and DT on relaxed density

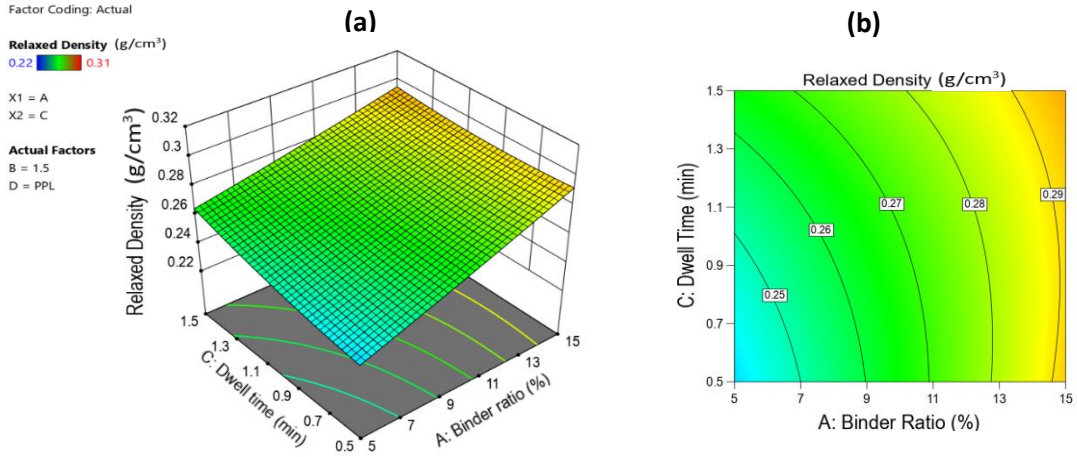

Figure 6.12. (a) 3D surface response, and (b) contour plots, for the effect of interaction between BR and DT on relaxed density

6.3.4.2 Compressive strength

The 3D and contour plots of compressive strength are shown in Figs. 6.13 and 6.14. Due to the inverse square root transformation applied, these model graphs do not represent the actual values but the transformed outputs. The maximum compressive strength was noted at the region where binder content was maximum and dwell time between 0.5 to 1.1 min (Fig. 6.13). This is consistent with the findings of Magnago et al. (2020), which noted that the compressive resistance of briquettes improves as the binder content increases. Overall, the highest compressive strength was observed in LBP-bonded briquettes. Previous studies, such as Jiao et al. (2020) observed that an increase in dwell time enhances compressive strength at lower pressure and decreases it at higher pressure. Compressive strength measures the maximum force the briquettes can withstand before cracking or breaking (Marreiro et al., 2021), making it a critical factor in simulating load resistance during transportation and storage (Obi et al., 2022). These findings show that LBP has good potential to yield briquettes with better compressive strength under low-pressure conditions. Similarly, as depicted in Fig. 6.14, the compressive strength increases as particle size decreases. While these findings agree with those of Zepeda-Cepeda et al. (2021) for briquettes made from sawdust, it is contrary to the findings of Mitchual et al. (2013) which reports that compressive strength increases as particle size increases. This confirms that the quality metrics of briquettes are not consistently dependent on a single factor but a combination of varying factors such as material type, compaction pressure, and particle size among others.

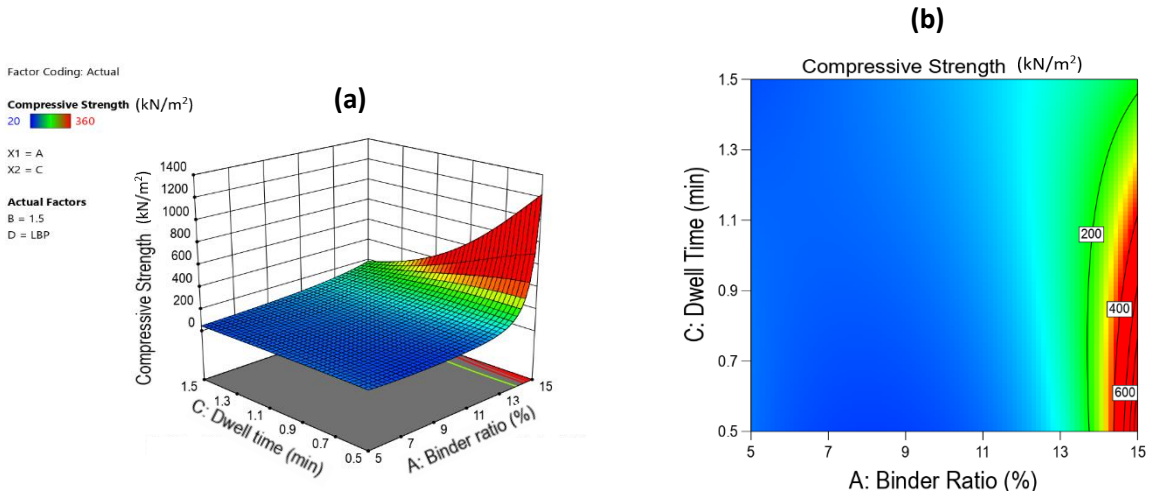

Figure 6.13. (a) 3D surface response, and (b) contour plots for the effect of interaction between DT and BR on compressive strength

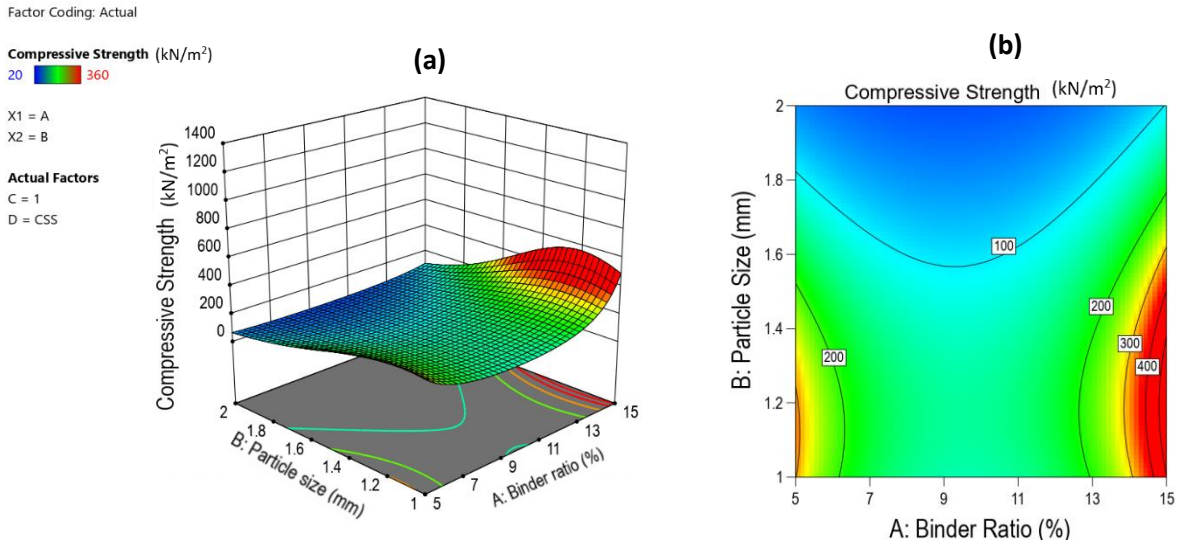

Figure 6.14. (a) 3D surface response, and (b) contour plots for the effect of interaction between DT and PS on compressive strength

6.3.5 Optimization

The criteria used in the optimization phase were aimed at maximizing the responses while maintaining the process variables within the design range (Nganko et al., 2024). The predicted optimum parameters include a 15% binder ratio, 0.5 min dwell time, 1 mm particle size, and cassava starch binder. Chukwuneke et al. (2021) also obtained a 15% optimal starch binder ratio for briquettes made from the combination of rice husks and sawdust. The 3D response surface and contour plots of the optimized responses are presented in Figs. 6.15 and 6.16. The model predicts an optimal relaxed density of 0.30 g/cm^3 (Fig. 6.15) and a transformed compressive strength of 0.032 kN/m^2.

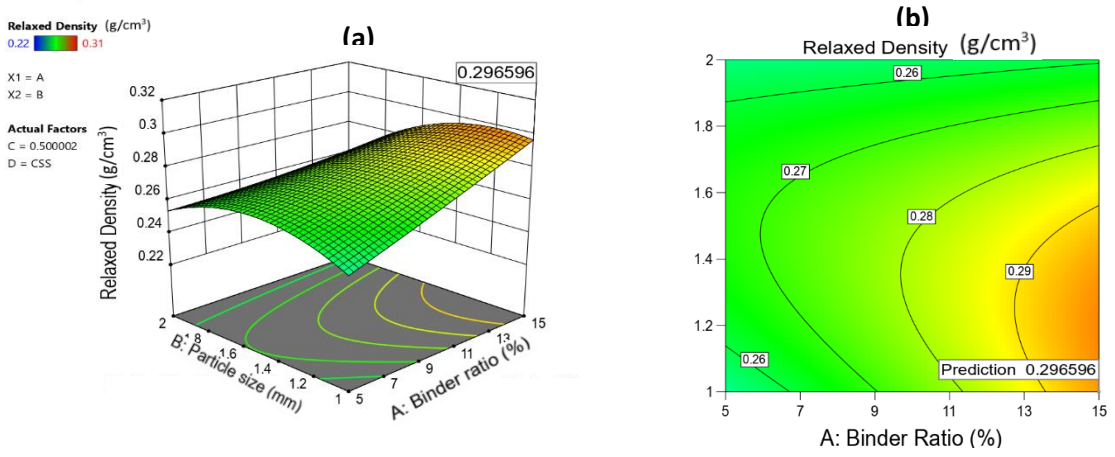

Figure 6.15. (a) 3D surface response, and (b) contour plots of the optimized relaxed density

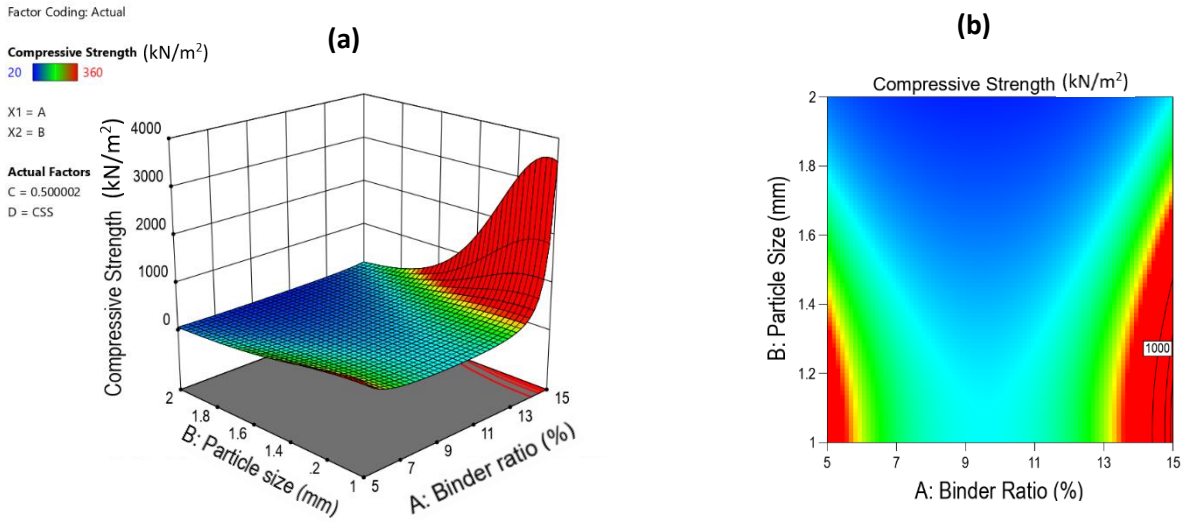

Figure 6.16. (a) 3D Surface response, and (b) contour plots of the optimized compressive strength

6.3.6 Validation

To confirm the veracity of the model predictions, a validation experiment was conducted based on the average of the first three (3) predicted solutions in the case of relaxed density. Because the compressive strength was transformed, the validation was done with three actual and predicted values. The results of the experimental and predicted values are summarized in Table 6.9. The percentage error obtained in both responses is <10% depicting a minimal difference between the predicted and confirmatory experiments. Further analysis using a t-test was performed to assess the deviation between the means (Table 6.10). The p-value obtained was 0.21 (>5%), indicating no significant difference between the experimental and predicted values.

Table 6.9. Experimented and predicted values

Variable	Experimental value	Predicted Value	Error (%)
Relaxed Density (g/cm^3)	0.30	0.30	
	0.29	0.30	
	0.29	0.30	
Average	*0.29*	*0.30*	*3.33*
Compressive Strength ($m^{0.5}\,s\,kg^{-0.5}$)	0.06	0.11	
	0.22	0.18	
	0.22	0.24	
Average	*0.17*	*0.18*	*2.65*

Table 6.10. Summary of t-test analysis

	Obs.	Mean1	Mean2	Dif.	St Err.	t value	p-value
EV - PV	2	0.23	0.24	0.008	0.003	3	0.21

6.3.7 Result of thermal and emission analysis

The result of the thermal analysis is shown in Table 6.11. The boiling time ranges between 3.1 to 9.3 minutes, with the samples made from cassava starch binder having the shortest boiling time. The burning rate and specific fuel consumption are between 10.22 to 37.10 g/min, and 160.55 to 342.26 g/l, respectively. The emissions recorded were between 1.26% to 2.89% for CO_2, 0.01% to 0.05% for CO, 4 to 14 ppm for HC, and 10 to 32 ppm for NO, respectively. The result of CO_2 emission is consistent with the findings of Pilusa and Huberts (2013) where 2.13 % (21332 ppm) was obtained from burning briquettes made from the mixture of spent coffee beans, paper pulp, coal fines, mielie husks, and sawdust. Overall, the emissions from briquettes are lower than that of charcoal except for NO, which may have been influenced by the binder. In this regard, a thorough life cycle analysis is the best approach to estimate the overall impacts of the two product systems (briquettes and charcoal). Moreover, Mwampamba et al. (2013) also observed that briquettes may have higher emissions due to the presence of binders.

Table 6.11. Result of thermal and emission analysis

Sample ID	Boiling Time (min)	Burning Rate (g/min)	SFC (g/l)	CO_2 (%)	CO (%)	HC (ppm)	NO (ppm)
CSS1	5.10	13.73	160.55	1.55	0.05	14.00	10.00
CSS2	3.80	23.95	236.98	1.90	0.01	14.00	11.00
CSS3	3.10	37.10	342.26	1.26	0.02	13.00	12.00
LBP1	9.30	10.22	233.99	1.68	0.02	9.00	22.00
LBP2	7.40	12.70	218.60	2.16	0.01	8.00	28.00
LBP3	7.40	10.41	180.75	2.03	0.01	4.00	31.00
PPL1	6.80	13.53	206.28	2.89	0.01	4.00	32.00
PPL2	6.10	13.44	194.31	1.31	0.01	7.00	22.00
PPL3	6.10	17.54	240.99	2.08	0.01	6.00	17.00

**Note:* SFC= specific fuel consumption, CCS = cassava starch briquette, LBP = Locust bean pulp briquette, PPL = Sweet potato peel briquette

6.3.8 Fourier Infrared Spectroscopy (FTIR) Results

Fig. 6.16 presents the results of FTIR analysis for CSS, LBP, and PPL briquettes, respectively. Overall, more than five peaks were observed in the whole spectra, indicating the presence of complex chemical bonds in the briquettes (Nandiyanto et al., 2019).

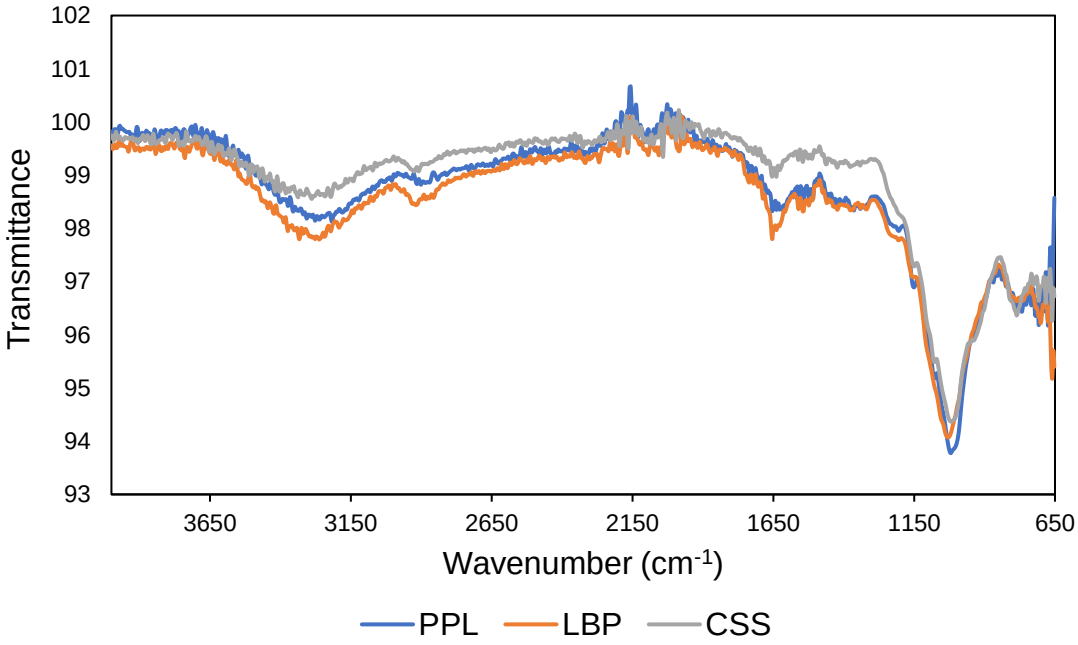

Figure 6.17. FTIR spectra for the three types of briquettes

In the single bond region (2500 – 4000 cm^{-1}), the 3300–3700 cm^{-1} spectra show the stretch vibration of the phenolic hydroxyl group (Adeleke et al., 2021). This peak is observed at around 3300 cm^{-1} in the three briquettes. Similarly, the same peak stretched to 3300 and 3200 cm^{-1} indicating hydrogen bonds in the briquettes. However, this peak is insignificant in CSS briquettes, implying that the hydrogen bond is less in CSS briquettes than in PPL and LBP briquettes. Phenolic hydroxyl enhances adhesion between particles, thereby improving the mechanical integrity of the briquettes (Mili et al., 2022). Similarly, Zhao et al. (2015) noted that the phenolic hydroxyl bond is among the most stable functional groups which could form a strong and stable conjugated structure. There is no sharp intensity transmittance within the 3670 and 3550 cm^{-1} regions in the three briquettes. This implies the absence of oxygen-related bonds such as phenol (Nandiyanto et al., 2019). In addition, no peaks were detected between 3200 and 3000 cm^{-1} in the three samples. This shows that the briquettes don't contain an aromatic structure which implies a potential reduction in

thermal stability (Akam et al., 2024). A narrow band is observed around 2900 cm^{-1} in the three briquettes, indicating the presence of a C-C bond. Similarly, the peak is very shallow in CSS briquettes, showing a low proportion of C-C bonds in CSS compared to PPL and LBP briquettes. C-C bond improves thermal and combustion efficiency and enhances the binding and durability of the briquette. However, no specific peak was detected between 2700 and 2800 cm^{-1} in the three briquettes, showing no aldehyde. In the triple bond region (2000 – 2500 cm^{-1}), a shallow peak was observed at around 2100 cm^{-1} in all the briquettes, showing the possible presence of C≡C. In this case, the peak is lower in the PPL briquette, showing a lesser constituent of C≡C bond than in CSS and LBP. In the double bond region (1500 – 2000 cm^{-1}), a peak is observed between 1650 and 1600 cm^{-1} in the three briquettes, showing the presence of some carbonyl double bond of amides or carboxylates functional group. This bond improves binding and dimensional stability, as well as the overall durability of the briquettes. Adeleke et al. (2021) attributed the peak around 1600 cm^{-1} to the presence of aromatic rings. In the fingerprint region (600 – 1500 cm^{-1}), a strong signal was observed around 1000 cm^{-1} in all the briquettes, implying high cellulosic and hemicellulose content, and the presence of polysaccharides which contributes to combustion stability and energy density. The content of cellulose and hemicellulose is influenced by the primary biomass (rice husk), which is highly lignocellulosic. However, this peak could also show the presence of a vinyl-related compound (Nandiyanto et al., 2019). While there is no significant difference among the briquettes, the PPL briquette showed a higher peak, implying higher polysaccharides, cellulose, and hemicellulose content. A shallow peak around 790 cm^{-1} was observed in all the samples indicating few constituents of para-aromatic compound. However, because the peak is relatively sharper in the CSS briquette, it shows that CSS has a higher content of para-aromatic compound than LBP and PPL briquettes. Para-aromatic compounds are pivotal in energy efficiency, thermal stability, and durability of briquettes.

6.4 Conclusion

The optimum process and response parameters of rice husk briquettes produced at low pressure using organic binders were determined. This is part of measures to improve the production efficiency of low-pressured briquetting. The optimal relaxed density and compressive strength were determined as 0.30 g/cm^3 and 0.032 m$^{0.5}$ s kg$^{-0.5}$ (transformed), achieved with a binder content of 15%, particle size of 1 mm, and dwell time of 0.5 min. These predictions were verified through a confirmatory experiment, which did not show any statistically significant differences between the experimented and predicted values, indicating that the model has adequately navigated through the design space. Additionally, to reduce overreliance on starch-based and inorganic binders in briquette production, the study discovered novel biomass binders (locust bean pulp and sweet potato peel) for use in briquette production. Based on the quality of the briquettes produced with these novel binders, especially how they outperformed the CSS briquettes in compressive strength, the findings demonstrate the potential of using the binders in briquette production.

The findings from this study provide a valuable reference for future research, especially aspects encompassing briquette production as optimum production conditions, quality prediction models, and novel binders have been determined. In addition, the study highlights the feasibility of producing briquettes from uncarbonized rice husks under low pressure. This is particularly relevant for low-income households that rely heavily on fuelwood and charcoal. Therefore, to reduce the over-reliance on fuelwood and charcoal and address the energy deficit in Nigeria, rice husk briquettes can be sustainably produced at low pressure from the huge amount of rice husks generated in the country. Furthermore, this would serve as an energy source and waste management strategy and contribute to climate change mitigation efforts. As the study progresses, future studies should investigate a range of compression pressures through optimization to determine the optimum conditions for producing uncarbonized rice husk briquettes. Similarly, densifying rice husks at low to medium pressure without milling should be explored. Given the low density of rice husks, co-densification with other biomass or using blends could improve the quality and thermal performance. Moreover, exploring pretreatment methods such as carbonization, hydrothermal treatment or torrefaction could mitigate issues like slagging and fouling associated with high ash content. In addition, future studies should investigate the briquettes' surface and core morphology based on the binder types using microstructural analysis.

CHAPTER 7 : A COMPARATIVE ENVIRONMENTAL IMPACT OF RICE HUSK BRIQUETTE AND CHARCOAL USING LIFE CYCLE ASSESSMENT (LCA)

Abstract

The increase in the rate of deforestation for fuel production in developing countries is alarming. Biomass processing into fuel briquettes has gained popularity in recent years as part of measures to abate deforestation and attain a sustainable green solution. This paper explored the cradle-to-gate life cycle of rice husk briquettes against charcoal to quantify the environmental impacts of the two product systems. The primary data were obtained from an experimental study on rice husk briquette production and a reference charcoal production site in the study area. The background data related to energy consumption and material utilization were obtained from the Ecoinvent version 3.9.1 database, and other secondary data were sourced from the literature. The LCA model was executed in OpenLCA software (version 2.0) using the environmental footprint (EF) impact assessment method based on a functional unit of 1 MJ of energy. The results from the contribution analysis revealed that each life cycle stage contributes differently to the various impact categories. The comparative results from the impact categories show that charcoal has a higher impact on the environment than rice husk briquette. In this vein, 0.02 kg CO_2 eq and 0.03 kg CO_2 eq were recorded as the climate change impact for briquette and charcoal, implying a climate change mitigation potential of 0.01 kg CO_2 eq (20%) emission for every MJ of energy generated from briquette in place of charcoal. Similarly, with a land use impact of 0.027 Pt for briquette and 6.266 Pt for charcoal, it shows that 6.239 Pt (99%) will be saved per MJ of energy. Other impact categories such as acidification, eutrophication, land use, human toxicity, and ozone depletion also showed that rice husk briquette is more environmentally benign than charcoal. The results suggest that rice husk briquettes have the potential to mitigate environmental impacts, especially in developing countries where rice husk is largely available and the use of charcoal and fuelwood has intensified. Hence, the findings would serve as a reference for future studies involving the LCA of cooking fuels and could be crucial in policy formulations related to waste management and environmental conservation.

Keywords: rice husk, briquette, charcoal, energy, LCA

7.1 Introduction

The production and use of energy from renewable sources have sparked particular interest across the globe (Mierzwa-Hersztek et al., 2019). This is in line with the efforts to curtail the use of non-renewable fuels which contributes greatly to the emission of greenhouse gases, thereby inducing climate change. One of the factors that made the energy sector among the highly emissive sectors is the substantial reliance on fossils. Hence, the rising GHG emissions can be curtailed by transiting to renewable energy (IPCC, 2022). With this, several countries have designed strategies for developing renewable energy industries (Zhao et al., 2022). Out of the various renewable energy options, there has been a rapid increase in the use of biomass energy. Biomass energy accounts for about 80% of the total renewable energy and contributes about 10% of total energy supplies (Aggarwal & Chandel, 2022). Its environmental benefits and its potential to replace the use of fossil fuels have made it attracted a lot of interest (Nazari et al., 2020).

Rice husk is one of the major biomasses produced globally. This is because it is a by-product of a major staple crop (rice) which has an annual production estimate of about 700 million tons (Jain et al., 2019). In Africa, Nigeria is the largest producer of rice with an annual production capacity of 8.4 million tons (FAO, 2021). Approximately, 0.28 kg of rice husk is generated from every kilogram of milled paddy (Siddika et al., 2021), thus, about 2.4 million tons of rice husk is generated annually in Nigeria. Despite the mammoth quantity generated, there is no clear strategy for managing the husk (Pal et al., 2022). The generated wastes are mostly burned or landfilled contributing to greenhouse gas emissions (Kainthola et al., 2019). Thus, the inappropriate handling of this generated waste negatively affects the environment and climate (Chang & Li, 2019). Therefore, harnessing energy from rice husks is timely and must be encouraged.

There are various valorization strategies for converting lignocellulosic biomass to energy. One of the commonest in terms of solid energy recovery is briquetting. Although the idea of briquetting was primarily developed to tackle the problem of excess waste generation, it is now majorly focused on energy production (Njezic et al., 2014). In Sub-Saharan Africa, briquetting is encouraged to reduce overreliance on fossils which are highly emissive and expensive, and also to curtail deforestation. About 2.6 billion people globally predominantly from the rural and peri-urban parts rely solely on fuelwood and charcoal in cooking and space heating (Schilmann et al., 2021). This has contributed greatly to deforestation and

climate change. In Africa, 3.4 million hectares of forest are lost annually (FAO, 2010). Nigeria is the second top charcoal-producing nation globally with a sum quantity of 29,864,965 tons and an annual average of 4,266,423.57 tons (Paramasivan & Premadas, 2019). This has contributed greatly to forest degradation, amounting to a yearly loss of 350,000 ha of forest in the country (FAO, 2021).

Briquetting involves densifying loosed biomass into a more compact and uniformly stable product called a briquette (Sugebo, 2022). Although the technology is not new, it is still an emerging technology in most parts of Africa (Kuparinen et al., 2014; Japhet et al., 2020). In Nigeria, despite having a large quantity of biomass production, there are limited valorization strategies (Japhet et al., 2020), as the few briquetting units available are mainly research-based and not designated for end-user production. To this end, it becomes imperative to assess the environmental impact of the process from cradle to grave to have insights into its impacts on the environment compared to the business as usual. Life cycle assessment (LCA), being a systematic analytical method for evaluating the environmental burdens of processes and products is one of the most influential tools used (Alengebawy et al., 2022; Bezama et al., 2013). This will not only provide information on environmental burden but will also give an insight into the overall sustainability of the technology (Muazu et al., 2017).

A couple of literature have been reported on the life cycle assessment of biomass briquettes. This includes the development of a simple and comparative LCA model for the biomass briquetting process (Muazu et al., 2022), cradle-to-grave analysis of a Lebanese biomass briquette plant (Saba, 2020), LCA of biomass and cardboard waste-based briquetting in Andean areas. Others are cradle-to-grave LCA of cornstalk briquette fuel in China (Wang et al., 2017), and integrated gate-to-gate LCA of solid fuel production from various biomass in Mexico (Muazu et al., 2022) among many more.

The bulk of the literature on LCA of rice husks is mainly on pretreatment measures such as rice husks torrefaction (Thengane et al., 2020), hydrothermal carbonization to pellets, pyrolysis to bio-oil, and anaerobic digestion to biogas (Unrean et al., 2018). Others include electricity generation from rice husks (Badri et al., 2012), and energy production through direct combustion (Quispe et al., 2019). Hence, studies on the LCA of rice husk briquette are grossly limited. Moreover, there is no study on the comparative LCA of rice husks briquette and charcoal. Thus, the objective of this study is to evaluate, for the first time in

Nigeria and, up to the Author's knowledge in West Africa, the environmental impacts associated with the stages involved in the production and use of rice husk briquette compared with charcoal.

7.2 Materials and Methods

7.2.1 Research Framework

The life cycle assessment was carried out on rice husk briquette made from a low-pressured production unit targeted for domestic application and was compared with charcoal as a reference. The two product systems (briquette and charcoal) have a common function which is to provide energy for cooking applications. A low-pressure production was considered to make the process more practicable and affordable especially for low to medium-income households who are the major users of charcoal. The main factors that influence the usage of charcoal in the study area are availability and cost (Yunusa et al., 2024). Similarly, rice husk was selected as the primary feedstock based on its availability and perceived sustainability in the study area.

The idea became imperative following the intense use of fuelwood and charcoal in Nigeria, especially among low-income households. Therefore, processing rice husks into fuel briquettes would serve as an alternative energy source with the potential to replace fuelwood and charcoal. Moreso, it would serve as a waste treatment and management strategy, thereby improving environmental sustainability.

Rice husk briquette is a solid biofuel developed by compressing a homogenized mixture of rice husk, water, and binder using a press or compression devise. It is a renewable energy source cleaner than traditional sources like fuelwood and charcoal (Ahiduzzaman, 2007; Oladosu et al., 2023). In this study, a bench-scale briquetting system was used, which has been previously characterized/optimized for the briquetting of rice husks (Yunusa et al., 2024). 200g of the mixture was filled per mold and compressed with a 5-ton hydraulic jack. Charcoal, the reference system, is produced through slow pyrolysis of wood and forest residues. In the reference site, charcoal is made using traditional earth kilns following the methods described in the production phase of the LCA stages.

7.2.2 Description of LCA Model

The LCA methodology employed in this study complies with the ISO14040/4044 (ISO, 2006) which is an international procedural framework for performing LCAs. The LCA model was executed in OpenLCA software (version 2.0) using the Ecoinvent 3.9.1 database. The study applies the four LCA stages reported in ISO14040/4044: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation.

7.2.2.1 Goal and Scope Definition

The goal of the study is to comparatively analyze the potential environmental impacts of rice husk briquettes produced with a low-pressure unit against charcoal made from woody biomass (through pyrolysis in an earth kiln), using a cradle-to-gate perspective. The definition of the evaluated system therefore includes all the major steps from raw material collection, preprocessing, processing, delivery, and use phase. However, the disposal phase (end of life) is outside the scope of this study.

a. Functional unit

The functional unit (FU) is 1 MJ of energy produced in each production system. The FU was selected to establish a common function that the product systems could cover.

b. System boundary

The LCA was conducted based on a small-scale rice husk briquetting unit and charcoal production in Nigeria. Figure 7.1 presents the framework of the study showing the boundaries of the product systems.

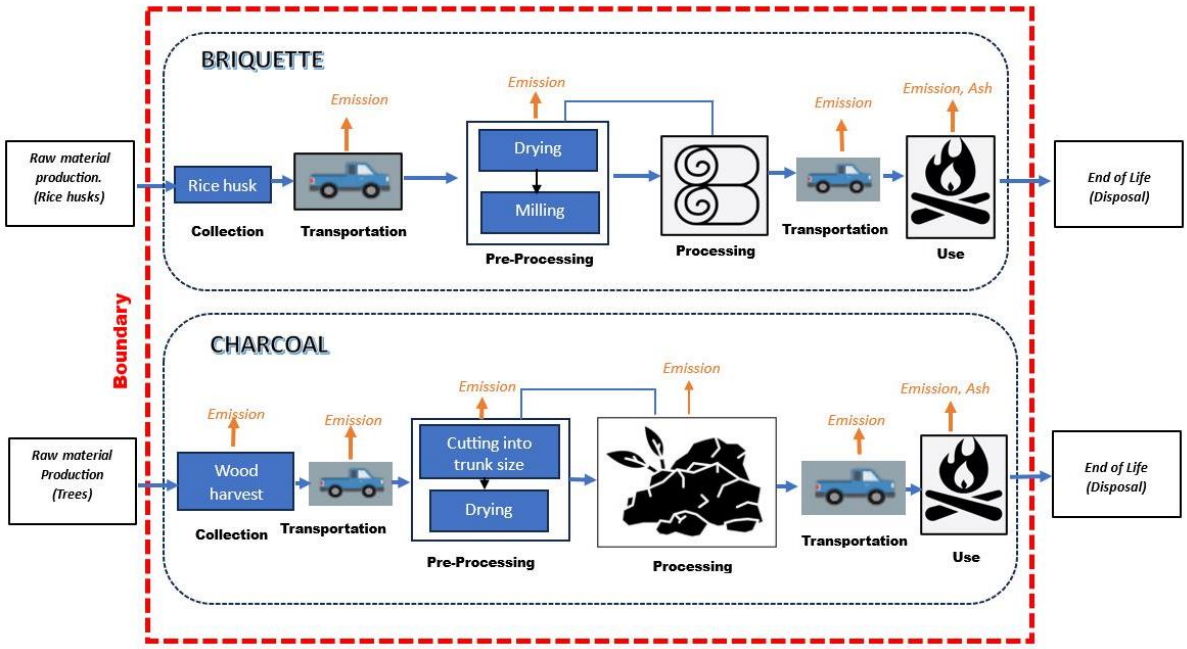

Figure 7.1. System boundaries for briquette and charcoal production

7.2.2.2 Life Cycle Inventory

In the inventory phase, primary and secondary data were collected and adapted to the functional unit. The primary or foreground data for the briquette processing were obtained from the indicated bench scale briquetting system through measurements and evaluations. The measurements were made at a facility that could be used in decentralized applications and therefore can be upscaled to a commercial size. The background data related to energy consumption and material utilization were sourced from the Ecoinvent 3.9.1 database. For the reference system (charcoal), the inventory data combines both primary and secondary data. Primary data relating to production, distribution, and use (e.g., material input, energy content of woods, thermal and emission performances of charcoal, and the distances covered) were obtained through laboratory measurements and interactions with major vendors and producers. While secondary data (e.g. time taken to harvest a tree and the emissions during charcoal production) were sourced from the literature. However, background data relating to energy and material consumption were sourced from the Ecoinvent database. Tables 7.1 to 7.3 show the inventory data of the two product systems and the transportation phase.

Table 7.1. Inventory data for the production of 1MJ of energy from briquette

System	Process	Description	Input/output per FU	Data Type/Source
Inputs				
Rice husk and binding biomass	Input feedstocks	This is the quantity of feedstocks required for the production of briquettes that will generate a MJ of energy	0.046 kg of rice husk and 0.034 kg of binder	Primary
Processing of rice husk	Milling of rice husk	The harmer mill machine weights 120 kg and is powered by a 5.22 kW diesel engine output	0.0007 kWh	Primary
Briquetting	Binder preparation	Binders were prepared on a 1kW electric stove	0.0244 kWh	Primary
	Briquette Production	The briquette production machine weights 100 kg and was powered by a 5 tons hydraulic Jack	-	Primary
Outputs				
Briquette	-	0.06 kg of briquette		Primary
Emissions and Ash	-	The briquettes were evaluated in an improved biomass cookstove and the emissions were measured using a gas analyzer. Other thermal performance parameters were calculated following the standard water boiling test WBT	CO_2: 3.6 g CO: 0.02 g HC: 0.0018 g NO: 0.0025 g Ash: 8.98 g	Primary

a. Allocation Unit

The allocation unit (AU) is computed based on the calorific values of the input materials and products. Thus, the AU was determined for rice husk and the binders (locust bean pulp, potato peel, and locust bean husk) in the case of briquette production and wood, branches, and leaves in the case of charcoal production.

The briquettes are composed of 85% – 95% rice husks and 5% – 15% binder. On average, the proportion of rice husk is about 90% while the proportion of binder is 10%. The calorific value of rice husk is 21.78 MJ/kg. Hence, 0.046 kg of rice husk is required to obtain 1 MJ of energy. Similarly, the calorific values of the binders are 34.48 MJ/kg for LBP, 32.45 MJ/kg for LBH, and 21.26 MJ/kg for SPP. On average, the biomass materials used as

binders have a calorific value of 29.4 MJ/kg. Hence, 0.034 kg of binder is required to produce briquettes with the potential of yielding 1 MJ of energy.

For the reference system (charcoal), wood is assumed to cover 95% of the input material, while the branches and dry leaves used in covering the wood are assumed to be 5% of the input material. An average calorific value of the four main species used in charcoal production in the study area was considered. These are, 14.16 MJ/kg for *Vitellaria paradoxa*,15.25 MJ/kg for *Mangifera indica*, 17.35 MJ/kg for *Anogeissus leiocarpa*, and 10.92 MJ/kg for *Tectona grandis*. Thus, the average, of 14.42 MJ/kg was used as the calorific value of the input material (wood). Hence, the wood required for generating 1MJ of energy from charcoal is 0.069 kg.

For the branches and leaves, the average calorific value of both was considered. For the dry leaves, the average calorific value of dry leaves of different tree species (17.755 MJ/kg) as given in Pnakovic & Dzurenda (2015) was used, while for the branches, the calorific value of the wood (i.e. 14.42 MJ/kg) was used. Hence, an average of 16.09 MJ/kg was obtained for branches and dry leaves. Therefore, 0.062 kg of dry leaves and branches is required to produce 1 MJ of energy from charcoal.

However, for the output product, the calorific value of charcoal produced from one of the species (*Tectona grandis*) was considered (29.2 MJ/kg) (Partey et al., 2017). The average calorific value of the three briquette types (LBP, CSS, and PPL), i.e., 16.8 MJ/kg was used as the output calorific value for briquette.

The various allocation values are employed in the material collection phase to allocate the impacts of the initial transportation of feedstocks. Equation 7.1 (Ferronato et al., 2023), was used in the estimation.

$$AU = \frac{CV_m}{CV_o} \times p \qquad (7.1)$$

Where CV_m is the calorific value of the input material, CV_o is the calorific value of the output product and p the percentage composition of the input material (decimal). Thus, 1.2 was obtained as the AU of rice husk and 0.183 as the AU of binders for briquette production. For charcoal production, 0.469 was obtained as the AU of wood, and 0.028 as the AU of dry leaves and branches

Table 7.2. Inventory data for the production of 1MJ of energy from charcoal

Operation	Process	Description	Input/output per FU	Data type/source
Inputs				
Wood harvest	Raw material	Time: It takes an average of 3.82 min to harvest one tree. Hence, based on the allocation unit (0.469), the time required per FU was estimated	0.0001 min	Secondary (Jourgholami et al., 2013)
		Energy: Woods are harvested using a 2.5 kW gasoline engine-powered chainsaw	0.000005 kWh	Primary
Woods	Input material	The quantity of wood needed to fulfill the FU	0.069 kg	Primary
Branches and leaves	Input material	In addition to wood trunks, branches, and leaves are added to ease carbonization	0.0622 kg	Primary
Resizing of wood into trunks	Processing of wood	Wood logs are resized using a 2.5 kW gasoline-powered chainsaw.	0.0002 kWh	Primary
Carbonization	Production	Wood trunks and residues are covered in the kilns and carbonized for 2 to 3 days	-	Primary
Outputs				
Charcoal	-	0.03 kg of charcoal		Primary
Emissions from carbonization	Burning of wood and residues	NO_2: 0.19 ± 0.22 ppm to 1.85 ± 1.53 ppm	0.001055 g	Secondary (Olujimi et al., 2016)
		SO_2: 0.8 ± 0.51 ppm to 3.82 ± 2.48 ppm	0.003329 g	
		CO: 2.93 ± 3.21 ppm to 959 ± 240 ppm	0.303071 g	
		CO_2: 317 ± 147 ppm to 3877 ± 2608 ppm	2.07604 g	
Emissions from the removal process	Opening and removal of charcoal	NO_2: 0.018 ± 0.25 ppm to 0.39 ± 0.40 ppm	0.00002 g	Secondary (Olujimi et al., 2016)
		SO_2: 0 ppm to 0.08 ± 0.21 ppm	5.78E-05 g	
		CO: 1.50 ± 2.05 ppm to 80 ± 102 ppm	0.03 g	
		CO_2: 221 ± 27 ppm to 1222 ± 1355 ppm	0.71 g	
Final use		Charcoal was burned in an improved cookstove and a gas analyzer was employed for emission measurements	CO_2: 2.78 g CO: 6.7825 g HC: 10.48 g NO: 0.001 g Ash: 8.9 g	Primary

7.2.2.3 Life Cycle Stages

a. Transportation of feedstocks

The transportation inventory is presented in Table 7.3. For briquette production, the feedstocks (rice husks), approximately 39 kg were collected from a rice processing factory in Giwa LGA, Kaduna State, Nigeria, and were transported with a small commercial vehicle weighing 1155 kg to the production site. The distance from the collection point to the production site is 9.6 km. The allocation unit is reported in kg km^{-1} per MJ of the FU. Other material and fuel consumption data were obtained from the database (Ecoinvent 3.9.1): transport, freight, and light commercial vehicles.

For charcoal production, the distance from the point of wood harvest to the production site ranges between 0.5 – 5 km, as the production sites are mostly within the forest. Thus, an average of 2.27 km was considered.

Thus the input per functional unit I_{FU} is determined using Equation 7.2 (Ferronato et al., 2023).

$$I_{FU} = M \times D \times AU \quad (7.2)$$

Where M is the mass of input material (rice husk and wood) required for generating 1 MJ of energy (0.046 kg for rice husk and 0.069 kg for wood), D is the traveled distance in transporting the material (9.6 km for rice husk and 2.27 km for wood) and AU is the allocation unit of the materials (1.2 for rice husk and 0.469 for wood). Thus, 0.5383 kgkm MJ^{-1} and 0.0735 kgkm MJ^{-1} were obtained as the I_{FU} for rice husk in briquette production and wood in charcoal production, respectively.

Table 7.3. Inventory data for transportation of materials for the production of briquette and charcoal for the generation of 1MJ of energy

Operation	Vehicle type/Description	Average distance (km)	Fue type	Input/Output per FU	Data type/source
Rice husk collection	Transport, freight, light commercial vehicle	9.6	Petrol	0.5383 kg km MJ^{-1}	Primary: weight of material and distance Ecoinvent database v3.9: energy use
Wood logs collection	Transport, freight, lorry	2.27	Diesel	0.0735 kg km MJ^{-1}	Primary: material and distance Ecoinvent database v3.9: energy use
Briquette Delivery	Transport, freight, light commercial vehicle	4.8	Petrol	0.288 kg km MJ^{-1}	Primary: weight of material and distance Ecoinvent database v3.9: energy use
Charcoal delivery	Transport, freight, lorry	203	Diesel	6.943 kg km MJ^{-1}	Primary: material and distance Ecoinvent database v3.9: energy use

b. Products Production

i. Briquette production

Rice husk processing

The collected feedstocks were pretreated to enhance densification in the processing stage. The rice husk was in a suitable moisture range of < 10 %, hence the drying phase was not considered in the boundary. However, size reduction was imperative because two-stage rice husks have large grade sizes estimated between 6.7 ± 0.6 to 8.3 ± 0.7 mm (Chen et al., 2017), indicating low surface areas. Thus, the samples were milled with the aid of a hammermill fitted with a 2 mm screen to obtain particle sizes $\leq 2\ mm$. The milling machine weighs about 120 kg with an engine power of 5.22 kW and a capacity between 200 to 600 kg/h depending on the input product. The energy consumption per functional unit (E = 0.00073 kWh MJ^{-1}) was determined using Equation 7.3 (Ferronato et al., 2023).

$$E = \frac{W_h}{C_i} \times R_{FU} \times AU \qquad (7.3)$$

Where W_h is the engine power of the hammer mill (5.22 kW), C_i is the material (rice husk) inflow into the machine per hour (400 kg/h), R_{FU} is the amount of rice husk required to produce 1 MJ of energy (0.046 kg), and AU the allocation unit of the rice husk (1.2).

Briquetting (densification)

In the briquetting phase, a manually operated hydraulic piston press was used. Hence, there wasn't any form of electricity or fossil consumption during densification. However, low-voltage electricity was employed in binder preparation. Here, a 1 kW electric stove was used in binder preparation. Thus, a 1 kWh of energy consumption was considered in this stage. Based on this, the flow: market for electricity, low voltage | electricity, low voltage | APOS, S-NG, was used. The binder preparation and mixing stages were largely omitted in previous life cycle assessments of biomass briquettes. Thus, there is no information on the energy consumption per functional unit in the literature. However, Equation 7.4 was employed to estimate the energy consumption in this stage per FU. In preparing the binder, 500 ml of water at room temperature was boiled in a 1 kW electric stove within 3-4 minutes. The raw binder transformed into a paste was poured into the boiling water and mixed continuously for an additional 5 minutes to achieve a gelatinized paste. In an hour about six (6) sets of binders are prepared. Considering two sets from each binder ratio, about 255 g of raw binder was made in an hour. Thus, the energy consumption in binder preparation ($E_b = 0.0244$ kWh MJ^{-1}) was estimated using Equation 7.4

$$E_b = \frac{W_h}{C_i} \times B_{FU} \times AU \qquad (7.4)$$

Where W is the power rating of the electric stove (1 kW), C_i is the inflow of raw binder into the stove per hour (0.255 kg/h), B_{FU} is the amount of binder required to produce 1 MJ of energy (0.034 kg), and AU the allocation unit of the binder (0.183).

ii. Charcoal production

Wood harvesting and processing

The harvesting phase involves felling trees, delimbing, and resizing of woods into trunks. The time taken to fall an average-sized tree using a chain saw, with and without delay is 3.14 to 4.5 minutes (3.82 minutes on average) (Jourgholami et al., 2013). An averagely sized tree weighs 1000 kg. The trees are felled with a 2.5 kW gasoline engine-powered chain saw. The inflow of wood into the machine per hour is 15,706.81 kg/h (estimated based on the average harvesting time and weight of one tree). The amount of wood required to produce 1 MJ of energy is 0.069 kg and the allocation unit of wood is 0.469. Thus, using Equation 7.3. The energy consumption per FU is 5.15×10^{-6} kWh (0.00000515 kWh).

After felling, further processing involves delimbing the branches, resizing into trunk sizes, and drying. However, because the drying phase was done naturally through the open sun and air, the energy consumption is negligible, hence not considered (Gan et al., 2022). The woods were delimbed and resized using a 2.5 kW gasoline engine-powered chain saw. Because delimbing and resizing into trunks take approximately equal time (Bailis et al., 2013), the energy requirement for delimbing and resizing is assumed to be the same as the energy expended in felling (0.000005 kWh).

Feeding of trunks and covering of kilns

Depending on the kiln size, fifteen (15) to twenty (20) trunks of wood are fed in for carbonization at a time (Mba, 2018). The trunks are covered with dry leaves and branches up to the top layer, and other possible voids before covering with earth. The emissions in this phase are negligible and hence not included in the inventory.

Carbonization

This is the process where wood and residues are burned slowly in an airtight kiln. The process begins at 100 ℃ to 200 ℃ with drying and proceeds through the pre-carbonization phase at 200 ℃ to 275 ℃, to the carbonization phase at 275 ℃ to 400 ℃ up to the final phase involving carbon fixation between 400 ℃ and 500 ℃ (Rodrigues & Braghini Junior, 2019). The whole process typically lasts for two to three days (Mba, 2018). This is the phase where charcoal is produced accompanied by some gaseous emissions. On average, at the end of the carbonization process, an averagely-sized tree yields approximately 3.5 bags (131 kg) of charcoal (Mba, 2018). NO_2, SO_2, CO, and CO_2 emissions were recorded in this phase.

According to Olujimi et al. (2016), NO_2 emission is between 0.19 ± 0.22 ppm to 1.85 ± 1.53 ppm, SO_2 between 0.8 ± 0.51 ppm to 3.82 ± 2.48 ppm, CO between 2.93 ± 3.21 ppm to 959 ± 240 ppm and CO_2 between 317 ± 147 ppm to 3877 ± 2608 ppm.

Opening and removal of charcoal

After carbonization, the flame is quenched and cooled by applying water. The kiln is gradually opened and the charcoal is removed. In this phase, emissions such as NO_2, SO_2, CO, and CO_2 are recorded. According to Olujimi et al. (2016), NO_2 emission is between 0.018 ± 0.25 ppm to 0.39 ± 0.40 ppm, SO_2 between 0 ppm to 0.08 ± 0.21 ppm, CO between 1.50 ± 2.05 ppm to 80 ± 102 ppm and CO_2 between 221 ± 27 ppm to 1222 ± 1355 ppm.

c. Packaging and delivery for final use

Unlike charcoal which is produced in the forest usually far from residential areas, the production of briquettes is assumed to take place within the community. On this premise, half the distance from the source of feedstock to the point of production (4.8 km) was considered for the delivery phase.

However, in the case of charcoal production, the production sites in the study area are located in the extreme south of the state (Jere North and Barde Ward). The Jere North production site was used as the reference site because it has a larger capacity and many charcoal dealers across the state purchase it from there. In addition, the reference distance is assumed to be from the production site to the town where the briquetting study takes place (Zaria) which is about 203 km.

The charcoal is packaged in sacks weighing 35 to 40 kg. The packaged charcoals are arranged and delivered in heavy-duty vehicles (transport, freight, lorry 16-32 metric tons, EURO1) over an average distance of 203 km to retailers and wholesalers. The input per functional unit was estimated using Equation 7.2 based on an AU of 1. Also from the calorific value of charcoal (29.2 MJ kg^{-1}) (Partey et al., 2017). 0.0342 kg of charcoal is required to generate 1 MJ of energy. Thus, the input per functional unit in transporting charcoal from the point of production and packaging to the point of retail and wholesale is 6.943 kg km MJ^{-1}.

d. Final Use

A laboratory analysis was conducted using the standard water boiling test (WBT) version 4.2.3 (PCIA & GACC, 2013), to simulate using briquettes and charcoal through the thermal properties (Burning rate, boiling time, emission, and fuel consumption). However, in assessing the impact of the use stage, reference was made to the functional unit (which is to produce 1 MJ of useful heat). Hence, the flow: Heat, district, or industrial, other than natural gas was employed from the Ecoinvent 3.9 database. This conforms with the assertion of Saba et al. (2020). Moreover, being that the quantity of waste ash generated was not measured, a secondary value of 8.9 g was considered following Ferronato et al. (2023) whose FU was also 1 MJ of energy.

7.2.2.4 Life Cycle Impact Assessment LCIA

The life cycle impact assessment aims to translate the inventory data into the environmental impact profile (Saba et al., 2020). In this study, the educational license of Ecoinvent was used in OpenLCA software v2.0 to model the impacts using the environmental footprint (EF) impact assessment method. The results from this impact assessment contain impacts from twenty-eight (28) categories. However, only sixteen (16) impact categories were considered in this study. These are acidification, climate change, land use, freshwater eutrophication, marine eutrophication, terrestrial eutrophication, human toxicity cancer, human toxicity non-cancer, ionizing radiation, particulate matter, photochemical ozone formation, resource use fossils, resource use mins. and metals, water use, and ozone depletion.

7.2.3 Sensitivity Analysis

Sensitivity analysis was employed to understand the relative changes between the results and the input parameters (Ferronato et al., 2023). Through this, the input parameters that are sensitive to the model were identified (Clavreul et al., 2012). The sensitivity analysis in this study was conducted as per Clavreul et al. (2012) using perturbation analysis. This is the process of varying the parameters to determine their influence or sensitivity on the impact categories. The sensitivity ratio (SR) was used to evaluate the sensitivities of the input parameters. In doing so, the normalized results of the parameters were varied by +10% and −10% and the most sensitive of the two SRs were retained and used. The local one-at-a-

time (OAT) approach was employed in computing the SR. The OAT estimation method was selected because it is simple to implement and the findings are easy to interpret (Clavreul et al., 2012). However, only three impact categories were selected for the analysis, viz: Acidification, climate change, and marine eutrophication (Fantin et al., 2015). While there are other important impact categories such as land use, they are not affected by sensitivities or parameter variation (Adams et al., 2015). This is because sensitivity analysis targets the parameters that are uncertain in the modeling process (Adams et al., 2015).

The sensitivity ratio (SR) is estimated as the ratio between the relative changes in result and parameters as given in Equation 7.5 (Clavreul et al., 2012).

$$SR = \frac{\frac{\Delta \text{ result}}{\text{initial result}}}{\frac{\Delta \text{ parameter}}{\text{initial parameter}}} \qquad (7.5)$$

Where Δ result is the change in the result and $\Delta\ parameter$ is the change in parameter

7.2.4 Uncertainty Analysis

Uncertainty analysis was conducted to assess the robustness of the LCA outcome as a measure of providing more information for decision-making (Clavreul et al., 2012; Muazu et al., 2017). The sources of uncertainty could be from the input parameter, methodology (e.g. assumptions and procedures), or embodied impacts (Muazu et al., 2017). In this study, the uncertainty analysis was conducted using Monte Carlo simulation based on a 95% confidence interval and 1000 runs (Saba et al., 2020). Monte Carlo is an integrated feature of the OpenLCA 2.0 software. The input parameters were assigned standard deviations in the inventory using data quality indicators in the pedigree matrices (Baidoo et al., 2024). Through this, the data completeness and reliability, as well as geographical, technological, and temporal correlations are assessed (Ciroth et al., 2016).

7.3 Results and Discussion

7.3.1 Contribution Analysis

The impact contribution of each life cycle stage of the two product systems is presented in Tables 7.4 and 7.5. As indicated, all the process stages contribute to the overall life cycle impacts. The 16 impact categories studied can be subdivided into four (4) sub-categories, viz: climate change, ecosystem quality, human health, and resources. In both product systems, each process stage contributes differently to the overall impact. For example, in Figure 7.2 the processing phase contributes most to climate change, land use, and acidification. Similarly, in Table 7.4, the processing phase contributes the most to ozone depletion and resource utilization (fossils) yielding a total impact of 4.31E-10 kg CFC11 eq and 0.22934 MJ, respectively. This could be because it is the only phase that involves the use of electricity (for binder preparation). Electricity is a major environmental impact contributor in LCA (Thengane et al., 2020; Zhiwei Wang et al., 2017). Thus, it is suggested that electricity use is minimized or avoided in briquette production to curtail the life cycle impacts, except when generated from renewable sources.

In contrast, for charcoal production (Figure 7.3) and Table 7.5, the use phase contributes most to climate change, ecotoxicity, and human toxicity, while the processing phase contributes most to acidification. The use phase is usually a higher contributor to environmental and health impacts because it is the phase where the product's functional unit (heat energy) is harnessed. In briquette, it contributes the most to eutrophication, ecotoxicity, human toxicity, and water use. In this study, the use phase involved burning the fuels (briquette and charcoal) in a cookstove to generate the heat required to boil 500 ml of water following the standard water boiling test. During this process, all embedded contents including the composite binders are incinerated and transformed into volatiles and ash contributing to total thermal energy, particulate, and other gaseous emissions. Ferronato et al. (2023) also observed that the use phase contributes the most impact on the life cycle of briquettes made from sawdust and cardboard.

In addition, an equal contribution was noted for the feedstock collection, pre-processing, and processing phases for the land use impact category of charcoal. While the feedstock collection and pre-processing stages contribute the highest and equally to freshwater eutrophication.

Table 7.4 Briquette production contribution analysis

Impact category	Unit	Feedstock Collection	Pre-Processing	Processing	Delivery	Use	Total
Acidification	mol H+ eq	5.48E-06	2.74E-06	2.11E-05	2.93E-06	4E-06	3.63E-05
Climate change	kg CO2 eq	0.0012	0.0004	0.0150	0.0006	0.0038	2.10E-02
Ecotoxicity, freshwater	CTUe	0.0206	0.0064	0.1123	0.0110	20.8756	2.10E+01
Eutrophication, freshwater	kg P eq	1.57E-07	5.07E-08	8.07E-07	8.42E-08	2.3E-06	3.40E-06
Eutrophication, marine	kg N eq	1.79E-06	1.06E-06	4.91E-06	9.58E-07	1.88E-06	1.06E-05
Eutrophication, terrestrial	mol N eq	1.93E-05	1.15E-05	5.43E-05	1.03E-05	1.97E-05	1.15E-04
Human toxicity, cancer	CTUh	1.67E-12	2.8E-13	3.58E-12	8.93E-13	5.11E-11	5.75E-11
Human toxicity, non-cancer	CTUh	2.11E-11	1.15E-11	1.38E-10	1.13E-11	3.83E-09	4.01E-09
Ionizing radiation	kBq U-235 eq	2.93E-05	5.91E-06	2.98E-05	1.57E-05	3.96E-06	8.46E-05
Land use	Pt	0.0064	0.0049	0.0082	0.0034	0.0039	2.68E-02
Ozone depletion	kg CFC11 eq	1.79E-11	5.1E-12	4.31E-10	9.55E-12	5.23E-12	4.69E-10
Particulate matter	disease inc.	1.13E-10	1.5E-11	9.93E-11	6.04E-11	2.53E-11	3.13E-10
Photochemical ozone formation	kg NMVOC eq	7.3E-06	3.48E-06	3.43E-05	3.9E-06	3.58E-06	5.26E-05
Resource use, fossils	MJ	0.01547	0.0044	0.2293	0.0083	0.0023	2.60E-01
Resource use, mins. & metals	kg Sb eq	8.62E-09	2.01E-09	1.09E-07	4.61E-09	4.99E-10	1.24E-07
Water use	m3 depriv.	0.0002	4.87E-05	-0.0004	8.41E-05	0.0002	1.38E-04

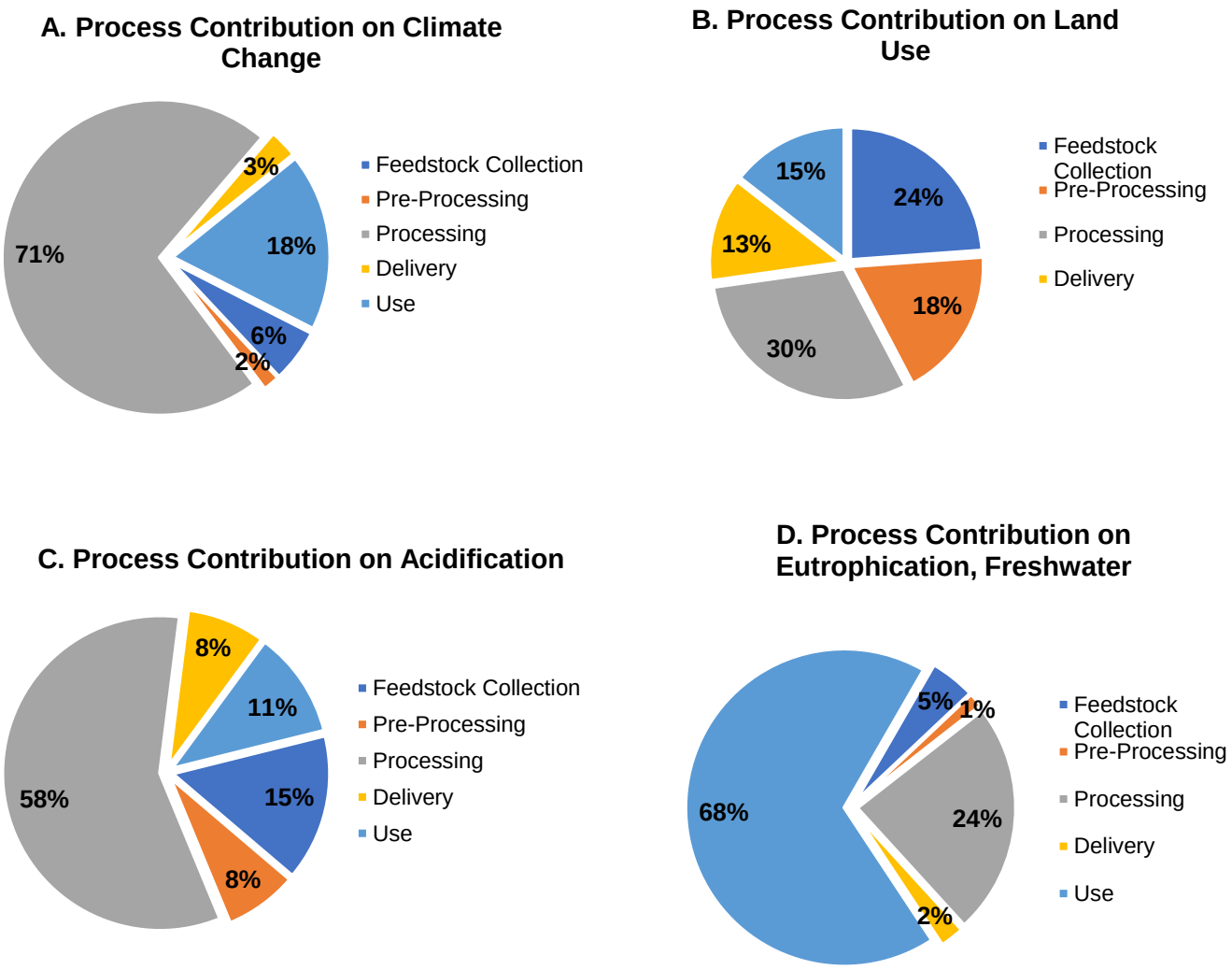

Figure 7.2. Process contributions to various life cycle impacts of rice husk briquette

Table 7.5. Charcoal production contribution analysis

Impact category	Unit	Wood Harvest	Wood Processing	Production	Transportation (Woods and Charcoal)	Final Use	Total
Acidification	mol H+ eq	2.5E-05	2.4E-05	3.4E-05	9.0E-06	2.7E-06	9.4E-05
Climate change	kg CO2 eq	3.4E-03	3.2E-03	9.2E-03	1.2E-03	1.1E-02	2.8E-02
Ecotoxicity, freshwater	CTUe	3.5E-01	3.5E-01	3.5E-01	2.4E-02	2.1E+01	2.2E+01
Eutrophication, freshwater	kg P eq	2.8E-06	2.7E-06	2.7E-06	2.5E-07	2.3E-06	1.1E-05
Eutrophication, marine	kg N eq	5.2E-05	5.2E-05	5.3E-05	3.5E-06	1.2E-06	1.6E-04
Eutrophication, terrestrial	mol N eq	9.5E-05	9.2E-05	1.0E-04	3.8E-05	1.2E-05	3.4E-04
Human toxicity, cancer	CTUh	1.0E-11	1.0E-11	1.0E-11	4.6E-13	5.1E-11	8.2E-11
Human toxicity, non-cancer	CTUh	-3.1E-11	-3.4E-11	-3.4E-11	1.4E-11	3.8E-09	3.7E-09
Ionising radiation	kBq U-235 eq	6.8E-05	6.4E-05	6.4E-05	1.7E-05	3.9E-06	2.2E-04
Land use	Pt	2.1E+00	2.1E+00	2.1E+00	1.7E-02	3.8E-03	6.3E+00
Ozone depletion	kg CFC11 eq	5.3E-11	5.0E-11	5.0E-11	1.5E-11	5.2E-12	1.7E-10
Particulate matter	disease inc.	2.6E-10	2.5E-10	3.0E-10	1.4E-10	2.3E-11	9.7E-10
Photochemical ozone formation	kg NMVOC eq	2.2E-05	2.1E-05	2.4E-05	1.1E-05	2.4E-06	8.0E-05
Resource use, fossils	MJ	3.8E-02	3.5E-02	3.5E-02	1.5E-02	2.3E-03	1.3E-01
Resource use, mins. & metals	kg Sb eq	2.8E-08	2.7E-08	2.7E-08	2.5E-09	4.9E-10	8.6E-08
Water use	m3 depriv.	1.4E-03	1.3E-03	1.3E-03	1.9E-04	2.2E-04	4.5E-03

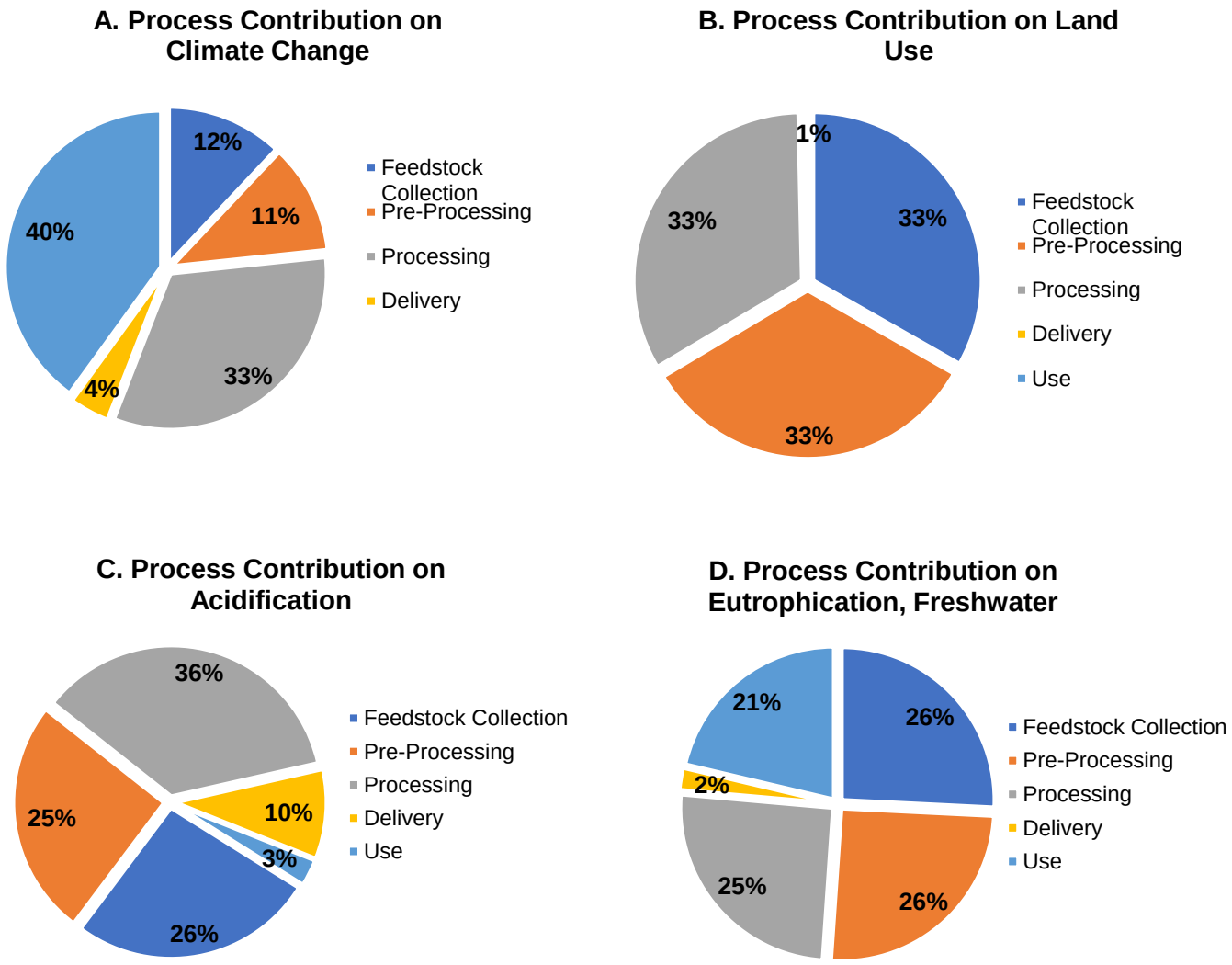

Figure 7.3. Process contributions to various life cycle impacts of charcoal

7.3.2 Comparative Performance

Figure 7.4 presents the normalized relative impact results of impact categories with distinct differences in the respective product systems. For each indicator, the maximum result is set to 100% and the results of the other variants are presented with that. As indicated, rice husk briquette showed lesser impact in most impact categories compared to charcoal except for resource utilization. This shows that for every MJ of energy generated from briquette in place of charcoal, there would be a significant reduction in environmental impacts. For example, the total impact contribution shows that rice husk briquette has a climate change impact of 0.02 kg CO_2 eq Per MJ while charcoal has 0.03

kg CO_2 eq Per MJ. This shows that for every MJ of energy generated and used from briquette in place of charcoal, climate change will be mitigated by 0.01 kg CO_2 eq (33.33%). Similarly, harnessing a megajoule of energy from rice husk briquette against charcoal will have the potential to reduce land use, acidification, particulate matter, and freshwater eutrophication by 6.27 Pt, 5.77E-5 mol H+ eq, 6.57 E-10 disease inc., and 7.6 E-6 kg P eq, respectively.

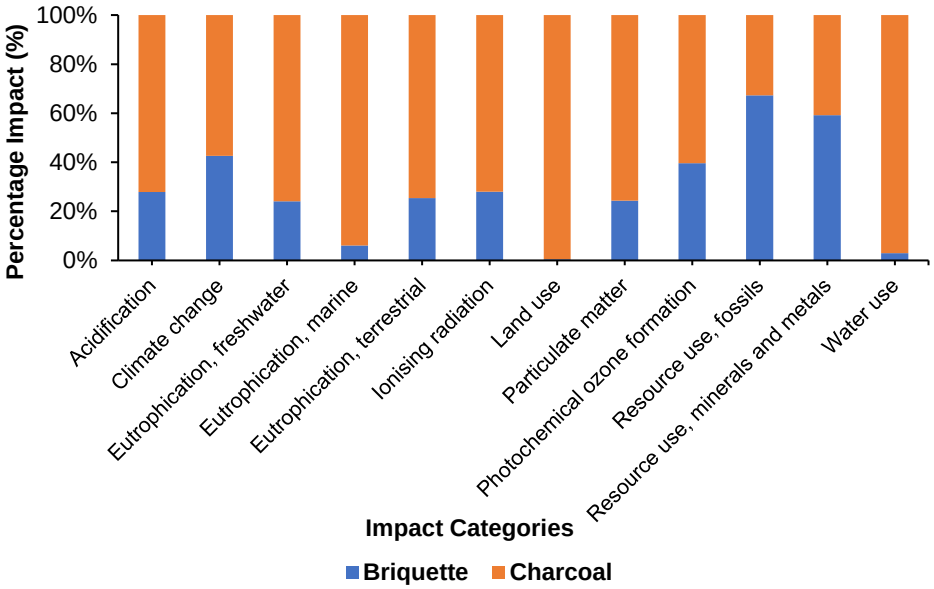

Figure 7.4. Relative impacts of briquette and charcoal production

7.3.3 Results of Sensitivity Analysis

The results of the sensitivity analysis are presented in Figures 7.5 and 7.6. The sensitivities of the briquette production and use scenario are shown in Fig. 7.5, while those of charcoal are shown in Fig. 7.6. The sensitivity ratios range between 0.91 to 0.95 for parameters used in the LCA of briquette and 0.91 to 1.0 for parameters used in the LCA of charcoal. If a parameter is increased by 10% and yields an SR of 1, it implies that the environmental impact is increased by 10%. Based on this, the most sensitive parameter in the briquette production and use scenario is the electricity used for binder preparation in the processing phase. This parameter has a SR of 0.95, 0.94, and 0.94, for climate change, acidification, and marine eutrophication, respectively. The findings imply that an increase in electricity consumption by 10% will increase the normalized climate change impact by 9.5%, and acidification and marine eutrophication by 9.4%, respectively. The results further verified

that electricity consumption is a very influential parameter that affects environmental impacts in briquette production. This corroborates the findings of Wang et al. (2017) which also noted electricity requirement to be a major environmental impact contributor. Thus, to curtail GHG emissions and other factors that exacerbate environmental impacts, electricity use must be minimized. In this case, the use of electricity from renewable sources is encouraged (Saba et al., 2020), especially as the electricity mix of Nigeria consists of 85% of fossils (oil, coal, and natural gas) (Adeshina et al., 2024). This is realistic as the country is blessed with enormous renewable resources. Alternatively, binders could be prepared using the cold gelatinization approach or the use of biomass fuels (e.g., pellets and briquettes).

In addition to electricity consumption, parameters like transportation and milling of rice husks also showed a reasonably high SR between 0.91 and 0.92 for the three impact categories. This indicates that by increasing the share of rice husk transportation and milling by 10%, the life cycle impacts will increase between 9.1% and 9.2%. In the case of transportation, siting the production points at the rice mills or very close to the processing mills will substantially curtail the impacts associated with transporting the rice husks. However, for households that typically choose to produce the briquettes themselves as advocated in this study, using less emissive transportation means like bicycles and motorcycles are suggested. This is even easier as rice husk is a low-density biomass making it possible to be transported through the above-mentioned mediums. In the case of milling, it is possible to densify rice husks directly without milling if the compression pressure is improved to between the medium and high-pressure range or by employing pretreatment measures such as carbonization or torrefaction.

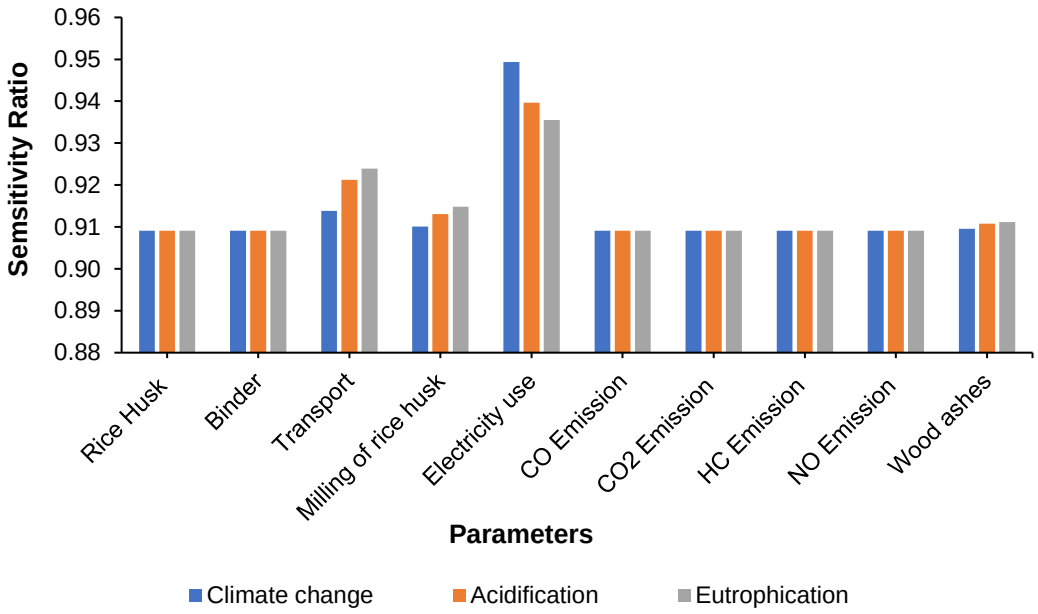

Figure 7.5. Parameter sensitivity ratios of briquette production

In the charcoal production scenario, the input materials (wood, leaves, and branches) presented the highest sensitivity ratio of 0.95 in the case of climate change, 1.0 in the case of acidification, and 0.95 in the case of marine eutrophication. This implies that an increase in the value of the parameters by 10% will increase the environmental impacts by 9.5%, 10%, and 9.5% for climate change, acidification, and marine eutrophication, respectively. Parameters that have SR values of 1 and above are the most sensitive, implying that a change or variation in their value will result in a large relative variation in the environmental impacts (Clavreul et al., 2012).

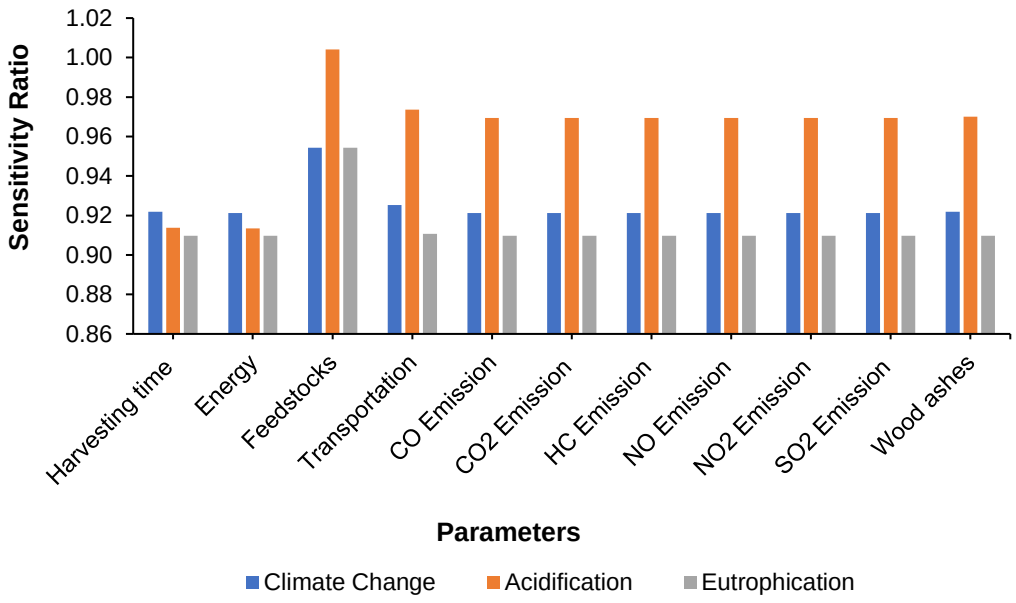

Figure 7.6. Parameter sensitivity ratios of charcoal production

7.4 Results of Uncertainty Analysis

Tables 7.6 and 7.7 present the uncertainty analysis results of the two product systems. The results contain the mean values, standard deviations, and percentage uncertainties of the 16 impact categories considered in this study. Like most LCA studies, where uncertainties are reported mainly due to the background data which are often based on estimates from outdated datasets (Baidoo et al., 2024), this study also has uncertainties that primarily emanated from assumptions, technological or geographical gaps, incomplete data, and lack of temporal information (Saba et al., 2020). These uncertainties are indications of data reliability, especially in cases where secondary sources are used and temporal correlation from the life cycle inventory (Baidoo et al., 2024; Bartocci et al., 2020). The uncertainty associated with the briquette's LCA is between 25.9% and 142.9% (Table 7.6), while that of charcoal LCA is between 76.6% and 141.3% (Table 7.7). These findings align with those of Baidoo et al. (2024), and less than that of Saba et al. (2020) who obtained as high as 287% to 530% in some impact categories. The uncertainty in the LCA of briquettes is lower than that of charcoal because the assumptions made in the LCA of briquettes were fewer. This implies that the data used were predominantly from a primary source.

Box plots were used to assess the distribution of the simulated impacts of the product systems (Figures 7.7 and 7.8). This contains the variability, outliers, and central tendency of selected impact categories (climate change, land use, acidification, and eutrophication). The distribution of the simulated impacts for briquette (Figure 7.7) is relatively stable for the selected categories. However, the simulation in charcoal shows a higher variability as the impacts are relatively skewed to the lower category depicting higher uncertainty. Similarly, the outliers are higher than those of briquettes which could signal high sensitivity. Following Saba et al. (2020), uncertainties of about 170% and below are considered acceptable. This is probably because Monte Carlo's uncertainties are often large due to the effect of system boundaries and choices of the user (Larsson Ivanov et al., 2018). Based on this assertion, the uncertainties in this study are within the acceptable range.

Table 7.6. Uncertainty related to the LCA of briquette production

Impact category	**Reference unit**	**Mean**	**Standard deviation**	**Uncertainty (%)**
Human toxicity, cancer	CTUh	7.93E-11	8.27E-11	104.28
Resource use, minerals and metals	kg Sb eq	1.47E-07	6.03E-08	41.04
Eutrophication, terrestrial	mol N eq	0.000144	3.74E-05	26.01
Acidification	mol H+ eq	4.5E-05	1.3E-05	28.95
Ionising radiation	kBq U-235 eq	0.000115	3.1E-05	26.86
Ecotoxicity, freshwater	CTUe	29.16211	33.71952	115.63
Land use	Pt	0.035757	0.011036	30.86
Eutrophication, freshwater	kg P eq	4.54E-06	3.75E-06	82.68
Particulate matter	disease inc.	4.31E-10	1.16E-10	26.83
Eutrophication, marine	kg N eq	1.33E-05	3.43E-06	25.90
Photochemical ozone formation	kg NMVOC eq	6.46E-05	2.02E-05	31.26
Resource use, fossils	MJ	0.305575	0.127206	41.63
Climate change	kg CO2 eq	0.024439	0.008447	34.57
Water use	m3 depriv.	0.000312	0.000446	142.86
Ozone depletion	kg CFC11 eq	5.45E-10	2.39E-10	43.81
Human toxicity, non-cancer	CTUh	5.54E-09	6.19E-09	111.77

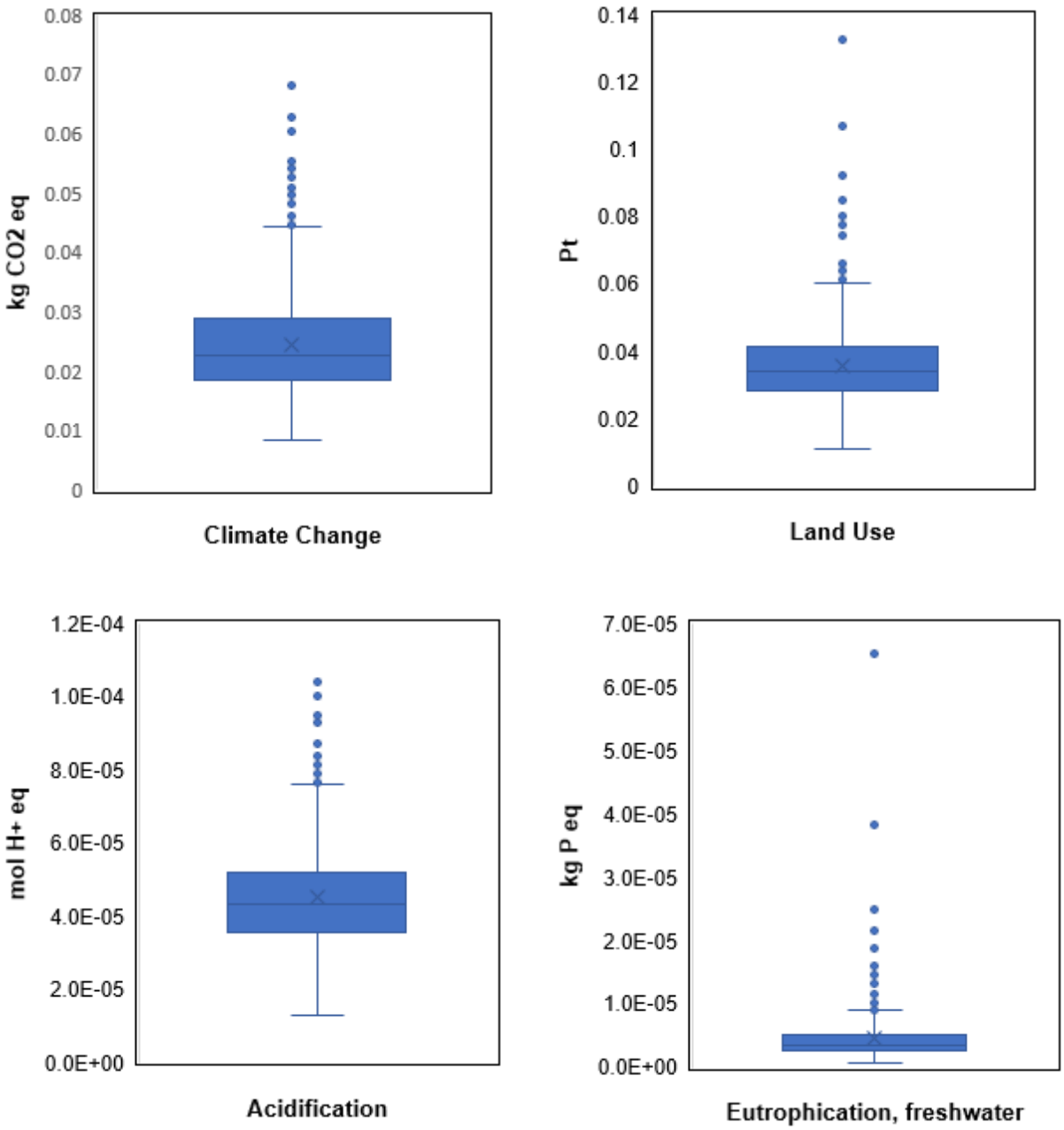

Figure 7.7. Monte Carlo simulation results of rice husk briquette

Although the variability is lower in the charcoal simulation (Figure 7.8), the data distribution is relatively skewed towards the lower impact. Similarly, the outliers are higher than those of briquettes which could signal high sensitivity. Overall, the uncertainties in the LCA are within the acceptable range. While the uncertainties in this study conform with Baidoo et al. (2024), it is less than that of Saba et al. (2020) who obtained as high as 287% to 530% in some impact categories.

Table 7.7. Uncertainty related to the LCA of charcoal production

Impact category	**Reference unit**	**Mean**	**Standard deviation**	**Uncertainty (%)**
Human toxicity, non-cancer	CTUh	5.5E-09	6.19E-09	112.47
Human toxicity, cancer	CTUh	1.34E-10	1.19E-10	88.82
Resource use, minerals and metals	kg Sb eq	1.59E-07	2.19E-07	138.16
Eutrophication, terrestrial	mol N eq	0.000595	0.000752	126.28
Acidification	mol H+ eq	0.000162	0.000198	122.46
Ionising radiation	kBq U-235 eq	0.000396	0.000524	132.37
Ecotoxicity, freshwater	CTUe	32.75953	33.97535	103.71
Land use	Pt	11.73922	16.58754	141.30
Eutrophication, freshwater	kg P eq	1.9E-05	2.22E-05	116.60
Particulate matter	disease inc.	1.68E-09	2.05E-09	121.86
Eutrophication, marine	kg N eq	0.0003	0.000415	138.70
Photochemical ozone formation	kg NMVOC eq	0.00014	0.000172	123.36
Resource use, fossils	MJ	0.2263	0.289898	128.10
Climate change	kg CO2 eq	0.038802	0.029706	76.56
Water use	m^3 depriv.	0.008153	0.010773	132.14
Ozone depletion	kg CFC11 eq	3.15E-10	4.09E-10	129.95

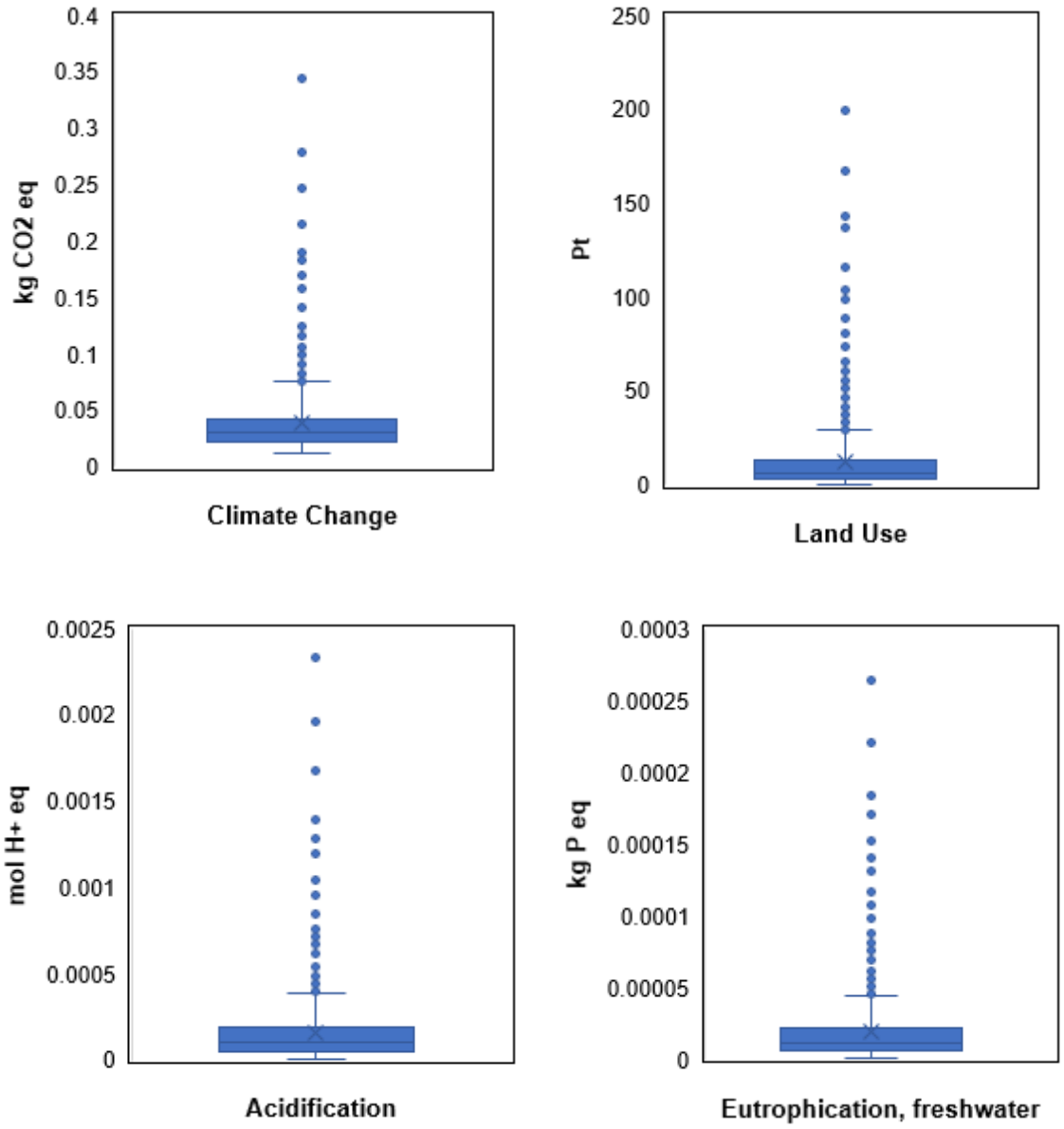

Figure 7.8. Monte Carlo simulation results of charcoal

7.5 Conclusion

This study considered a comparative LCA of rice husk briquette and charcoal from cradle (material collection) to gate. This was to quantify the various impacts that emanate from the two product systems using the environmental footprint impact assessment method. The outcome of the process contribution analysis showed that each process stage contributes differently to the whole life cycle. However, the use phase contributes more to eutrophication, ecotoxicity, human toxicity, and water use in briquette, and contributes more to climate change, ecotoxicity, and human toxicity in charcoal. The outcome from the comparative analysis revealed that briquette production has less environmental impacts than charcoal production. For example, for every MJ of energy generated and used from briquette against charcoal, 0.01 kg CO_2 eq (20%) climate change impact and 6.23904 Pt (99%) land use impact or environmental burden will be curtailed. If this value is extrapolated for the whole quantity of charcoal used in the study area, climate change and its related impacts would be substantially reduced. For example, if 50% of the rice husk generated in Nigeria is harnessed into briquettes, about 1.6 million tonnes would be produced. This quantity of briquette can mitigate climate change by 261 million kg CO_2 eq per year.

Sensitivity analysis was employed to comprehend the relative impact of the input parameters on the outputs. The outcome from the sensitivity analysis revealed that electricity use in the production phase is the most sensitive parameter in the LCA of briquette. This implies that electricity consumption is a very influential parameter in LCA. Thus, to abate environmental impacts, the life cycle stages involving electricity use such as the pretreatment and binder preparation phases for low-pressure production and the densification phase for high-pressure densification, must be carried out with less electricity or electricity from renewable energy sources. Further outcomes from the sensitivity analysis of charcoal showed the input materials (wood, leaves, and branches) as the most sensitive parameter. Similarly, the result from the uncertainty analysis showed that the uncertainties are within the tolerable limits.

Therefore, the study affirms that briquette production and use are more environmentally benign than charcoal. Thus, it validates that valorizing lignocellulosic biomass (e.g. rice husk) for energy instead of cutting down trees curtails deforestation, land degradation, and biodiversity loss, which enhances environmental sustainability. Hence, the findings would serve as a reference for future studies involving LCA of cooking fuels and could be crucial

in policy formulations in areas like waste to energy and environmental conservation. However, to achieve large-scale adoption and use of briquette as an alternative to fuelwood and charcoal, it is important to have it widely available and affordable. This could be achieved by setting up a large-scale and appropriate production technology. Through this medium, fuel briquettes would potentially serve as a sustainable energy source with the potential to contribute to the attainment of carbon neutrality and climate change mitigation.

CHAPTER 8 : CONCLUSION AND RECOMMENDATIONS

8.1 Conclusion

The following conclusions are drawn from the specific objectives:

i. Charcoal and fuelwood are the most used cooking energy in Kaduna State, Nigeria, with an average daily consumption between 1 and 5 kg per household. The choice of the stated energy types is mainly influenced by cost and availability. Household factors such as income, education level, age, occupation of household head, and marital status influence the choice of cooking energy. Furthermore, the study found that although traditional cooking energy options such as charcoal and fuelwood are the most used forms of cooking energy in the study area, other options such as electricity and LPG were present in most households in the urban parts. Thus, the energy use pattern conforms more with the fuel stacking theory than the energy ladder theory.

ii. *Anogeissus leiocarpus* (African birch), *Khaya senegalensis* (African mahogany), *Parkia biglobosa* (African locust bean), and *Eucalyptus cam.* (Red gum), having presented good physical and thermal properties in conformity with the international wood pellet standards are the most suitable wood species for energy production. However, it is imperative to note that *Khaya senegalensis* is classified as a vulnerable species according to the International Union for Conservation of Nature (IUCN), and thus possesses a very high risk of extinction. Therefore, measures must be put in place to ensure its sustainable utilization. In addition, in environments where non-suitable species are the dominant or available woods, biomass blends or additives could be employed to adapt the quality to the ISO commercialization standards. In the same context, using improved cookstoves is another measure to minimize fuel use and toxic gas emissions during combustion. These measures if adopted would substantially curtail deforestation.

iii. Uncarbonized rice husk briquettes with optimal quality for domestic use can be produced under low pressure (≤ 5 MPa). The study found that to produce briquettes with rice husks at low pressure 15% binder, 1 mm particle size of rice husks, and 0.5 min residence time are optimum. With these optimal conditions, quality metrics of 0.71 g/cm^3 compressed density, 84.8% impact resistance, and 0.30 g/cm^3 relaxed density are achievable. Similarly, the study found that locust bean pulp and sweet potato peel (gelatinized with locust bean husk solution) have good potential as binders in briquette production.

iv. The comparative environmental life cycle analysis showed that briquette production and use have less environmental impact than charcoal. Based on this, for every MJ of energy produced and use from briquette against charcoal, climate change will be mitigated to a magnitude of 0.01 kg CO_2 eq (20%), and the environmental burden from land use will be reduced by 6.24 Pt (99%). If this value is extrapolated for the whole quantity of charcoal produced and used in the study area, climate change and land use impacts would be substantially reduced. For example, if 50% of the rice husk generated in Nigeria is harnessed into briquettes, about 1.6 million tonnes of briquettes would be produced. This quantity of briquette can mitigate climate change by 261 million kg CO_2 eq per year. Therefore, the study affirms that briquette production and use is more environmentally benign than charcoal.

8.2 Recommendations

8.2.1 Recommendations for Policy: Nigerian Government (Energy Commission of Nigeria; Federal and State Ministries of Environment; Federal and State Ministries of Agriculture), and NGOs

i. Measures such as constant tree planting, and restricting wood fuel energy production to species like *Anogeissus leiocarpus* (African birch), *Parkia biglobosa* (African locust bean), and *Eucalyptus cam.* (Red gum) should be implemented to curtail deforestation in Kaduna State and the country.
ii. Cleaner energy options like electricity (from renewable sources), LPG, and bio-based fuels (e.g. biogas, briquettes, and pellets) should be made available and affordable to minimize the use of traditional solid fuels and open fires.
iii. An appropriate and affordable technology for briquette production should be implemented for large-scale production.
iv. A practical strategy for utilizing rice husks and other agricultural residues such as for energy production (briquettes, pellets, etc.) should be developed and implemented.
v. A service delivery protocol should be developed and implemented for waste-to-energy conversion as a measure of forest conservation and climate change mitigation. This will aid the sustainable use of agricultural waste for energy.
vi. A national or country-based database should be developed for accurate LCA analysis.

8.2.2 Recommendations for Future Research

i. The energy use characterization should be conducted routinely to understand the changes over time.
ii. The attitude and willingness of households to change from using charcoal and fuelwood to briquette should be assessed.
iii. The experimental impact of blends and additives on wood species with low physical and thermal performance should be further researched into.
iv. Future research should explore the valorization of rice husk into briquettes at low to medium pressure without milling the husk, to minimize the energy expended in milling.

v. Co-densifying rice husks and other forms of biomass and using blends such as charcoal dust could be explored to reduce the effect of silica and ash in rice husks.
vi. The study investigated the quality metrics under constant pressure. Thus, future studies could investigate a range of compression pressures to determine the optimum or ideal pressure for producing uncarbonized rice husk briquette.
vii. In terms of the binding material, studies should explore more non-edible organic materials, especially those largely available and considered as waste to promote food security and waste management.
viii. Future research should conduct a detailed economic analysis of producing rice husk briquette and compare it with conventional solid fuels.
ix. Future studies should explore the comparative environmental impact of other solid fuels (firewood, wood pellets, and coal) with rice husk briquette.

8.2.3 Contribution to Knowledge

As a contribution to knowledge, the study provides the status of household energy use and factors influencing cooking energy choice in Kaduna State, Nigeria. In addition, novel biomass binders with good potential use of briquettes have been identified. Also, the possibility of valorizing rice husk into fuel briquettes at low pressure without carbonization has been validated. Similarly, wood species with the best thermochemical performance in the study area have been reported. The study also determined the optimum conditions for producing rice husk briquette using a low-pressure system. In addition, a model has been developed to predict selected quality metrics (compressed density, relaxed density, impact resistance, and compressive strength) of rice husk briquette.

Finally, the comparative environmental impacts of rice husk briquette and charcoal have been determined. As a contribution to policy, the findings can serve as a reference for policy review and formulation on climate change mitigation, waste-to-energy production, and forest conservation. Similarly, the study has suggested sustainable measures to reduce the indiscriminate cutting of trees for fuel production by recommending the valorization of rice husk into fuel briquette and recommending wood fuel energy production to sustainable wood species that meet the standard suitability metrics. In addition, the study has provided practical measures for utilizing rice husks and other agricultural residues, through which a waste management strategy could be implemented.

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APPENDICES

Appendix 1: List of Publications from the Thesis

Journal Publication

i. **Yunusa S.U.**; Mensah E.; Preko K.; Narra S.; Saleh A.; Dalha I. B.; and Abdulsalam M. **(2024)**. Optimizing selected quality metrics of rice husk briquettes: a response surface methodology approach. Biomass Conversion and Biorefinery. Springer. https://doi.org/ 10.1007/s13399-024-05906-6

ii. **Yunusa S.U.**; Mensah E.; Preko K.; Narra S.; Saleh A.; and Safietou S. **(2024)**. Assessing the nexus between household dynamics and cooking energy choice: Evidence from Kaduna state, northwestern Nigeria. Energy Nexus. Elsevier. https:// doi.org/10.1016/j.nexus.2024.100310

iii. **Yunusa S.U.**; Narra S.; Mensah E.; Preko K.; and Saleh A. **(2024)**. Physical and Thermochemical Properties of Selected Wood Species in Nigeria: A Fuel Suitability and Pelleting Potential Assessment. Fuels. MDPI. https://doi.org/10.3390/fuels5030015

iv. **Yunusa S.U.**; Mensah E.; Preko K.; Narra S.; Saleh A.; Safietou S.; Isiaka M.; Dalha I.B.; and Abdulsalam M. **(2023)**. Biomass cookstoves: A review of technical aspects and recent advances. Energy Nexus. Elsevier. https:// doi.org/10.1016/j.nexus.2023.100225

v. **Yunusa S.U.**; Mensah E.; Preko K.; Narra S.; Saleh A.; and Safietou S. **(2023)**. A comprehensive review on the technical aspects of biomass briquetting. *Biomass Conversion and Biorefinery*. Springer. https://doi.org/10.1007/s13399-023-04387-3

vi. **Yunusa S.U.**; Mensah E.; Preko K.; Narra S.; Saleh A.; and Safietou S. Development and optimization of rice husk composite briquettes as a sustainable cooking energy solution in Nigeria. *Under Review*

Book Chapters

i. **Yunusa S. U.;** Narra S.; Mensah E.; Preko K.; Saleh A. **(2024).** Biomass briquette production using a novel binder: A comparative quality analysis between two types of rice husk in Nigeria. 18. Rostocker Bioenergieforum. Band 124. Environmental Engineering Series. ISBN: 978-3-86009-559-1. Vol. 18, Pages: 237-251.

ii. **Yunusa S.U.**; Mensah E.; Preko K.; Narra S.; Saleh A.; Safietou S.; and Sadiq N. H. (2024). Characterization of three lignocellulosic biomass materials as novel binders in briquette production**.** In innovations in Circular Economy and Renewable Energy in Africa. pp 153 – 166. Springer. https://doi.org/10.1007/978-3-031-68330-5

Conference Proceedings

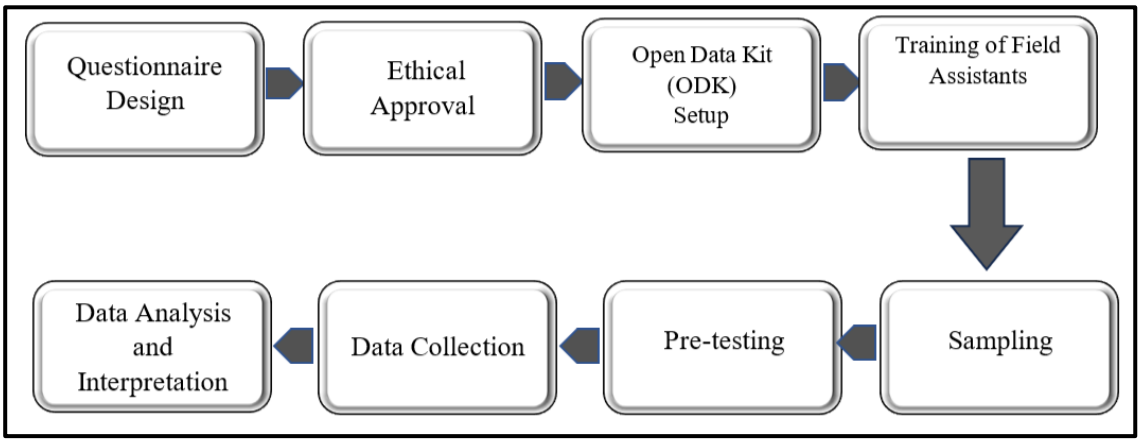
i. **Yunusa S.U.**; Mensah E.; Preko K.; Narra S.; Saleh A.; and Safietou S. (2023). Evaluation of selected physical and thermochemical properties of rice husk of one- and two-stage milling for briquette production. *Proceedings of the 23rd Nigeria Institution of Agricultural Engineers (NIAE) International Conference*, **(30th October - 3rd November 2023)**, University of Maiduguri, Nigeria. 43, 430-442.

ii. **Yunusa S.U.**; Mensah E.; Preko K.; Narra S.; Saleh A. (2024) Strategies for improving the quality of low-pressured rice husks briquettes: A Mini-Review. *2nd International Conference on Circular Economy, Renewable Energies and Green Hydrogen in Africa (ICERA)*, **(8th – 10th October 2024)**, Lome, Togo.

Workshop

i. **Yunusa S.U.**; Alberto B.; Narra S.; Mensah E.; Preko K.; Saleh A.; and Safietou S. (2024). A Comparative Environmental Life Cycle Assessment of Small-Scale Rice Husk Briquetting Unit and Charcoal Production in Kaduna State Nigeria. **LCA Workshop and Mini-Symposium, Kumasi, Ghana (21st October – 1st November 2024)**

Appendix 2: Flowchart of the Household Survey



Appendix 3: Household Survey Questionnaire

Household Questionnaire on Characterization of Primary Cooking Energy in Kaduna State, Nigeria

Serial No _____ Date of Interview _____Interviewers name _____
Name of respondent _____Age_____Gender_____ (Female =1, Male = 0)
Local Government Area _____District _____
Ward_____Street _____
Household Income (Assessed by enumerator based on household type) (1= low, 0 = others)

Marital Status_____ (1=Married, 0 = others)

Interview time _____

(The interviewer must ensure that the interview is with the main cook of the household)

Introduction

Good morning/afternoon. My name is_____ from_____We are conducting a survey on household cooking fuels. The survey aims to characterize the various cooking energy used in households within Kaduna State, Nigeria. All the information given will be kept strictly confidential and only be used for this study. I would be highly obliged if you can spare us some of your time. Please do you wish to continue? Thank you.

SECTION A: Personal Information

1. Who is the head of the household?
   1= Husband 2 = Wife 3 = Others (specify) _____
2. What is the occupation of the head of household?
   1 = Farming 2 = Civil Servant 3 = Business/self-employed 4 = Part-time employed
   5 = Others (specify) _____
3. What is the level of education of the head of the household?
   1 = None, 2 = Primary, 3 = Junior Secondary, 4 = Senior secondary, 5 = Diploma, 6 = HND
   7 = B.Sc., 8=M.Sc., 9= PhD, 10 = other
4. What is your highest level of education?
   1 = None, 2 = Primary, 3 = Junior Secondary, 4 = Senior secondary, 5 = Diploma, 6 = HND
   7 = B.Sc., 8=M.Sc., 9 = PhD, 10 = other
5. What is the size of your household?

   1= alone 2 = 2, 3 = 3, 4 = 4 5 = 5 or more

SECTION B: <u>Stove information</u>

Answers to questions 7 to 10 are to be filled in the table below. (If possible, the enumerator is expected to request to see the stoves in the household to fill out the table for questions 7 to 10).

6. What stoves are present in the household?
7. For how long have you had these stoves? (*in months for each stove*)
8. What is the condition of the stoves present?:
1 = good condition, 2 = cracks on the body, 3 = cracks on the liner, 4 = broken door, 5 = broken pot-rest, 6 = worn out metal, 7 = broken liner, 8 = no pot rest, 9 = worn out grate, 10 = other (specify)
9. For how long (hours) do you use the stove(s) in a day?

1 = <2 hr, 2 = 2-4 hr, 3 = 5-7 hr, 4 = 8-10 hr, 5 = 11-13 hr, 6 = >13

SECTION C: <u>Fuel use information</u>

10. What type of fuel or energy source does this household use for cooking and other activities?
    1= firewood, 2= charcoal 3= kerosine 4= agricultural or crop residue 5= LPG 6= electricity 7=coal, 8= Briquette/pellets 9= Biogas 10= other
11. Which of the above-mentioned fuels is the primary fuel you use for cooking?
    1= firewood, 2= charcoal 3= kerosine 4= agricultural or crop residue 5= LPG 6= electricity 7=coal, 8= Briquette/pellets, 9= Biogas 10= other
12. What made you select the above fuel(s) as your primary fuel?
    1= freely available, 2= less costly 3= efficiency 4= no specific reason 5= others (specify) ____
13. What quantity of fuel do you use per day? (The enumerator should help analyze quantity)
    1= <1kg, 2=1-5kg, 3=6-10kg, 4=11-15kg, 5 = 16 - 20kg, 6 = 21 – 25 kg, 7 = 26-30kg, 8 = >30kg (specify if possible)
14. How often do you purchase fuel?
    1 = daily, 2 = weekly, 3 = monthly, 4 = other
15. How much do you spend on the purchase of fuel based on the above frequency? (i.e. daily, weekly or monthly)
    1= < ₦500, 2= ₦500 - ₦1000, 3= ₦ 1001 - ₦2000, 4= ₦2001 - ₦3000, 5= >₦3000
16. What is the origin of the fuel (specify town)

Question 18-20 is only for households involve in farming or with access to agricultural residues

17. Are the residues used as fuel for cooking? YES, NO?

18. If YES, how efficient does it compare with firewood and charcoal in terms of quality?

1= Very efficient, 2 = Moderately efficient, 3 = Not efficient, 4 = Can't say

19. Have you used processed biomass as fuel before? 1= Yes, 2= No

20. If YES, what are the sources in terms of quantity and how does it compare with firewood or charcoal?

1= Fuel/cost saving, 2 = cooks fast, 3 = Easily accessible, 4 = low emission, 5 = Safety, 6 = comfort, 7 = better taste of food, 8 = others (specify):_____

General perceptions

21. Do you think your method of cooking is affecting your health and the environment?
1= Yes, 2= No
22. What is your preferred/dream source of energy?

Appendix 4: Ethical Approval

COMMITTEE ON USE OF HUMAN SUBJECTS FOR RESEARCH
Directorate of Academic Planning and Monitoring
AHMADU BELLO UNIVERSITY, ZARIA

Ag. Chairman: Professor B.F. Okeshola, B.Sc., M.Sc. (A.B.U.), Ph.D (Bayero University, Kano), MSSAN
https://abu.edu.ng/human-subject Phone Number: 08036499929 e-mail: humansubject.abu.edu.ng

Appl. No: ABUCUHSR/2023/Civil Engineering/004 7th February, 2023
Approval No: ABUCUHSR/2023/004

Engr. Suleiman Usman YUNUSA
WASCAL Centre,
Department of Civil Engineering,
Kwame Nkrumah University of Science and Technology,
Kumasi, Ghana

Dear Sir,

PROVISIONAL APPROVAL OF RESEARCH TITLED "ASSESSING THE POTENTIAL OF BIOMASS (RISK HUSK) BRIQUETTE IN CLIMATE CHANGE MITIGATION"

This is to convey the provisional approval of the ABUCUHSR to you for the aforestated study domiciled in the Department of Civil Engineering, Kwame Nkrumah University of Science and Technology. The approval is predicated on the assumption that you shall maintain and cater for the study subjects as indicated in your application.

Monitoring of the Research by spot checks, invitations, interactions with the subjects by any other means the Committee deems fit shall be undertaken at the convenience of the Committee.

This approval can and shall be revoked should a significant breach in the terms and condition of the approval occur. It is hence your responsibility to ensure that the agreed terms are maintained to the end of the Study.

The said approval shall be posted on the ABUCUHSR Page on the University's website.
Note upon completion of the research, ethical clearance certificate will be issued.

Yours sincerely

Prof. F.B. Okeshola
Ag. Chairman, ABUCUHSR

ETHICS COMMITTEE ON USE OF HUMAN SUBJECTS FOR RESEARCH
07 FEB 2023
Ahamdu Bello University Zaria

Cc Director, IAII&CT
" Director, WASCAL Centre, Kwame Nkrumah University of Science & Technology, Ghana
" Prof. E. Mensah, Agricultural and Bio-systems Engineering, KNUST, Ghana
" Dr. Aminu Saleh, Department of Agricultural and Bio-resource Engineering, ABU
" Prof. F.B. Okeshola, Ag. Chairman, ABUCUHSR

Appendix 5: LCA Dataset license confirmation

openLCA nexus

Confirmation for Academic Licence (free of charge)

Thank you for ordering an academic LCA database from openLCA Nexus, for academic use.

According to the EULA of the database you ordered, you need to confirm the following:

- You are ordering the licence on behalf of an academic institution, and
- The licence will be used for academic purposes only, by students and staff registered at that institution.

Since you ordered a licence free of charge, you also need to confirm that the academic institution is in one of the following UN classified countries: (https://www.un.org/development/desa/dpad/wp-content/uploads/sites/45/WESP2020_Annex.pdf)

Afghanistan	Comoros	Gambia	Madagascar	Republic of Moldova	Tajikistan
Angola	Congo	Ghana	Malawi	Rwanda	Timor-Leste
Bangladesh	Côte d'Ivoire	Guinea	Mali	Sao Tome and Principe	Togo
Benin	Democratic People's Republic of Korea	Guinea-Bissau	Mauritania	Senegalc	Tunisia
Bhutan	Democratic Republic of the Congo	Haiti	Mongolia	Sierra Leone	Uganda
Bolivia (Plurinational State of)	Djibouti	Honduras	Morocco	Solomon Islands	Ukraine
Burkina Faso	Egypt	India	Mozambique	Somalia	United Republic of Tanzania
Burundi	El Salvador	Indonesia	Myanmar	South Sudan	Uzbekistan
Cabo Verde	Eritrea	Kenya	Nepal	State of Palestine	Vanuatu
Cambodia	Eswatini	Kiribati	Nicaragua	Sudan	Viet Nam
Cameroon	Ethiopia	Kyrgyzstan	Niger	Syrian Arab Republic	Yemen
Central African Republic		Lao People's Democratic Republic	Nigeria		Zambia
Chad		Lesotho	Pakistan		Zimbabwe
		Liberia	Papua New Guinea		
			Philippines		

Your contact details	
Organisation: Ahmadu Bello University	Department: Agricultural & Bioresources Engineering
Name: Suleiman U. Yunusa	Phone: +2348130628584
Street: Samaru	Fax:
Zip-code: 810107	Name of supervising Professor**: Dr. Aminu Saleh
City: Zaria	Professor or Institution Email**: SUyunusa@abu.edu.ng
Country: Nigeria	Order no.: 263675

** Without this information we cannot grant you access to the ecoinvent database.

Licence conditions and signature: **I hereby declare the accuracy of the statement above:**	
Name: Suleiman Usman Yunusa	Institution stamp: DEPT. ABU. P.M.B. 1044. ZARIA. 12/04/2023
Position: Lecturer II	
Signature: Suleiman	
Date: 12/04/2023	

➡ Please upload this page directly into the **"orders"** section of your **Nexus account.**

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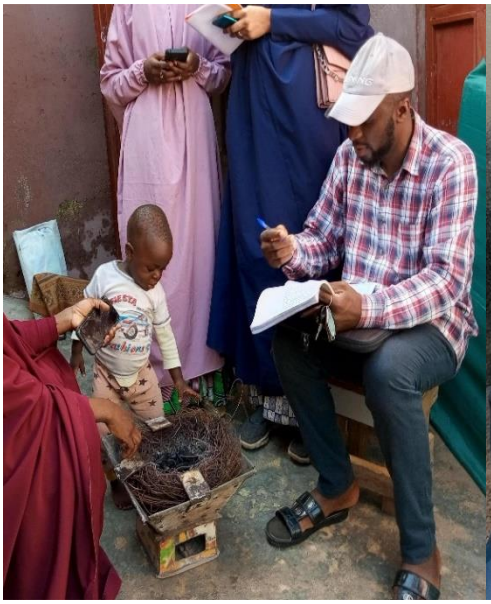
Appendix 6: Pictorial views from fieldwork

- **Household Survey**




- **Conventional fuel inventory collection**


- **Feedstock Characterization**

- **Feedstock Pretreatment**

- **Briquette production**

- **Briquette Analysis**