EFFECT OF PROCESS PARAMETERS AND FEEDSTOCKS ON SELECTED BRIQUETTE PROPERTIES

OKWARA MAYABI WILBERFORCE

A Thesis Submitted to the Graduate School in Fulfillment of the Requirement for the Master of Science Degree in Agricultural Engineering of Egerton University

EGERTON UNIVERSITY

OCTOBER, 2022.

DECLARATION AND RECOMMENDATION

Declaration

I declare that this thesis is my original work and it has not been wholly or in part presented for any award in any university or institution to the best of my knowledge.

Signature: Date: **21th October, 2022**

Okwara Wilberforce Mayabi

BM11/13600/19

Recommendation

This thesis is the candidate's original work and has been prepared with our guidance and assistance. It is submitted for examination with our approval as official University supervisors.

Signature: Date: **October 21, 2022**

Prof. Daudi Nyaanga

Department of Agricultural Engineering

Egerton University

Signature: Date: **21th October 2022**

Dr. Eng. Kabok P. Aguko, PhD, MEBK, CE

Department of Agricultural Engineering and Renewable Energy

Jaramogi Oginga Odinga University of Science and Technology (JOOUST)

COPYRIGHT

© 2022 Wilberforce Mayabi Okwara

All rights reserved. Under copyright law, no part of this publication may be reproduced by print, stored in a retrieval system or transmitted in any form or by any means: scanning, tape, photocopying, recording or otherwise, without prior written permission from the author and/or Egerton University.

DEDICATION

This research work is dedicated to my father Ernest Okwara, who has been a source of encouragement and inspiration during challenging times of my academic programme. I appreciate his prayers, understanding and support during my study and research period to ensure that I pursued education to great altitudes of success. I also dedicate this thesis to my brothers and my sisters for continuous support during my education. Also, to my numerous friends: Musa, Baqe and Amos who have supported me throughout the process. I appreciate all what they have done, especially their prayers and advice needed to overcome challenges encountered along the research process.

In a special way, this thesis is dedicated to all my trainers of good will; the primary and secondary school teachers, University lecturers and all those who have immensely contributed to my success in the academic exploration.

Finally, this thesis is dedicated to all humankind who depends on briquettes as clean energy for sustainable and socio-economic development with challenges of emissions, low efficiencies and limited affordable biomass sources.

ACKNOWLEDGEMENTS

My sincere gratitude goes to Almighty God for the Grace, Guidance, Protection and Good health thus enabling me accomplish this work. Special thanks to Egerton University staff in the Faculty of Engineering and Technology, who provided a very conducive environment and opportunity for my mentorship during my theoretical and research training period.

Distinguished gratitude goes to my supervisors; Prof. Daudi Nyaanga and Dr. Eng. Peter Kabok. They offered scholastic guidance, constant encouragement, valuable suggestions and great support throughout the development of this thesis. Their approach allowed me great freedom to pursue independent work of interest. In addition, they kept my ideas focused in the right direction. They always listened to me and advised on how to get solutions to come up with worthwhile research thesis. It is a great opportunity and fortune to work with such great supervisors, for they have immensely multiplied my determination in research conceptualization and development. I am thankful to Prof. Eng. J. Onyando (Dean), Dr. M. Njue, Dr. M. R. Wambua (COD), Dr. V. O. Odongo, Dr. P. M. Kundu, Dr. S. Nyakach and the entire Faculty of Engineering and Technology for their encouragement and advice during the proposal, research and thesis development.

I thank the Centre of Excellence in Sustainable Agricultural and Agro-business Management (CESAAM) through the Ministry of Education, Science and Technology (MoEST) for providing scholarship and financial support for the research project. Also, I recognize The Kenya Climate Smart Agriculture Project (KCSAP) who helped me develop the idea on renewable energy, Nakuru Water and Sanitation Services (NAWASSCOAL) and Department of Food Science and Dairy, Egerton University for providing equipment used to collect data used in this study. I would also like to appreciate all the field assistants that helped me during the data collection.

ABSTRACT

Energy availability at the domestic level continues to pose a challenge worldwide, especially in Africa. Densification of biomass into briquettes has been considered as a substitute alternative fuel. Briquettes based on two feedstocks have shown improved characteristics; however, knowledge about the effect of briquettes with more than two feedstocks and best mix ratios is not thoroughly studied. The broad objective of this study was to assess the effect of process parameters and agricultural wastes (rice husk- maize cobs and bagasse) as feedstocks on selected briquette properties at different mix ratios (1:1:1, 1:2:2, 1:3:3, 2:1:2, 2:2:3, 2:3:1, 3:1:3, 3:2:1 and 3:3:2) after carbonization using a drum kiln. Then char was milled to less than 2mm, blended, and mixed with molasses binder for densification and agglomeration. The performance characteristics (using Water Boiling Test in a "jiko okoa" cookstove) including ignition time, time to boil, burning rate, specific fuel consumption, and power output were determined. A mixture of 1:1:1 was used for the three, screw press, drum and hand agglomeration for briquettes production. The high density (screw press) briquettes which had better characteristics were used to determine their physical and combustion properties at selected feedstocks mix ratios. Taguchi-based Grey Relational Analysis was used to determine optimal condition for briquettes which was attained at mix ratio of 3:2:1 using the screw press technique. Physical properties of briquettes; moisture content and density were 6.43% and 904 kg/m^3 respectively. Combustion characteristics of these optimal briquettes were 3.63% ash content, 18.56% volatile matter, 77.81% fixed carbon and 29.04 MJ/kg calorific value. The quality of briquettes was influenced by technique and mix ratios. These research findings are of importance to briquettes users as a source of clean energy and environment conservation thus realization of Sustainable Development Goal (SDGs #7).

TABLE OF CONTENTS

DECLARATION AND RECOMMENDATION ..... **ii**

COPYRIGHT ..... **iii**

DEDICATION ..... **iv**

ACKNOWLEDGEMENTS ..... **v**

ABSTRACT ..... **vi**

LIST OF TABLES ..... **xi**

LIST OF FIGURES ..... **xii**

LIST OF SYMBOLS ..... **xiii**

LIST OF ABBREVIATIONS AND ACRONYMS ..... **xiv**

CHAPTER ONE **1**

INTRODUCTION **1**

1.1 Background. 1

1.2. Statement of the Problem 3

1.3. Objectives 4

1.4. Research Questions 4

1.5. Justification 4

1.6. Scope and Limitation 5

1.7 Definition of Terms 7

CHAPTER TWO **8**

LITERATURE REVIEW **8**

2.1 General Overview on Briquetting Process 8

2.1.1 Development of Carbonization Kiln 9

2.2. Briquetting Technologies 10

2.2.1 Pressurized Briquette Production 12

2.2.2 Non-pressurized Briquette Production 16

2.3 Parameters Affecting Briquetting Process 18

2.3.1 Pressure 18

2.3.2 Temperatures 20
2.3.3 Varying Retention Time 22
2.3.4 Die Geometry and Speed 22
2.4 Stove Performance Properties using Briquettes 22
2.4.1 Briquettes Performances using Water Boiling Test 23
2.5 Biomass Feedstocks 24
2.5.1 binder. 29
2.5.2 Mix Ratios 30
2.5.3 Effect of Physical Characteristics on Briquettes Properties 31
2.5.4 Combustion Characteristics of Briquettes 34
2.6 Optimization of Briquetting Parameters. 36
CHAPTER THREE. 40
MATERIALS AND METHODS. 40
3.1 Research Site, Experimental System and Material Preparation 40
3.1.1 Research Site 40
3.1.2 Development of Carbonization Kiln System 41
3.1.3: Fabrication of Screw press and Drum Agglomerator 42
3.1.4 Material Preparation 44
3.1.5 Mix Ratios 45
3.2 Effect of Briquetting Techniques on Performance Properties of Briquettes 45
3.3 Effect of Mix Ratios of Husk: Corncobs: Bagasse on Briquettes' Physical and Combustion Properties 46
3.3.1 Physical Properties of Briquettes 47
3.3.2 Combustion Properties of Briquettes 47
3.4 Optimization of Briquette Properties Parameters. 48

3.5 Data Analysis 49

CHAPTER FOUR 51

RESULTS AND DISCUSSIONS 51

4.1 Effect of Selected Briquetting Techniques on Performances Properties of Briquettes. 51

4.1.1 Effect of Briquetting Techniques on Ignition Time 51

4.1.2 Effect of Briquetting Techniques on Time to Boil (min) 52

4.1.3 Effect of Briquetting Techniques on Burning Rate 52

4.1.4 Effect of Briquetting Techniques on Specific Fuel Consumption 54

4.1.5 Effect of Briquetting Techniques on Power Output 55

4.2 Effect of Mix Ratios of Husk: Corncobs: Bagasse on Physical and Combustion Properties of Briquettes 56

4.2.1 Physical Properties of Briquettes 57

4.2.2 Combustion Properties of Briquettes 60

4.2.3 Analysis of Variance for Physical and Combustion Properties of Briquettes 66

4.3 Optimization of Briquette Properties Parameters 66

4.3.1 Analysis of results for Taguchi based single objective optimization 66

4.3.2 Multi-objective Optimization using Taguchi-Grey Relational Analysis 68

CHAPTER FIVE 71

CONCLUSIONS AND RECOMMENDATIONS 71

5.1 Conclusions 71

5.2 Recommendations 72

REFERENCES 73

APPENDICES 92

Appendix A: Design Calculations and Procedures 92

Appendix B: Experimental Data and Statistical Analysis 98

Appendix C: Research Photos 108

Appendix D: Research Permit (NACOSTI) 111

Appendix E: Relevant Publications Based on the Study 112

LIST OF TABLES

Table 2.1: Comparison of Different Briquette Presses 11
Table 2.2: Cellulose, Hemicellulose and Lignin Contents in Some Agricultural Residues 23
Table 2.3: Burning Characteristics of Rice Husk and Corncob Briquettes 28
Table 2.4: Combustion Characteristics of Rice Husk and Corncob Briquettes 28
Table 2.5: Physical and Fuel Characteristics of Rice Husk and Corncob Briquettes 26
Table 2.6: Physical and Combustion Properties of Briquettes from Corncob and Rice Husk 36
Table 3.1: Design Result Data for Screw Press Development 40
Table 3.2: Drum Agglomerator Design Dimensions and Data 43
Table 3.3: Briquettes Physical and Combustion Properties 46
Table 3.4: Operation parameters and Levels 48
Table 3.5: Optimization of Experimental Layout 49
Table 4.1: Effect of Technique on Briquettes' Performance Parameters 48
Table 4.2: Effect of Mix Ratios of Rice Husk: Corncobs: Bagasse on Briquettes Moisture Content and Density 55
Table 4.3: Effect of Mix Ratios of Rice Husk: Corncobs: Bagasse on Combustion Properties... 59
Table 4.4: Signal to Noise Ratios for Physical and Combustion properties 65
Table 4.5: Optimal Physical and Combustion Properties 69

LIST OF FIGURES

Figure 1.1: Conceptual framework 6
Figure 2.1: Flow of briquetting process 9
Figure 2.2: Effect of compaction pressure on briquette properties 20
Figure 2.3: Briquette density and compression pressure at different temperatures 21
Figure 2.4: Temperatures during the three phases of the WBT 24
Figure 2.5: Density of different biomass briquettes produced at different moisture contents 33
Figure 2.6: Effect of briquetting pressure, particle size, and temperature on density 34
Figure 2.7: Steps involved in Taguchi Method 37
Figure 3.1: Map of Kenya, Nakuru County and Egerton University 40
Figure 3.2: Kiln Design 41
Figure 3.3: Schematic Diagram of a Straight Screw Press 43
Figure 3.4: Improved Egerton Screw Press Machine 43
Figure 3.5: Drum Agglomerator 44
Figure 4.1a: Effect of briquetting techniques on burning rate 54
Figure 4.1b: Effect of briquetting techniques on specific fuel consumption 55
Figure 4.1c: Effect of technique on briquettes power output 56
Figure 4.2a: Effect of Mix Ratios of Selected Feedstocks on Briquette's Moisture Content 58
Figure 4.2b: Effect of Mix Ratios of Selected Feedstocks on Briquettes Density 60
Figure 4.2c: Effect of mix ratios and density on calorific value of briquettes 62
Figure 4.2d: Effect of feedstocks mix ratios on briquettes combustion properties 63
Figure 4.2e: Effect of mix ratios and density on briquettes fixed carbon 65
Figure 4.3: A graph showing S/N ratios and its corresponding GRG in multi objective optimization 69

LIST OF SYMBOLS

Symbol	Description
°C	Degrees Celsius
<	Less than
ρ	Density
%	Percentage
>	Great than
g/min	Grams per minute
g/ml	Grams per milliliter
J/g	Joules per grams
kg	Kilograms
MJ	Mega Joules
kW	Kilowatts
R	Radius
V	Volume

LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation/Acronym	Description
AC	Ash Content
ANOVA	Analysis of Variance
ASABE	American Society of Agricultural and Biological Engineers.
ASAE	American Society of Association Executives
ASTM	American Society for Testing and Materials
CCT	Control Cooking Test
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CV	Calorific Value
DA	Drum Agglomerator
DB	Dry Basis
FAO	Food and Agriculture Organization
FC	Fixed Carbon
GA	Genetic Algorithm
GHGs	Green House Gases
GPS	Global Positioning System
GRG	Grey Relational Grade
HM	Hand-Made
IEA	International Energy Agency
KBMA	Kenya Briquette Manufacturers Association
KEFRI	Kenya Forestry Research Institute
KNBS	Kenya National Bureau of Statistics
LPG	Liquid Petroleum Gases
MC	Moisture Content
Min	Minutes
SAS	Statistical Analysis Software
Sec	Seconds
S/N	Signal to Noise

SP	Screw Press
SFC	Specific Fuel Consumption
UNEP	United Nations Environmental Program
WB	Wet basis
WBT (V.4.2.3)	Water Boiling Test Version 4.2.3
WHO	World Health Organization
WKRM	Western Kenya Rice Mills
VM	Volatile Matter

CHAPTER ONE

INTRODUCTION

1.1 Background.

In any society, energy is one of the components of sustained development and poverty eradication (De Filippo & Serrano-López, 2018). Energy is vital for social-economic growth (Awasthi et al., 2020). However, energy availability at the domestic level continues to pose a challenge across the world, especially in Africa, where deforestation and the high cost of cooking gas and kerosene are experienced (Cardil et al., 2020; Sharma et al., 2020; Trigueiro, 2020). Urbanization rates are rising in most developing countries; thus, demand for charcoal is expected to rise (Ochola, 2018). Most of the population uses wood charcoal since they cannot pay for electricity and Liquid Petroleum Gas (LPG) for cooking (Ozoh et al., 2018).

On the other hand, fossil fuels worldwide are limited while demand for developed industries' energy consumption has increased (Kaur et al., 2020). The ecological issues have become a priority for an environmentalist to conserve natural resources; however, high usage of these limited available fossil fuels has led to serious outcomes (Kaur et al., 2020). Thus, to meet the ever-increasing energy demand and avoid dependence on fossil fuel, waste biomass has been considered a substitute alternative fuel source.

Biomass is produced globally every year from agriculture. According to United Nations, Food and Agriculture Organization (FAO), over 9 billion tonnes of crop residues were created in 2017, while over 5 billion cubic metres of forestry waste products were recovered in the same year (Sherwood, 2020). They are deposited on the farm to decay or be burnt directly in the atmosphere; these disposal methods have ecological problems (Kwon et al., 2020; Usmani et al., 2021; Welfle et al., 2020). These huge volumes of biomass can be converted to energy. The use of biomass fuel has been proposed to be a good source of energy for domestic cooking since it will ensure secure, clean, and affordable energy that will lead to economic development, thus lifting people out of poverty (Garcia-Freites et al., 2020) .

Significant quantities of biomass are available in Sub-Saharan Africa for conversion into domestic energy sources (Adeleke et al., 2021; Adeniyi & Ighalo, 2020; Tolessa et al., 2020). However, they are underutilized due to poor handling and combustion characteristics (Chirchir et al., 2013; Miranda et al., 2021). It is also not easy to handle, utilize, transport, store biomass in its original form (Gilvari et al., 2020; Nguyen et al., 2020; Nunes et al., 2020). According to da Silva et al. (2020) it has been reported that biomass in its original form has a high moisture content, low bulk density, irregular shapes, and sizes. Inefficient technologies used to process and utilize biomass makes it unclean, unaffordable, and unreliable (Awasthi et al., 2020). Densification should be undertaken to enhance the reliability and handling of the biomass (Kpalo et al., 2020). Kenya is one of the countries that would highly benefit from biomass densification to improve the availability of solid fuel.

Being a developing nation, Kenya is faced with limited access to clean energy sources (Pachauri, 2013). According to Mangla et al. (2020), limited access has been caused by high consumption rates, associated concerns that include energy security and demand, and material-energy recovery, which leads to sustainable energy system development. Most African rural populations use wood fuels as their primary energy source. Over 70% of Kenyans still rely on wood or charcoal for fuel, which leads to a decline in forest cover (Bailis et al., 2020; Jackson et al., 2018; Jacobson & Ciolkosz, 2020). Availability and exploitation of agricultural residues can reduce deforestation since they can generate energy for industrial and domestic use (Kashif et al., 2020; Latterini et al., 2020). This would ensure the exploitation of biomass densification to ensure there is improvement in the availability of clean energy sources to the country's populace.

According to Tumuluru et al. (2010), biomass densification can be classified into baling pelleting, extrusion, and briquetting. Bailing is the packing of biomass into a dense manageable form that is efficient and easy to use, pelleting, extrusion, and briquetting. Nielsen et al. (2020) described pelleting as combining and densifying finely, dusty, unpalatable, and difficult-to-handle agricultural feed material to form larger particles used as bioenergy. Extrusion is the process done on wet lignocellulosic biomass for producing biogas or bioethanol using single or twin-screw machines at a high temperature, usually around $150^{o}C$ – 250°C (Behling et al., 2016) A study by Kpalo et al. (2020) described briquetting as converting agricultural waste into dense and uniformly shaped briquettes with better physical and combustion characteristics than the initial waste biomass that is easy to use, transport, and store. This is achieved using a boiler, pelletizer, screw press, piston press, or roller press (Akpenpuun et al., 2020).

Studies on briquetting using these technologies have been extensively done (Akpenpuun et al., 2020; Dulal & Singh, 2021; Ikubanni et al., 2020; Jiao et al., 2020; Kpalo et al., 2020;

Orisaleye et al., 2020; Welfle et al., 2020). Piston press technology can accommodate biomass with a high moisture content of up to 22% and has been studied by Singla et al. (2020), having a 70 mm diameter and capacity of 1200 kg^{-1}, while Rahaman and Salam (2017) studied a manually operated piston press. Screw press has been reviewed by Prasityousil and Muenjina (2013) to produce briquettes from municipal wastes and sawdust. Hydraulic presses have been used for satisfactory operation, even with moisture content beyond 22%. Davies and Davies (2013) and Bello and Onilude (2020) evaluated hydraulic presses to produce briquettes from water hyacinth and composite sawdust. Also, Navalta et al. (2020) used hydraulic presses to investigate the effects of compression pressure (8, 10 and 12 MPa) on sugarcane bagasse and rice bran briquettes. Bembenek (2020) and Bembenek et al. (2020) have extensively studied the roller press to produce briquettes.

Further, briquettes' properties are affected by the type and combination of feedstocks used. The durability and mechanical strength of the briquettes produced from one kind of biomass can be improved by blending with another biomass material (Song et al., 2020; Tumuluru & Fillerup, 2020). Studies have been done on briquettes' physical and combustion characteristics using carbonized agricultural residues for briquettes. Feedstocks such as corn cob (Akpenpuun et al., 2020; Kpalo et al., 2020; Oliy & Muleta, 2020), sawdust (Bello & Onilude, 2020; Song & Hall, 2020) rice husk (Akpenpuun et al., 2020; Niño et al., 2020) cotton stalk (Song & Hall, 2020; Yilmaz et al., 2020) and hazelnut shell charcoal (Demirel et al., 2019; Demirel et al., 2020) charcoal dust (Ajimotokan et al., 2019; Gwenzi et al., 2020) sugarcane bagasse (Brunerová et al., 2020; Costa et al., 2019) have been studied. However, little information is available on the effect of process parameters on a selected technology of briquetting using three mixed feedstocks. Also, the best mix ratios of selected local feedstocks and the briquettes' physical and combustion quality are not well understood. This study, therefore, aims at identifying the effect of the process on three feedstocks mix and resultant parameters on briquette properties and the available energy.

1.2. Statement of the Problem

Industrialization, population, and economic growth in developing countries have led to rapid energy growth demand. World environmental concerns advocate for limiting use of fossil fuels due to increased adverse impacts of climate change from greenhouse gas (GHGs) emissions. Agricultural and forest residues are produced in large quantities across the globe. Environmental consequences and health hazards associated with the disposal of these wastes are still a concern. Thus, energy demand can be met by using biomass. Densification of biomass materials into briquettes can be adopted. Briquettes' properties vary depending on the technique used. Also, the characteristics of these densified biomasses differ depending on the number of feedstocks used. Briquettes from single feedstock have poor thermal, combustion, and performance characteristics (Navalta et al., 2020). Most of the briquettes based on two feedstocks have improved features (Soares et al., 2020). However, knowledge about the effect of briquettes with more than two feedstocks, their mix ratios, and different briquetting technologies on the properties of the briquettes is not fully understood.

1.3. Objectives

The broad objective of this study was to evaluate the effect of process parameters and feedstocks on selected briquette properties. The specific goals were to determine the;

i. Effect of screw press, drum Agglomerator and hand briquetting on briquettes' performance properties using rice husks, corncobs and sugarcane bagasse mix.
ii. Effect of mix ratios of rice husks, corncobs and sugarcane bagasse on briquettes' density, ash content, fixed carbon, volatile matter, and calorific value
iii. Optimal physical and combustion properties of briquettes based on three mix and techniques.

1.4. Research Questions

i. How do screw press, drum Agglomerator and hand briquetting affect briquettes' performance properties using rice husks, corncobs and sugarcane bagasse mix?
ii. How do mix ratios of rice husks, corncobs and sugarcane bagasse affect briquettes' density, ash content, fixed carbon, volatile matter, and calorific value?
iii. How can the briquettes' physical and combustion properties be optimized based on three mix and techniques?

1.5. Justification

According to Tran et al. (2020) environmental problems and health hazards associated with disposal of wastes are still a concern. Sharma et al. (2020) reported that energy availability at the domestic level continues to pose a challenge worldwide, especially in Africa, where deforestation and the high cost of cooking gas and kerosene are experienced. Thus, to meet the ever-increasing energy demand and avoid dependence on fossil fuel, waste biomass has been considered an alternative fuel source. More than 32% of annual deaths globally are caused by poorly processed biomass fuels (Yun et al., 2020). Thus, for energy efficiency and improved carbonization process, it is vital to use an experimental kiln that is environmentally friendly (to reduce ozone layer depletion) and does not release greenhouse gases in the atmosphere. Furthermore, an appropriate technique for briquetting is also key. A thorough understanding of the engineering agglomeration, durability and mechanical strength of the briquettes produced from one type of biomass can be improved by blending with another biomass material (Soares et al., 2020). To obtain high-quality briquettes from improved carbonization, three briquetting technologies; screw press, drum agglomerator, and handmade, and mix ratios of three feedstocks; rice husks, maize cobs, and sugarcane bagasse, were studied and conditions evaluated. From the study, opportunities to transform bioenergy for rural communities to contribute to achieving Sustainable Development Goal (SDGs) #7 were important. Also, the promotion of reliable, affordable, and modern energy in meeting Bioenergy for Sustainable Local Energy Services and Energy Access in Africa, Kenya's Vision 2030 blueprint for economic development, and Kenya's Energy Act, 2019 was paramount in informing this study.

1.6. Scope and Limitation

The scope of the research was to use an experimental kiln for carbonization. The feedstocks utilized included rice husk, corncobs, and sugarcane bagasse. The study focused on hand-making, screw press, and drum agglomerator as the techniques for briquettes production.

The research was limited to 1:1:1, 1:2:2, 1:3:3, 2:1:2, 2:2:3, 2:3:1, 3:1:3, 3:2:1, and 3:3:2 mix ratios adopted from a study by Arellano et al. (2015). Molasses was used as a binder. The specific properties studied were: performance characteristics in; specific fuel consumption, power output, burning rate, ignition, and burning time. Physical characteristics considered only moisture content and density. The combustion characteristics included; ash content, fixed carbon, volatile matter, and calorific value. Figure 1.1 shows the conceptual framework of the study.

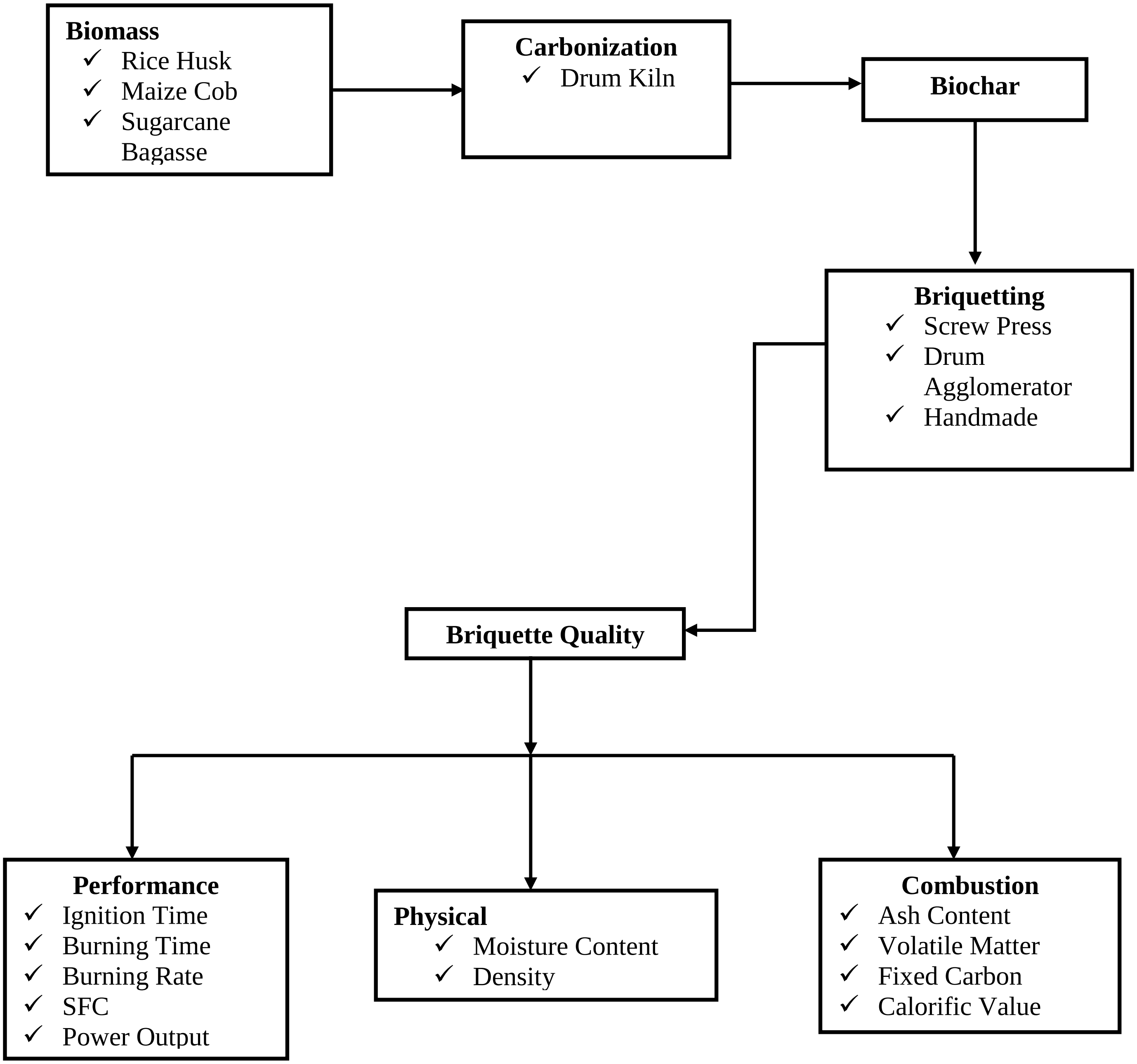


Figure 1.1: **Conceptual Framework**

1.7 Definition of Terms

Effect	Changes that occur as a result or consequence of an action.
Feedstocks	This is a raw or unprocessed renewable biomass material that can be used directly to produce energy or converted to another form of fuel, briquettes or pellets, for energy.
Briquettes	This is a compressed block of combustible biomass material (carbonized or uncarbonized) used as fuel.
Ignition time	This is the average time taken to lit briquettes or the average time taken to lit biomass before carbonization process.
Burning time	Time taken to completely burn the briquettes in a stove.
Retention time	It is a measure of the average time taken for biomass to be completely carbonized and/or the length of time material is retained in the die or drum during briquetting
Biochar	Solid material obtained from the carbonization process of biomass in a kiln in an oxygen-limited environment.
Simmering	Cooking liquid or something with liquid in it at a temperature slightly below boiling point at a specified period of time.
Greenhouse gases	Gaseous constituents of the atmosphere that absorb and emit radiation at specific wavelengths within the thermal infrared range causing greenhouse effect. They include; Carbon dioxide, Ozone, Water vapor, Methane and Nitrous Oxide.
Fossil fuels	Hydrocarbon- containing material formed underground from the remains of both dead plants and animals that are burned to release energy by humans. Example includes; petroleum and natural gas.
Technique	A skillful or efficient way of carrying out a particular task, execution or performance of a scientific procedure.
Parameters	This is a fixed limit or measurable factor forming one of a set that defines the conditions of its operation.

CHAPTER TWO

LITERATURE REVIEW

2.1 General Overview on Briquetting Process

Biomass densification can be a high compaction technology or binder-less technology in which biomass residues are compressed under high temperature and pressure (Kumar et al., 2020). According to Trubetskaya et al. (2020) biomass residues have lignin, a non-crystallized aromatic polymer with no fixed melting point. Still, at 200°C – 300°C, lignin starts to become soft, melted, and liquefied. At high pressure, lignin solidifies, thus forming briquettes (Matyjewicz et al., 2020). At low-compaction technology, the binder is needed to bind the biochar together before creating molds (Kpalo et al., 2020; Seco et al., 2020). During carbonization, biomass is heated in the absence of oxygen or a limited oxygen environment, and reaction conditions are monitored to maximize char production (Chirchir et al., 2013). This involves three main stages, namely endothermic, pyrolysis, and exothermic, determined by the required temperature. During endothermic, drying removes moisture content embedded in the biomass at about 100˚C or below (Mamvura & Danha, 2020; Song & Hall, 2020). The energy for this step comes from the partial combustion of the charged kiln. According to Li et al. (2020) pyrolysis process follows where biomass undergoes decomposition in the absence of oxygen. Carbon dioxide, carbon monoxide, and condensable vapour are released through thermal desorption. Air is admitted to the carbonizing kiln to allow biomass to be burned. Finally, the exothermic process starts where the spontaneous breakdown of biomass occurs at temperatures above 280˚C, leading to the formation of carbonized residue (Chirchir et al., 2013). Unless other external heat is applied, the exothermic process stops, and the temperature reaches a maximum of about 400˚C. The briquetting process is summarized in Figure 2.1.

Source: Kpalo et al. (2020)

Figure 2.1: **Flow of Briquetting Process**

2.1.1 Development of Carbonization Kiln

Different types of carbonization kilns have been developed around the world, however, several factors still influence carbonization process (Rodrigues & Braghini, 2019). According to Plaza et al. (2019) development of carbonization kiln is influenced by factors like simplicity and flexibility, auto thermal operations, maximization of the solid products fraction, affordability, feedstock material density, availability of equipment and material to be used and ease of operations. Thus, the volume of the kiln required can be determined using Equation 2.1.

$$V = \frac{M}{\rho} \quad 2.1$$

Where;

V = Volume of the kiln (m^3)

M = Mass of the feedstock (kg)

ρ = Bulk density of the feedstock material (kgm^{-3})

The height and the radius of the kiln can be determined using Equation 2.2.

$$V = \pi R^2 H \quad 2.2$$

Where;

V = Volume of the kiln (m^3)

R = Radius of the kiln (m)

H = Height of the kiln (m)

2.2. Briquetting Technologies

Ju et al. (2020) classified briquetting technology as high or low- pressure compaction. The compaction pressures were further classified as low (5 MPa), intermediate (5-100 MPa), and high (100 MPa and above). Ibitoye et al. (2021) organized technology based on piston or screw press equipment. According to Kpalo et al. (2020) compression process can be done through piston presses or screw extruders. Felfli et al. (2011) and Tumuluru et al. (2011) identified these machines to include screw press extruder, roller press, piston press that is either mechanical or hydraulic, and manual press. A comparison of these machines is provided in Table 2.1.

Table 2.1: **Comparison of Different Briquette Presses**

	Screw Press	**Roller Press**	**Piston Press (Hydraulic/Mechanical)**
Optimum moisture content of raw material (%)-	4 - 8	10 - 15	10 - 15
Particle size required (mm)	2.6	Less than 4	6 - 12
Shape	Cylindrical	Generally, elliptical (depends on the shape of the die)	Cylindrical
Dimensions (mm)	Length: 1940 Width: 750 Height: 1310 (Similar dies produce smaller extruded logs)	Almond shaped briquettes dimension: 31.75 (length) x 20.32 (width) x 11.16 (depth). (Depends on the shape of the die)	32 (dial) x (25 (thick)
Wear of contact parts	High	Low	Low
Output from machine	Continuous	Continuous	In strokes
Specific energy consumption (KWh/ton)	36.8 - 150	29.91 - 83.1	37.4 - 77
Throughput (ton/h)	0.5 - 1	5 - 10	2.5
Unit density (g/cm^3)	1 - 1.4	No information	Less than 0.1
Bulk density (g/cm^3)	0.5 - 0.6	0.48 - 0.53	0.4 - 0.5
Combustion performance of briquettes	Very good	Moderate	Moderate

Maintenance	Low	High	High
Homogeneity of densified biomass	Homogenous	Not homogenous	Not homogenous

Source: Tumuluru et al. (2011)

Dinesha et al. (2019) noted that briquettes produced from these processes have high densities than original materials, usually ranging between 900 - 1300 kgm^{-3}.

2.2.1 Pressurized Briquette Production

The effect of applied pressure and binder properties was studied by Thabuot et al. (2015) using a manual hydraulic press. Pressure levels of 40, 50, 60, and 70 kPa were used for investigating briquettes' properties. Results produced briquettes of 12 mm average inside diameter, 38 mm average outside diameter, and 25 - 30 mm height. Upon pressure increase, density increased to 260 - 416 kg/m^3. Optimum densification pressure was attained at 70 kPa with a 20% molasses binder. Most densified briquettes were from bamboo and sawdust with a heating value of 21.26 MJ/kg. Rubberwood residue produced the least densified briquettes having the least burning rate of 2.01 g/min. It was concluded that the burning rate of the briquettes decreases with an increase in applied pressure. Aransiola et al. (2019) determined the effect of binder type concentration and compacting pressure on some physical properties of corncob briquettes using a hydraulic press. Cassava starch, corn starch, and gelatin were used at different concentrations of 10, 20, and 30% using pressure levels of 50, 100, and 150 kPa. The results showed that from the three factors investigated, a 30% concentration of cassava binder at a pressure of 150 kPa produced briquettes with the most positive attributes. Briquettes had a moisture content of 4.43 and 7.62% (d.b), relaxed density between 729-987 kg/m^3, and compressive strength ranged from 1.02 to 8.32 MPa. The study concluded that the higher the binder concentration and compacting pressure, the better the quality of briquettes for storage and transportation.

A uniaxial compaction hydraulic jack was used by Orisaleye et al. (2018) to determine the effect of densification variables on the density of corncob briquettes. Selected values of pressures 9, 12, and 15 MPa, temperature between 90°C and 120°C, hold time of 7.5 and 15 min, and particle size of <2.5 and >2.5 mm were studied. Using graphical analysis, it was observed that an increase in pressure, temperature, and particle size reduction increased the density of briquettes. Also, hold time did not show a definite pattern for its effect on density. Briquette's density ranged from 570 and 1300 kg/m^3. It was concluded that pressure, temperature, and particle size were statistically significant ($p < 0.05$) while determining density in the hydraulic press. In a hydraulic press, Husain et al. (2002)conducted a briquetting of palm fibre and shell with a moderate pressure of 5 - 13.5 MPa. The relationship between pressure and density was established. The results showed briquettes with a density between 1100 and 1200 kg/m^3, then the calorific value of about 16.4 MJ/kg, ash content of about 6%, and an equilibrium moisture content of about 12%.

Bello and Onilude (2020) investigated combustion characteristics of high-density briquettes that were produced from sawdust using a screw press. Performance characteristics were evaluated in a cookstove. Upon analysis, results showed that briquettes burned with a steady flame. This was concluded to have been caused by high density since lower density briquettes reached the burning phase faster. Also, a screw press machine was used by Djangba et al. (2021) in a systematic review on the future potential of tea waste briquetting from rice husk. A 3 kW motor was used to run the machine. Results showed that briquettes produced met the physical standards recommended by Kenya Briquettes Manufacturers Authority (KBMA).

According to Kpalo et al. (2020) and Djangba et al. (2021), screw presses can produce denser and stronger briquettes than those produced by piston presses. Although screw presses briquetting machines are popular densification equipment suitable for a small-scale application, this study adopted the technique since briquettes are often of higher quality than piston units.

A. Fabrication of Screw Press

Screw press is widely used for agglomeration in which the screw is the main part. A detailed analysis of the press is necessary for making the design effective and for achieving better quality briquettes (Kyaw et al., 2019). The following equations were used to design the screw press as adopted from a study by Kyaw et al. (2019).

Torque on Rotating Shaft

$$T = \frac{6300\, hp}{N} \tag{2.3}$$

Where;

hp = horsepower of motor (5hp)

N = motor (1400 rpm)

Diameter of the Screw Shaft

$$D^3 = \frac{\sqrt{(K_b\, x M_b)^2 + (K_t\, x\, M_t)^2}}{\pi S_s} \quad (2.4)$$

Where;

D = Shaft Diameter

M_b = Bending Load

$M_{t\,=}$ Torsional Load

K_t = Combined shock and Fatigue factor applied to Torsional Moment (1~1.5), (used 1.2)

S_s = Allowable Shear Stress in Shaft (400 MPa)

$$Permissable\ Stress = \frac{0.5\ x\ S_s}{f_s} \quad (2.5)$$

Where;

f_s = factor of safety = 3 (Assuming)

Now, $\frac{P_1}{P_2} = e^{\mu\theta}$ (2.6)

Torque, $M_t = (P_1 - P_2)$ x radius

For the bending moment, $M_{t=}$ $(P_3 - P_4)$ x R

Load Lifted by Screw

$$W_e = \frac{\frac{D_m}{2}\tan\theta + \frac{\mu}{\cos\alpha}}{1 - \mu\tan\theta\cos\alpha} \quad (2.7)$$

Where;

D_m = Mean Thread Diameter

μ = Coefficient of friction

α = Tapering angle,

θ = Tapering angle

Pressure Lifted by Screw Thread

$$P_r = \frac{W_e}{A_p} \quad (2.8)$$

But, $A_p = \pi D_m nh$

Where;

P_r = Pressure Lifted

A_p = Pressing Area

h = Screw depth at maximum pressure end

n = No. of Threads

Briquette Capacity

$$Q_e = 60\frac{\pi}{4}D_s^2 \; x \; d_s^2 P_s N_s \varphi\rho \quad (2.9)$$

Where;

Q_e = Briquette capacity

D_s = diameter of the screw thread

d_s = base diameter of the screw thread

P_s = Screw pitch

N_s = rotational speed of the screw shaft

φ = filling factor

ρ = bulk density

Power and Torque on the Screw Shaft

$$P = T_s \; x \; \omega_s \quad (2.10)$$

But, $$T_s = F_{rm}\frac{\tan\theta + \frac{f}{\cos\theta_n}}{1 - \frac{f\tan\theta}{\cos\theta_n}} \quad (2.11)$$

Where;

P = Power

T_s = Torque

ω_s = 14.66 rad/sec

F = Axial Load

f = friction coefficient (0.3)

r_m = Mean Thread Diameter (θ = 180˚)

Longitudinal and Hoop Stress

$$\sigma_1 = \frac{PD_m}{4t} \quad (2.12)$$

$$\sigma_H = \frac{PD_m}{2t} \quad (2.13)$$

Where;

σ_1 = Longitudinal stress

σ_H = Hoop Stress

P = Pressure

D_m = Mean Diameter

2.2.2 Non-pressurized Briquette Production

Handmade briquettes are mostly from uncarbonized raw materials, hammer-crushed to obtain fine particles. The particles are then dried to reduce moisture content. Briquetting is done using bare hands as the binder is added to crushed feedstocks, and final drying is done. Ngusale et al. (2014) conducted a study on briquetting in Kenya Nairobi and its peri-urban areas. The study investigated briquetting technologies, including manual handmade briquettes from locally available feedstocks. The results showed no standard ratio nor specific mixture for optimum briquette production for handmade briquettes. However, Vivek et al. (2019) conducted a comparison study on fuel briquettes. They reported that a correct blend of raw materials could produce quality briquettes to address the energy crisis issue.

Centrifugal force created by a rotating drum forces particle to collect and densify. Non-pressurized technology requires a binder to aid in agglomeration. The material is fed into the disc in a drum Agglomerator while the liquid binder is sprayed on fine carbonized material. A study by Abdoli et al. (2018) reported that a federate and liquid spray affect the quality of produced briquettes. Also, a higher angle leads to a shorter retention time leading to less time for particle collecting. Hence, angle and speed are of the essence in this technology. The study found that high capacity and throughput applications are usually achieved with some recycling depending on the briquette desired. Borowski (2021) studied an overview of particle agglomeration techniques to waste utilization through briquetting. The extrusion technique of briquetting was used to transform bio-wastes into agglomerates used as an alternative fuel. The carbonized stalks were the first hammer milled to pass a 2 mm screen, and a ratio of 5:1 feedstock to binder was maintained. The results showed spherical-shaped briquettes with a density that ranged between 400- 500 kg/m^3. The study concluded that drum agglomerators could produce briquettes on an industrial scale since the production rate is very high.

B. Fabrication of Drum Agglomerator

Design and fabrication of rotary drum agglomerator used equations 2.14 - 2.19 that were adopted from a study by Borowski (2021).

Diameter and height of the drum

$$V = \frac{\pi d^2 h}{4} = \frac{m}{\rho} \tag{2.14}$$

Where;

V = Volume of the drum

d = diameter of the drum

h = height of the drum

m = mass of the feedstocks

ρ = density of the feedstock

Angle of repose of the scrapper

$$\sigma = \tan - 1 \left(\frac{2h}{d}\right) \tag{2.15}$$

Where;

σ = angle of repose

h = height of the drum

d = distance around the drum

Inclination angle of the drum

$$Y = \tan - 1 \,(m) \tag{2.16}$$

Where;

Y = inclination angle

m = tan θ

Rotating speed of the drum

$$\omega = \frac{\theta}{t} \approx \frac{rev}{min}$$

$$= \frac{2\pi}{60}\ \frac{rad}{s} \approx 0.105\,\frac{rad}{s} \qquad (2.17)$$

Where;

ω = rotating speed

θ = displacement (2π)

t = time (min)

rad = radians

s = seconds

Power required to run the agglomerator

$$P = T_s\ x\ \omega_s \qquad (2.18)$$

Where;

P = Power

T_s = Torque

ω_s = 14.66 rad/sec

Torque on Rotating drum

$$T = \frac{6300\ hp}{N} \qquad (2.19)$$

Where;

hp = horsepower of motor (3 hp)

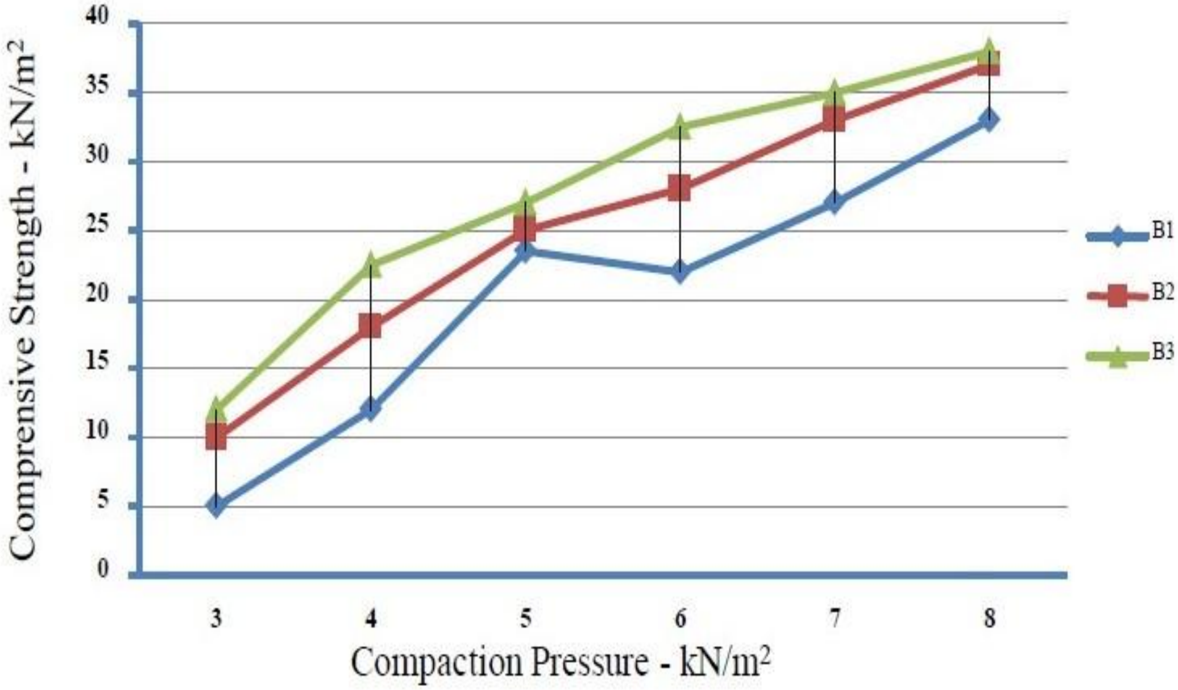
N = motor (1400 rpm)

2.3 Parameters Affecting Briquetting Process

2.3.1 Pressure

Densification of biomass can be done under high or low compaction pressures that require a binder to enable inter-particle bonding. The effect of briquetting pressure on banana peel briquettes was investigated by Wilaipon (2009) using a pressure range of 3 - 11 MPa and molasses as a binder. Upon analysis, briquettes produced at compaction pressure over 7 MPa were found to pass both impact resistance and compressive strength tests. Also, Aransiola et al. (2019) conducted a study to determine the effect of compacting pressure on some physical properties of corncobs briquettes. Pressures of 50, 100, and 150 kPa were used. Results showed that briquettes exhibited the most positive attributes at a compacting pressure of 150 kPa and 30% cassava binder concentration. Among them, moisture content ranged between 4.43 - 7.62% (d.b), the relaxed density range of 729 - 987 kg/m3, while compressive strength ranged from 1.02 - 8.32 MPa. Panwar et al. (2011) investigated the effect of compacting pressures on several biomasses; mango leaves, eucalyptus leaves, sawdust, and wheat straw. Pressures of 30, 50, 70, 90, and 100 MPa were used to evaluate briquettes' characteristics. Results showed optimum pressure to be 70 MPa, where briquettes had good densities and better performances during transportation and handling. The four feedstocks were observed to have bulk densities of 75 - 193 kg/m^3 but increased significantly after densification to 730 - 1044 kg/m^3 with 8% as optimum moisture content.

The effect of briquetting conditions, pressure and moisture content on biomass that grows in salty soils was investigated by Yumak et al. (2010). Three pressures of 15.7, 19.6, and 31.4 MPa with 7, 10, and 13% moisture contents were used. Results indicated that briquettes produced from 7-10% moisture rate, 31.4 MPa pressure, and temperature of 85 - 105°C passed all statistical analysis tests. Styks et al. (2020) conducted a study to determine the effect of compaction pressure on pellet selected quality parameters. Pressures of 131, 196, 262, and 327 MPa were selected. Results showed that with an increase in compaction pressure up to a certain level, density and durability that were investigated also increased. However, beyond that point, parameters qualities also decreased. The effect of varying compaction pressure on briquettes properties was studied by Saptoadi (2008) to investigate the effect of applied pressure. The pressures used ranged from 3 to 8 kN/m^2 with an interval of 1 kN/m^2. Properties studied were density (B1), moisture content (B2), bending and compressive strength, (B3) of the briquettes. The results showed that an increase in compaction pressure leads to a rise in investigated briquettes properties, as shown in Figure 2.2.



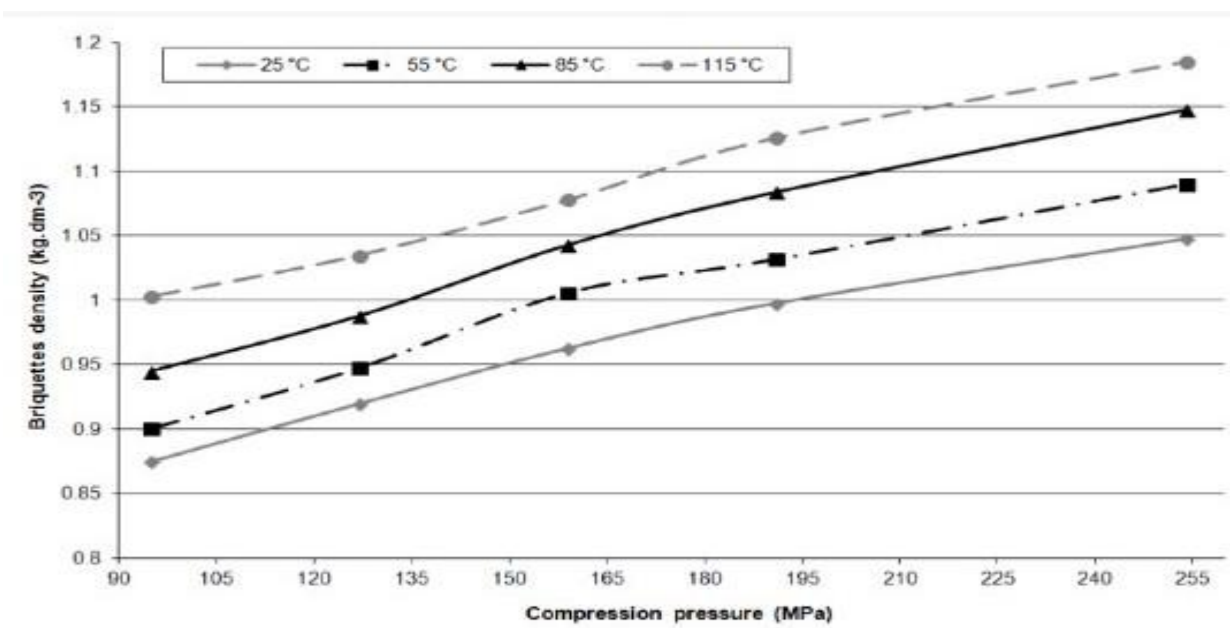
Source: Saptoadi (2008)

Figure 2.2: Effect of Compaction Pressure on Briquette Properties

2.3.2 Temperatures

During briquetting, temperatures affect both biomass feedstock and the die of the technology, this aid in the release of lignin in high-pressure compaction technologies. Nurek et al. (2019) conducted a study on the effect of temperature and moisture content on briquettes made of shredded logging residues. Temperatures of 22^{o}C and 73°C with moisture contents of 10, 15, and 20% were used to investigate the physical properties of obtained briquettes. The results showed briquettes with densities ranging from 799 to 1215 kg/m^3. Also, using both temperatures, moisture content of 10% gave the highest value of durability coefficient. It was concluded that temperatures during densification influence the susceptibility to compaction and durability of briquettes; hence, the higher the temperature, the better the briquettes. Okot et al. (2018) studied maize cobs briquettes produced at varying temperatures of 20^{o}C - 80°C. Results showed that densification at 80°C had briquettes with high density and durability/mechanical strength required.

The effect of pyrolysis temperature on the quality and combustion of biochar briquettes was investigated by Wang et al. (2017). Results showed a volume density decreased initially when pyrolysis temperature was increased. Also, durability and mass yield were noticed to decline with increasing temperatures. The temperature of 550°C was optimal for pyrolysis that gave a higher heating value of 21.05 MJ/kg, while volumetric energy densities were in the range of 1000 - 1400 kg/m^3. Evaluation of fuel char briquettes from human waste was studied by Ward et al. (2014). In the study, chars were pyrolyzed at 300^{o}C, 450^{o}C, and 750°C. The results showed that fecal matter pyrolyzed at 300°C had similar energy content to wood chars with a heating value of 25.6 MJ/kg. Energy content decreased when a temperature of 750°C was used, giving a heating value of 13.8 MJ/kg. It was concluded that fecal matter pyrolyzed at low temperatures had a higher heating value of 25 MJ/kg. This value is comparable to commercial wood charcoal briquettes; hence making a fecal matter briquette at low temperature is a potential energy source. Relation between briquette density and compression pressure at different compression temperatures is shown in Figure 2.3.



Source: Križan et al. (2014)

Figure 2.3: **Briquette Density and Compression Pressure at Different Temperatures**

2.3.3 Varying Retention Time

The length of time the material is retained in the die influences briquette properties. However, Bazargan et al. (2014) examined the effect of holding time on the tensile crushing strength of the briquettes using kernel shell biochar. Various holding times were subjected to 80 MPa pressure. Results showed that saving time did not affect the stability of briquettes. The findings agree with previous studies, which have concluded that the holding time or retention/dwell time has no significant effect unless lower compaction pressures are used. Bazargan et al. (2018) investigated the influence of retention time on the tensile crushing strength of kernel shell briquettes. Data showed that reducing retention time had no significant impact on the tensile crushing strength of the briquettes. It was later concluded that there is no significant influence on retention time at higher pressures, but it can have a considerable effect at lower pressures.

2.3.4 Die Geometry and Speed

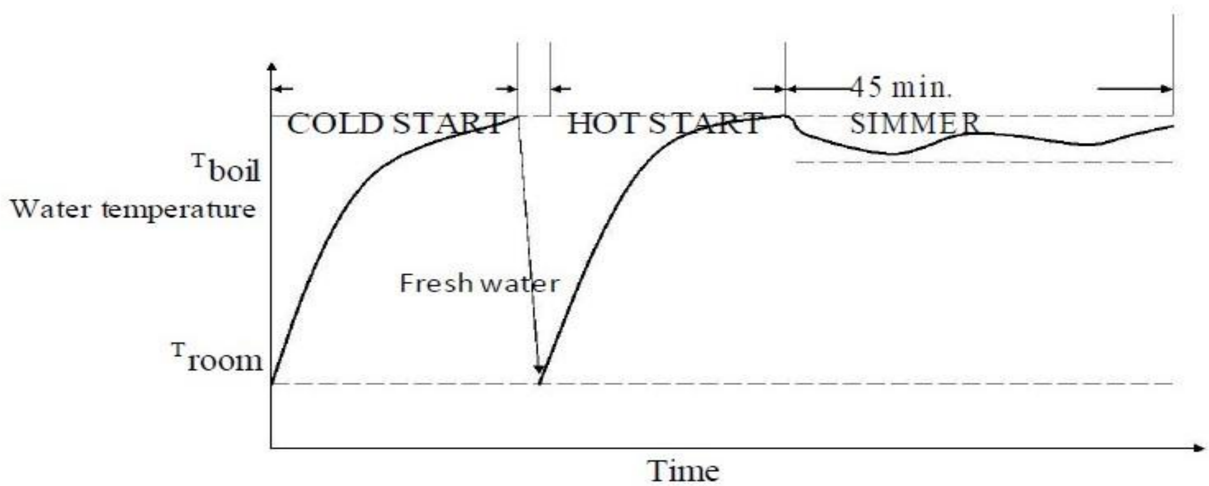
The size and shape of the die affect briquette properties such as moisture content, density, and durability. Tumuluru (2019) investigated the effect of pellet die diameter on the density and durability of pellets using wheat straw, sorghum, lodgepole pine, and cone stover. 8 mm and 10 mm die were used. 8 mm resulted in higher unit density values. However, bulk and tapped densities, 10 mm break pellets from corn stover, sorghum, and lodgepole pine had higher values than wheat straw. When durability was considered, wheat straw made using an 8 mm die, and corn stover made using a 10 mm die resulted in higher values. Tumuluru et al. (2015) investigated the impact of process conditions on the density and durability of briquettes using wheat, oat, canola, and barley straw. A high die temperature of 120^{o}C – 130 °C was used for the optimal process. Results showed that for durability rating >90 % to be achieved, higher die temperatures of >123°C should be used.

2.4 Stove Performance Properties using Briquettes

According to Suluh et al. (2021) performance of any solid biomass fuel (rice husk-sugarcane bagasse-corncobs briquettes) can effectively be evaluated when burnt in a biomass stove. This is done by combustion of briquettes to acquire data for fuel optimization and the expected fuel savings offered. Biomass fuels are also proposed to be a good source of renewable energy for domestic cooking (Kpalo et al., 2020). Cookstoves internally lined with local clay of low thermal conductivity have been suggested as efficient in performance and more effective in burning briquette fuels and tested using Water Boiling and User Acceptability Tests (Akolgo et al., 2021). Gupta et al. (2020) conducted a study to investigate the performance of composite sawdust briquette fuel in biomass stoves. Water boiling tests with intermediate, high power, and low power phases were carried out. The results showed that the heat utilized increased from the intermediate to the low power phase. However, specific fuel consumption, power output, and the burning rate decreased from intermediary to low power phase. Bello and Onilude (2020) studied combustion characteristics of high-density briquettes and their performance in briquette stoves. They reported a slow briquette self-ignition time in the open air and stove. It was concluded that high density was responsible for slow propagation resulting in a longer burning rate.

2.4.1 Briquettes Performances using Water Boiling Test

Information on solid fuels' quantitative and qualitative performance is carried out by two main types of tests, namely the Water Boiling Test (WBT) and Controlled Cooking Test (Obi et al., 2016). On the Water Boiling Test protocol, which is the primary test, Gupta et al. (2020) investigated the procedure. It can either be a high-power phase or a low power phase. The high-power phase is conducted at both hot and cold start. Water is boiled beginning with a hot stove to identify the difference in the stove's performance when it is hot and cold in a high-power hot start phase. During this phase, it is assumed that the stove body has reached a steady-state hot operating temperature by the end of the first boil. In the low power phase, boiled water from the hot start is simmered at approximately 3˚C below boiling point for about 45 minutes (Berrueta et al., 2008). Figure 2.4 shows temperatures during the three phases of the WBT.



Source: MacCarty et al. (2010)

Figure 2.4: **Temperatures during the Three Phases of the WBT**

Water Boiling Test (WBT) is a well-developed test that gives the time taken by a given quantity of fuel to heat (Tryner et al., 2014). It can be used to assess fuel optimization and design when combusting a solid fuel.

2.5 Biomass Feedstocks

Significant quantities of biomass are available worldwide for conversion into a domestic energy source (Kpalo et al., 2020). They consist primarily of wood, agricultural waste that includes field residue and process residues, animal manure, and municipal solid waste consisting of household and food processing wastes. Although wood from trees constitutes the most significant amount of biomass stock and the most used form of biomass in Africa, crop residues are also utilized. They are receiving increased attention due to the unsustainability of the wood. Biomass from forestry has been the primary source of wood fuel in Kenya (Roman et al., 2021). Briquette's feedstocks utilized as fuel have several essential characteristics that influence their use. These include moisture content, bulk density, ash content, and chemical composition. The energy value of a fuel is reduced by high moisture content, lower moisture content, and bulk density is also an essential feature as it affects transportation, assembling, and storage (Saeed et al., 2021). A study by Lunguleasa et al. (2021) showed that the durability and mechanical strength of these briquettes produced from one type of biomass could be improved when blended with another biomass material. The content of some common agricultural residues and wastes are shown in Table 2.2.

Table 2.2: Cellulose, Hemicellulose and Lignin Contents in Some Agricultural Residues

Lignocellulose material	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Hardwood stems	40 - 55	24 - 40	18 - 25
Softwood stems	45 - 50	25 - 35	25 - 35
Corncobs	45	35	15
Bagasse	40	30	15
Sawdust	40	25 - 35	20 - 30

Rice husks	35 - 40	15 - 20	20 - 25
Nutshells	25 - 30	25 - 30	30 - 40

Source: Welker et al. (2015)

Ndindeng et al. (2015) produced briquettes from rice husks and investigated the primary influencers of hardness in briquettes. The results showed that the briquetting process increased the density of rice husk from 120 to 600 kgm^{-3}. When the average time for making briquettes was 3.6 min, briquettes' hardness ranged from 101 to 170 N. The start-up time was between 2 - 3 min, the burning rate was found to be 126 - 145 g/min, and specific fuel consumption was 121 - 136 g/l. Yahaya and Ibrahim (2012) carried out water boiling tests about briquettes produced from rice husk using starch as a binder. This result showed that it took 15 minutes to boil two litres of water, whereas it took 1.2 kg of firewood 21 minutes to boil the same quantity of water. They reported a pale yellow to pale blue for the briquettes for the flame test. From their conclusion, the briquettes produced indicated superiority over firewood in combustion and quantity, respectively.

Efomah and Gbabo (2015) investigated the physical, proximate, and ultimate analysis of rice-husk briquettes produced from a vibratory block mould briquetting machine. Proximate and ultimate analysis was determined by ASTM analytical methods, while physical properties were determined by direct measure and calculations. They reported a maximum density of 1100 kgm^{-3}, relaxed density was 500 kgm^{-3}, the briquettes had a mass of 1.10 kg and were brown. The proximate analysis showed 68.20% volatile matter, 16.10% ash content, 12.67% moisture content, and 15.70% fixed carbon. Using Parr isoperibol bomb calorimeter, the heating value was 15,175 kJ/kg. Although the heating value was good enough for domestic application, it can be concluded that rice husk biomass does not give good fuels as it gives a high percentage volatile matter, ash content, moisture content, and low percentage fixed carbon should not be the case.

Brunerová et al. (2020) generated briquettes using sugarcane bagasse and subjected them to fuel parameters analysis within its suitability for direct combustion. The generated sugarcane bagasse from the whole sugarcane stem mass was 35 - 45%. They found out that briquettes produced by high-pressure briquetting press had a high-quality level of low ash content (0.97%) and a high net calorific value of 17.06 $Mjkg^{-1}$. They also reported quality mechanical durability of 99.29% compressive strength (150.82 Nmm^{-1}) and bulk density of 1,022.44 kgm^{-1} which all the results indicated positive results.

Optimum parameters for the formulation of charcoal briquettes produced from bagasse using clay as a binder was studied by Onchieku et al. (2012). The study used a brick-built kiln to carbonize while using a manually operated drum mixer. Using a ratio of 40:1 for carbonized bagasse to clay, the study showed the most optimum parameters. The briquettes recorded a very high ash content percentage of 36.4%, which is undesirable. However, they gave good values of 27.2% volatile matter and 4.390 kcal/g calorific energy. The briquettes were reported to burn without sparks and were smokeless, thus producing no irritating smell. They also ignited quickly and took relatively long before getting extinguished.

Oladeji and Enweremadu (2012) evaluated the effects of some processing parameters on corncob briquettes' physical and densification characteristics. ASAE Standard methods were used to determine the characteristics of the briquettes. The results showed that the moisture content of the corncob residue was 9.64%, while that of the relaxed briquette dropped to 7.46%. Biomass material had a density of 50.32 $kgm^{-3,}$ but after compaction to a ratio of 2.27 to 6.50, the initial, maximum, and relaxed densities ranged from 151 - 225 kgm^{-3}, 533 - 981 kgm^{-3}, and 307 - 417 $kgm^{-3,}$ respectively. This showed a maximum percentage volume reduction of 626%. From their conclusion, the briquettes showed stability for six months, which was highly influenced by binder ratio, particle, and pressure.

Fuel characteristics of briquettes produced from corncob and rice husk residues were studied by Oladeji (2010) using a prototype briquetting machine. The results showed that briquettes densified from their two residues make good biomass fuels. However, findings show that corncobs briquettes have more biomass fuel attributes than rice husk. Corncobs briquettes had a moderate moisture content of 13.47%, a higher density of 650 $kgm^{-3,}$ and a lower relaxation ratio of 1.70. The briquettes had a long glow time of 370 seconds and a slow propagation rate of 0.12 cm/s. The briquettes showed higher volatile matter of 86.53%, a higher heating value of 20, 890 kJ/kg, and compressive strength of 2.34 kN/m^2 compared to rice husk 67.98%, 13,389 $kJkg^{-1}$, and 1.07 kN/m^2, respectively. Although corncob briquettes had more positive attributes than rice-husk briquettes, the study concluded that both briquettes did not crumble upon transportation and storage since the value obtained for their relaxed densities were close to the maximum densities of the briquettes.

Table 2.3: **Burning Characteristics of Rice Husk and Corncob Briquettes**

		Briquettes	
Parameter	**Unit**	**Rice husk**	**Corncob**
Afterglow time	S	354.0	370.0
Flame propagation rate	cm/s	0.10	0.12

Source: Oladeji (2010)

Table 2.4: Combustion Characteristics of Rice Husk and Corncob Briquettes

		Briquettes	
Parameter	**Unit**	**Rice husk**	**Corncob**
Moisture content	%	12.67	13.47
Compressive strength	kN/m^2	1.07	2.34
The heating values	kJ/kg	13,389	20,890
Initial density	kg/m^3	138.0	155.0
Maximum density	kg/m^3	524.0	650.0
Relaxed density	kg/m^3	24.0	385.0
Density ratio	-	0.45	0.59
Compaction ratio	-	3.80	4.19
Relaxation ratio	-	2.22	1.70

Table 2.5: Physical and Fuel Characteristics of Rice Husk and Corncob Briquettes

		Briquettes	
Parameter	**Unit**	**Rice husk**	**Corncob**
Length of the briquette	M	0.075	0.075
Breadth of the briquette	m	0.075	0.075
Thickness of the briquette	m	0.008	0.006
Weight of the briquette	kg	0.025	0.024
Compaction pressure	MPa	2.10	2.10
Carbon content	%	42.1	19.72

Hydrogen content	%	5.8	15.56
Oxygen content	%	51.67	62.12
Sulphur content	%	0.05	0.82
Ash content	%	18.60	1.40
Nitrogen content	%	0.38	0.38
Volatile matter	%	67.98	86.53
Fixed carbon	%	13.4	12.07

Source: Oladeji (2010)

2.5.1 Binder

Based on the different compositions of the materials, the briquette binder can be divided into organic, inorganic, and compound binders. Manyuchi et al. (2018) studied a co-briquetting of coal fine sawdust using molasses as a binder. The effect of the binder on the briquette's combustion characteristics was investigated. Results indicated that as molasses concentration increased, calorific value, fixed carbon, and compressive strength increased by 16%, 8%, and 50%, respectively. The study concluded that molasses as a binder is critical in producing high-quality briquettes that do not shatter. Also, molasses was used as a binder by Jittabut (2015) to produce briquettes from a mixture of rice straw and sugarcane bagasse in the ratio of 100:50. Physical and thermal properties were evaluated after that. Results showed that volatile matter was 68.14-74.67%, ash content was 7.84 -12.85%, fixed carbon was 9.06 - 13.63%, and moisture content was 4.2 - 6.2%. The study concluded that briquette's physical parameters were the best indicator for additive quality. Chirchir et al. (2013) reported that binder type and ratios affected both physical and combustion characteristics. However, the study showed that briquettes bonded by molasses had better combustion characteristics.

Dinesha et al. (2019) studied briquettes using rice husk, maize cob, groundnut shell, and sugarcane bagasse as the feedstocks. Banana peel and cassava peel gel were used as binders. They reported an average energy value of 26.612 MJ/kg, 28.255 MJ/kg, 33.703 MJ/kg, and 32.762 MJ/kg for rice husk, maize cob, groundnut shell, and sugarcane bagasse, respectively using cassava peel. When banana peel gel was used, the corresponding values were 29.98 MJ/kg, 28.981 MJ/kg, 32.432 MJ/kg, and 31.508 MJ/kg. A study by Falemara et al. (2018) on briquette production from groundnut shells, corncobs, and wood residues using 15%, 20%, and 25% starch levels as binder showed that 25% starch level briquettes had better quality in terms of density and combustion properties.

Therefore, molasses was chosen as a binder in this study since it enhances the characteristics of the briquettes (Sen et al., 2016). Also, molasses results in briquettes with a lower attrition index and increased compressive strength (Akbar et al., 2021).

2.5.2 Mix Ratios

The physical and thermal properties of rice husk and sugarcane bagasse with molasses as a binder were studied by Demirbas (2004) with ratios of 10:0, 4:1, 1:1, 1:4, 1:10, and feedstock to molasses binder ratio of 2:1. Ultimate and proximate analyses to determine the average composition of their physical constituents were undertaken. The properties included density, compressive strength, and moisture content. Results showed that fixed carbon was 9.06 – 13.63%, the volatile matter was 68.14 – 74.67%, ash content was 7.84 – 12.85%, and moisture content was 4.2 – 6.2%. The heating value was in the high range of 16.3 – 17.83 MJ/Kg, density ranged between 0.53 – 0.58 kg/m^3, as the compressive strength ranged between 32.4 – 44.7 kg/cm^2. Ultimate analysis indicated that content of C H O N S was 38.6 – 43.2%, 5.4 – 6.2%, 34.5 – 36.4%, 0.27 – 0.44% and 0.02 – 0.045%, respectively. The briquette from rice husk-sugarcane bagasse had optimum ratio at the ratio 1:1. Further, physical and mechanical properties of briquettes produced from rice husk and sugarcane bagasse at ratios of 4:1, 3:2, 1:4, and 2:3 were investigated by Jamradloedluk and Wiriyaumpaiwong (2007). The blends were mixed with molasses as the binder in the ratio of 6:1 and compacted at 300 bars and 150˚C for the 30 seconds. The rice husk-sugarcane bagasse produced at a ratio of 40:60 formed briquettes that fulfilled specifications for mechanical strength and durability.

Ajimotokan et al. (2019) evaluated physio-mechanical characteristics of fuel briquettes produced from blends of corncob and rice husk at a mixing ratio of 4:1, 7:3, 3:2, and 1:1 with 25, 50, and 65 kPa compaction pressures and starch as binder. The results showed that briquettes made from 80:20 mixing ratio of corncob to rice husk with 65 kPa compaction pressure gave the highest compressive strength of 111 $kNm^{-2,}$ and the minor compressive strength of 39 kNm^{-2} came from a mix ratio of 50:50 and 25 kPa compaction pressure. Briquettes from a mix ratio of 1:1 with 65 kPa compaction pressure spent the longest time to collapse when immersed in water, taking up to 972 seconds, while mix ratio of 4:1 rice husk to corncob to rice-husk with 25 kPa compaction pressure had the least collapse time of 480 seconds. It was concluded that relaxed density increases with the percentage of rice husk in the produced briquettes. The durability of produced briquettes increases with a decrease in particle size.

Arellano et al. (2015) evaluated the fuel properties of briquettes made from coconut shells, corncob, and sugarcane bagasse at a ratio of 33%-33%-33%, 50%-25%-25%, and 50%-37.5%-12.5% at a compacting pressure of 2.2 MPa, 4.4 Mpa, and 6.6 Mpa. The study showed that constituent briquettes from 50%-25%-25% combination gave the highest calorific value of 19.9 $MJkg^{-1}$. They reported that compaction pressure had a significant effect on the volume displacement of the briquette and concluded that the mix ratio greatly affected the stability and fuel properties of the briquettes.

Akpenpuun et al. (2020) studied the physical and combustion properties of briquettes produced from a combination of rice husk, sawdust, and wastepaper using starch as a binder. They used a ratio of 2:7:1, 3:6:1, 4:5:1, 5:4:1, 6:3:1 and 7:2:1. Data obtained was analysed and found that moisture content of all briquettes ranged between 8 to 15% as density was between 800 to 900 kgm^{-3}. Calorific value was found to range from 0.03 to 0.27 $MJkg^{-1}$. The quality of the briquettes in terms of density and burning time was optimal when using 20% sawdust, 70% rice husk, and 10% paper which gave a relaxed density of 387.4 kgm^{-3} and ignition time of 18 seconds. It was concluded that the durability of the briquettes improved with increased starch proportion.

Briquettes with two feedstocks showed better characteristics than those produced from a single feedstock. However, Akpenpuun et al. (2020) conducted a study using three different feedstocks. Results showed better briquettes properties than those produced with two feedstocks. It is from these findings that three feedstocks were adopted in this study.

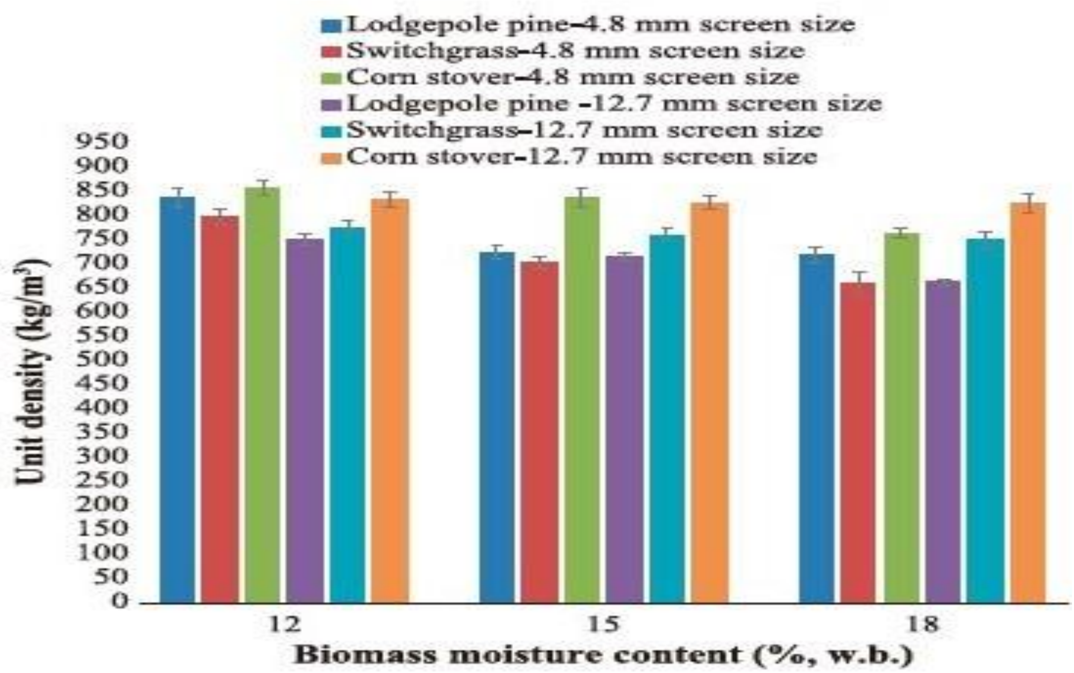
2.5.3 Effect of Physical Characteristics on Briquettes Properties

The physical characteristics of biomass feedstock are essential parameters that determine biomass briquettes' overall quality. This includes moisture content and density of the used biomass.

A. Effect of Moisture Content in Briquetting

This is the most crucial parameter of biomass feedstock that should be considered during densification. Tumuluru et al. (2010) reported that moisture content facilitates starch gelatinization, protein denaturation, and fibre solubilization processes, and optimum moisture content varies with the type of feedstocks used. Low moisture content hinders proper agglomeration of the particle, while high moisture content increases the energy required for drying. Kaliyan and Morey (2010) suggested an 8 - 12% value range for optimum densification. Tumuluru (2018) conducted a briquetting test using lodgepole pine, switchgrass, and corn stover as biomass. Three moisture contents of 12%, 15%, and 18% wet basis were used to study the effect on briquette quality. The attributes were measured after five days of production. It was noted that 12% and 15% (w.b) biomass moisture content resulted in a higher unit and bulk density >480 $kg/m^{3.}$ The moisture content of 18% (w.b) was noticed to increase briquetting energy consumption.

Demirbas (2004) evaluated biomass materials as energy sources using tea waste as feedstock. The study reported optimum moisture content of 15 - 18% for tea waste samples. Also, Demirbas and Sahin-Demirbas (2004) conducted a study on moisture content and reported a moisture content of 15% for wood sawdust produced briquettes at 350 MPa. The study concluded that the briquettes' compressive strength and shatter index increase as moisture content increases. Okot et al. (2018) conducted a study on the effects of operating parameters on maize cob briquette quality. It was found that increasing moisture content had a negative impact on briquettes' quality. It was also found that a relatively low moisture content of 7% - 8% could produce briquettes that meet high density and durability quality certification standards. Brožek (2016) used four moisture content levels of 5.7%, 7.7%, 15.7%, and 23.9% in investigating the influence of moisture on the final properties of briquettes produced from tree chips. It was observed that a moisture content of 7.7% produced briquettes with the best properties. The initial moisture content of 7.4%, 9.1%, 10.3%, 11.7%, 12.6%, 14.5%, 16.5%, 19.6%, and 22.0% of sawdust was studied by Matúš et al. (2015), who reported that 12.6% moisture content produced best briquettes concerning physical and mechanical properties. A study conducted by Kaliyan and Morey (2015) reported that density of compared biomass reduces with an increase in moisture content. The effect of moisture content of different biomass is shown in Figure 2.5.

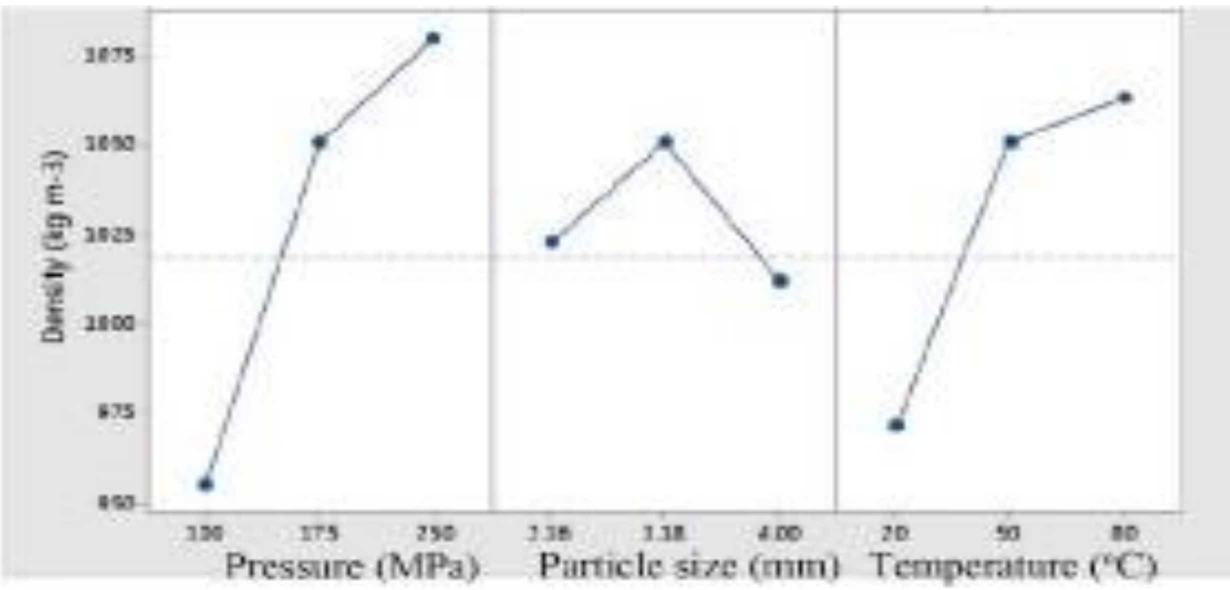


Source: Tumuluru (2018)

Figure 2.5: **Density of Different Biomass Briquettes Produced at Different Moisture Contents**

B. Effect of Density on Briquetting

Density plays a very vital role in determining efficiency for transportation and storage of briquettes. It is the factor that influences the engineering design of transport equipment, storage, and conversion process. Mani et al. (2006) conducted a study on bulk density of feedstocks and reported that corn stove and switchgrass had the lowest densities of 131 - 158 kgm^{-3} and 115 - 182 kgm^{-3}, respectively. A similar study conducted by Kaliyan and Morey (2010) also showed that corn stoves and switchgrass had the lowest densities of 103 - 160 kgm^{-3} and 181 - 220 kgm^{-3}. They concluded that the low bulk densities are due to lower screen sizes during grinding. Colley et al. (2006); Kaliyan and Morey (2010) and Sokhansanj and Turhollow (2004) have reported from their findings that depending on the type of biomass feedstock and densification conditions. Densification would result in densities in the range of 450 to 700 kgm^{-3}. On the other hand, depending on the briquetting machine used, Panwar et al. (2011) report that the bulk density of the briquettes would increase approximately 10 - 20 times of its original feedstock density. Kaliyan and Morey (2010) investigated factors that influence bulk density and found out that density depends on feedstock type, particle size, temperature, roller speed, feeder screw speed, and densification method. Figure 2.6 shows the effect of briquetting parameters; pressure, particle size, and temperature on density.



Source: Okot et al. (2019)

Figure 2.6: **Effect of Briquetting Pressure, Particle Size, and Temperature on Density**

2.5.4 Combustion Characteristics of Briquettes

Combustion characteristics of briquettes from industrial residues and biological sludge were investigated by Avelar et al. (2016), who reported a higher volatile matter (90.2%) for cotton textile industry residues compared to biological sludge using wood as biomass which recorded volatile matter of 82%. Briquettes produced from pinewood, timothy grass, and wheat straw were studied by Nanda et al. (2015) and found to have a volatile matter of 71.7%, 78.2%, and 70.1%, respectively. Yanfen and Xiaoqian (2010) investigated paper sludge and coal and reported volatile matter of 48.7% and 33.1%, respectively. Sewage sludge recorded a volatile matter value of 55.1% from a study conducted by Liu et al. (2010). Also, Munir et al. (2009) conducted a study on the volatile matter using sugarcane bagasse, cotton stalk, and shea meal and recorded 71.6%, 76.1%, and 66.3%, respectively.

Fixed carbon was conducted by Avelar et al. (2016) using biological sludge and industry residue. The results showed that fixed carbon was inversely proportional to the percentage of volatile matter. The range was 7.21% fixed carbon in sludge, whereas in the cotton industry, residues were 0.86%. UNEP (2006) reported that fixed carbon helps us estimate the fuel's heating value. Further, UNEP reported that the fixed carbon determines the calorific value of the fuel.

García et al. (2012) conducted a study concerning ash content from different fuels. The study proved that type of biomass influences ash content since they reported values of 0.6 - 9.8% for commercial fuels, 1 - 9.6% energy crops, 1.8 - 4.8% cereals, and 0.4 - 12.6% for industrial waste. A study conducted by Avelar et al. (2016) on combustion characteristics showed a high ash content of biological sludge and cotton textile industry residues. The two-biomass had ash content values of 11.8% and 8.93%, respectively. Sotannde et al. (2010) investigated factors that determine the percentage of ash content and reported ash content influenced by binder type during briquetting and the number of briquettes used during cooking.

A study conducted by Nurek et al. (2019) on combustion characteristics found out that the combustion rate of briquettes is influenced by density. It tends to reduce porosity that hampers the infiltration of oxidants during combustion. Rotich (1996) carried out a study on the calorific value of briquettes using rice husk as the feedstocks. The results showed calorific values ranging from 17.6 – 18.1 MJ/kg. Wilaipon's (2009) study on maize cobs briquettes found calorific values to range between 14.1 – 15.4 MJ/kg. Chirchir et al. (2013) used a mixture of rice and bagasse using molasses as a binder and obtained a calorific value of 13.1 - 26.03 MJ/kg. According to Yang et al. (2007) an increase in moisture content leads to a decrease in calorific value.

Oladeji and Lucas (2011) studied the physical and combustion properties of corncob and rice husks briquettes, and results were recorded as shown in Table 2.6

Table 2.6: Physical and Combustion Properties of Briquettes from Corncob and Rice Husk

Properties	Corncob	Rice husk
Moisture content (%)	13.47	12.67
Density (Kgm^{-3})	650	524
Relaxation ratio (%)	1.71	21.83
Flame propagation rate (cm/s)	0.12	0.10
Volatile matter (%)	86.53	67.98
Heating value (MJ/kg)	20.89	13.389
Compressive strength	2.34	1.07

Source: Oladeji and Lucas (2011)

2.6 Optimization of Briquetting Parameters.

Taguchi design method, according to Yusuff et al. (2021), is a powerful optimization tool that utilizes orthogonal array (OA), signal–to–noise ratio (S/N) ratios, main effects, and Analysis of Variance (ANOVA). OA provides a set of minimum experiment runs while S/N are logarithmic functions of desired output and serves as optimization functions. Taguchi robust design has widely been applied in engineering problems and is simple, efficient, and is a systematic approach for optimization and quality (Mitra et al., 2015). It provides a set of most minor experiments run while S/N is a logarithm function for optimization (Zhang et al., 2021). S/N ratio can be maximized, minimized, or kept at a nominal value. For maximization, the bigger the S/N ratio, the better, while the lower, the better (Mitra et al., 2015). According to Athreya and Venkatesh (2012), selecting the correct orthogonal array to be used is achieved using Equations 2.20.

$$N = P\,(L - 1) + 1 \qquad (2.20)$$

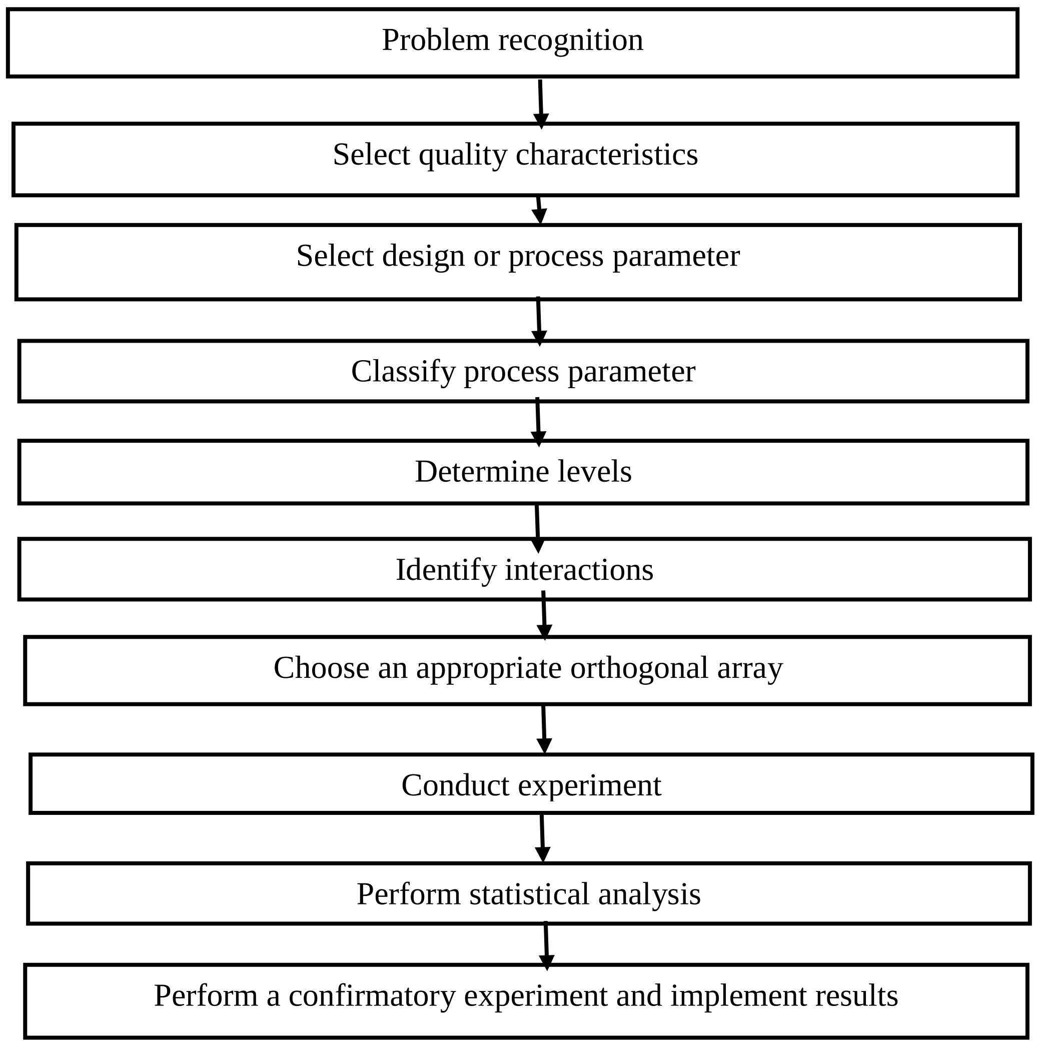
Where;

N = minimum number of experiments

L = number of levels

P = number of parameters.

Main effects and ANOVA are done after statistical analysis of the S/N ratio. The main effect is used in determining the optimal combination of operating process parameters. In contrast, ANOVA is used to evaluate the error variance and determine the significance of the selected parameters (Fei et al., 2013). Steps involved in Taguchi are provided in Figure 2.2.



Source: Mitra et al. (2015)

Figure 2.7: Steps involved in Taguchi Method

Agomuo et al. (2019) optimized the calorific value of briquettes from rice husk and sawdust ratios using the Taguchi approach. Mixed ratios of 9:1, 4:1, and 7:3 rice husk: sawdust was used at compacting pressure of 3, 4, and 5 MPa with a particle size of 0.6, 0.8, and 1.0 mm.

The analysis results showed an optimal design with a calorific value of 22826 J/g, which increased by 27.76% from an original value of 17867 J/g. Thapa and Engelken (2020) studied the optimization of parameters by Taguchi-Grey relational analysis for feedstock from agricultural and agro-processing wastes. The results using a Taguchi L9 orthogonal array experimental design showed an optimal parameter level setting for production to be at 3.18 mm wheat feedstock material blended with pine shavings at a mix ratio of 60:40. Also, Analysis of Variance (ANOVA) was conducted and showed that the magnitude of the significance of parameters on performance was in the order of binder> blend ratio> grind> feedstock material.

Since maximization of the properties in briquette production was desired, *larger-is-better*, as the response and the signal to noise ratio of the observation was calculated using Equation 2.21 (Thapa & Engelken, 2020). Standardized transformations formulas were needed for the responses. When the target value was "larger is better", the original sequence was normalized using Equation 2.22. The deviation coefficient was determined using Equation 2.23. The Grey relational coefficient was also used for multiple relational and calculated using Equation 2.24, while Grey relational grade (GRG) was calculated using Equation 2.25. Finally, optimal values of GRG were predicted using Equation 2.26

$$S/N\ ratio\ (\eta) = 10log10\left(\frac{1}{n}\right)\sum_{1}^{r}\frac{1}{Y_{ij}^{2}} \tag{2.21}$$

Where;

Y_{ij} = observed response value (i = 1, 2, …, n; J = 1, 2, …, k)

η = number of replications

$$x_i^*(k) = \frac{x_i(k) - minx_i(k)}{maxx_i(k) - minx_i(k)} \tag{2.22}$$

Where;

$x_i^*(k)$ = normalized value of the kth performance characteristic in the ith experiment

$x_i(k)$ = original kth performance value in the ith experiment.

$$\Delta x_i(k) = |x_0(k) - x_i^*(k)| \tag{2.23}$$

Where;

$\Delta x_i^*(k)$ = deviation coefficient

$x_0\ (k)$ = reference sequence or ideal series, and

$x_i^*(k)$ = comparability sequence

$$\xi_i(k) = \frac{\Delta \min + \Psi\Delta max}{\Delta x_i + \Psi\Delta max} \tag{2.24}$$

Where;

$\xi_i(k)$ = grey relational coefficient

Ψ = distinguishing coefficient

Δmin = smallest value of $\Delta x_i(k)$

Δmax = largest value of $\Delta x_i(k)$

$$Y_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \tag{2.25}$$

Where;

n = number of output response characteristics

$$\gamma_e = \gamma_m + \sum_{i=1}^{q}(\overline{Y_i} - Y_m) \tag{2.26}$$

Where;

γ_m = the total mean of the GRG

q = Number of input parameters/factors

$\bar{Y}_i$ = Mean GRG value at the optimal level for the i^{th} parameter

CHAPTER THREE.

MATERIALS AND METHODS.

3.1 Research Site, Experimental System and Material Preparation

3.1.1 Research Site

The research was conducted at Egerton University Energy Laboratory, Department of Agricultural Engineering, Njoro, Nakuru County (Latitude 0^{0}22’30.0” S Longitude 35^{0}55'30.0" E). Laboratory tests for analysis of briquettes were carried out at Egerton University's Food Science Department and Chemistry Department.

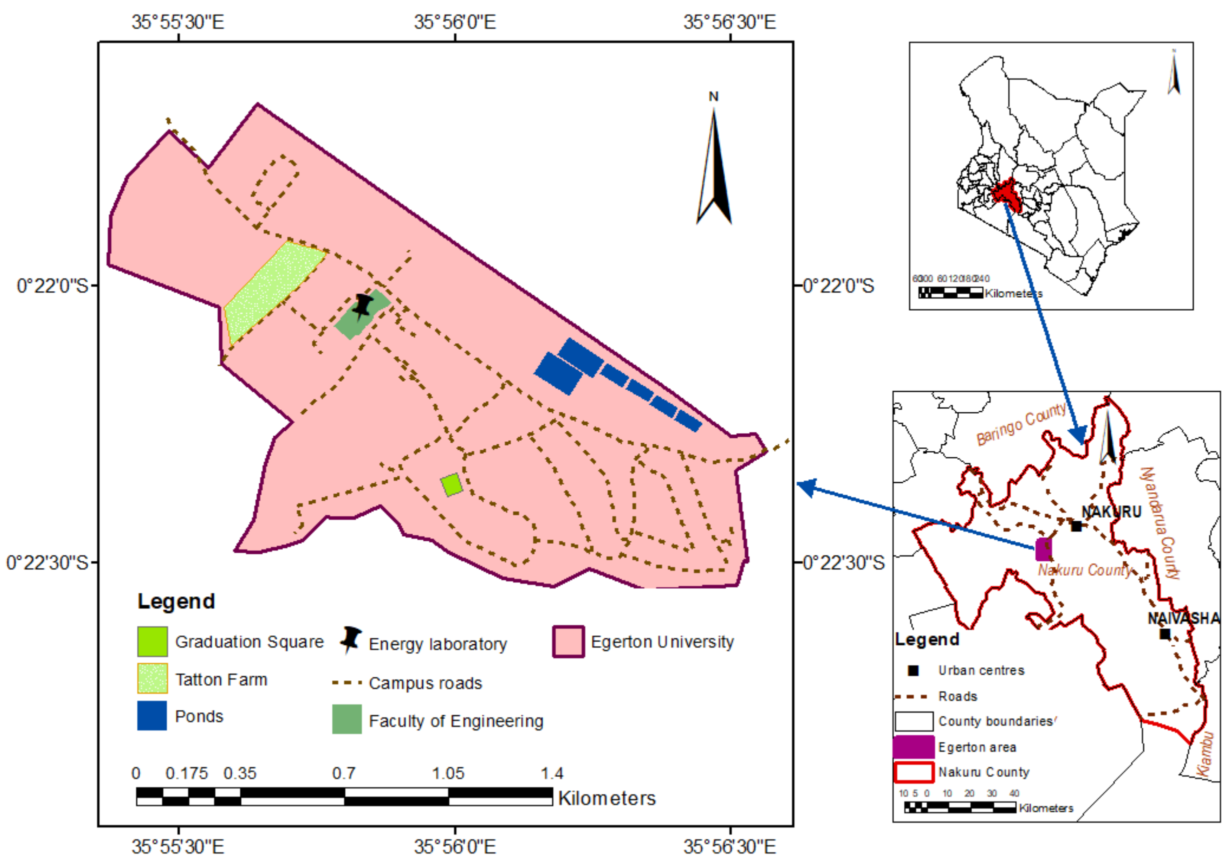


Figure 3.1: **Map of Kenya, Nakuru County and Egerton University**

Maize cobs were gotten from Tatton Farm of Egerton University for crops harvested in 2020. Rice husks were gotten from National Irrigation Authority (NIA) Ahero, which lies under

Western Kenya Rice Mills (WKRM) while sugarcane bagasse was obtained after processing sugar at the Kibos factory located approximately 10 km East of Kisumu.

3.1.2 Development of Carbonization Kiln System

The carbonization kiln system was developed based on basic principles of insulation to conserve heat, sealing to exclude oxygen after ignition and ease of operation and transportation of the system. Based on the availability of the material, space and portability, the diameter of the kiln was designed to be 0.5 m. From Equation 2.1**,** density of maize cobs was found to be 815 kg/m^3 which was the highest among the three feedstocks. Mass M of the feedstocks was then calculated and found to be 120 kg that was to be carbonized for each experiment. Volume V of the kiln was calculated and obtained to be 0.15 m^3. Height (H) of the carbonization kiln was determined using Equation 2.2 and was 0.75 m. The overall kiln height was 1 m after allowing a firing zone of 0.25 m (see Appendix A.1).

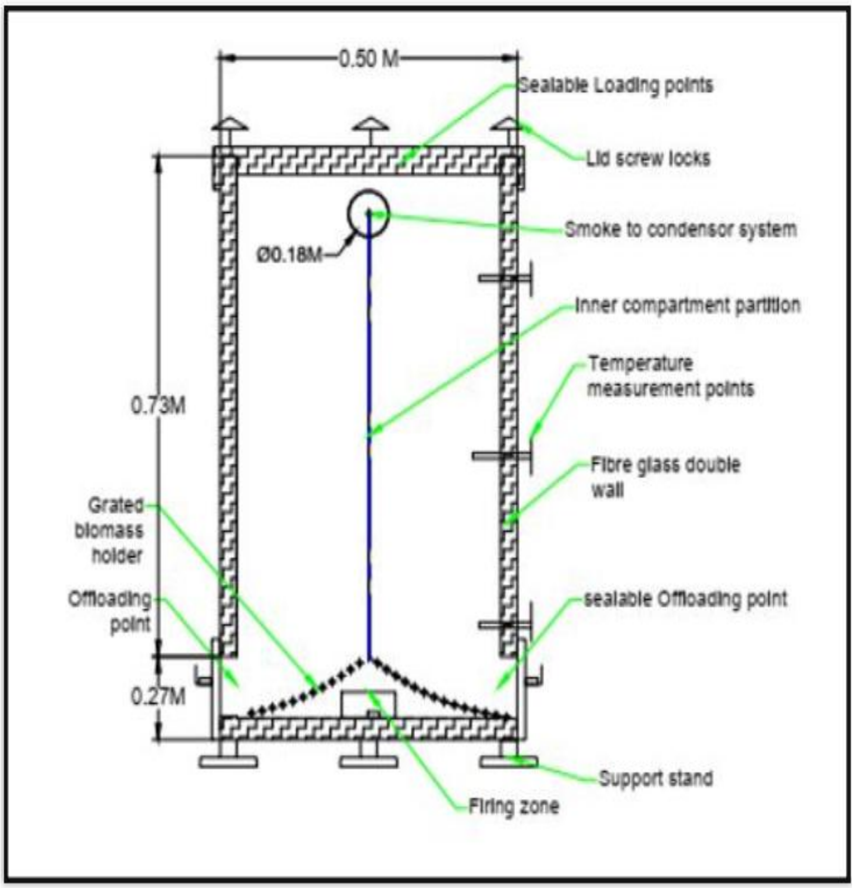


Figure 3.2: Kiln Design

The drum kiln was made of gauge 18 metal sheet with two layers and vermiculite between the sheets to give an insulation effect. The drum kiln was fitted with two thermometers to help monitor temperature variation (see Appendix C.5)

3.1.3: Fabrication of Screw press and Drum Agglomerator

Fabrication of screw press was adopted from the existing technique at Egerton University and modified. A 5 hp (horsepower) single-phase motor was used to drive the machine. The design result data from calculations (Equations 2.3 - 2.13) are presented in Table 3.1 while schematic diagram for screw press is shown in Figures 3.3 and 3.4. Design calculations are outlined in Appendix A.2

Table 3.1: **Design Result Data for Screw Press Development**

Name	Result	Units
Permissible stress	66.67	N/m^2
Shaft diameter	38	Mm
Torque	22.5	Nm
Power required	4.5	kW
Load lifted by screw	10	kN
Pressing area	0.05	M^2
Pressure lifted by screw	1.5	Mpa
Briquettes capacity	15.35	Kg/min

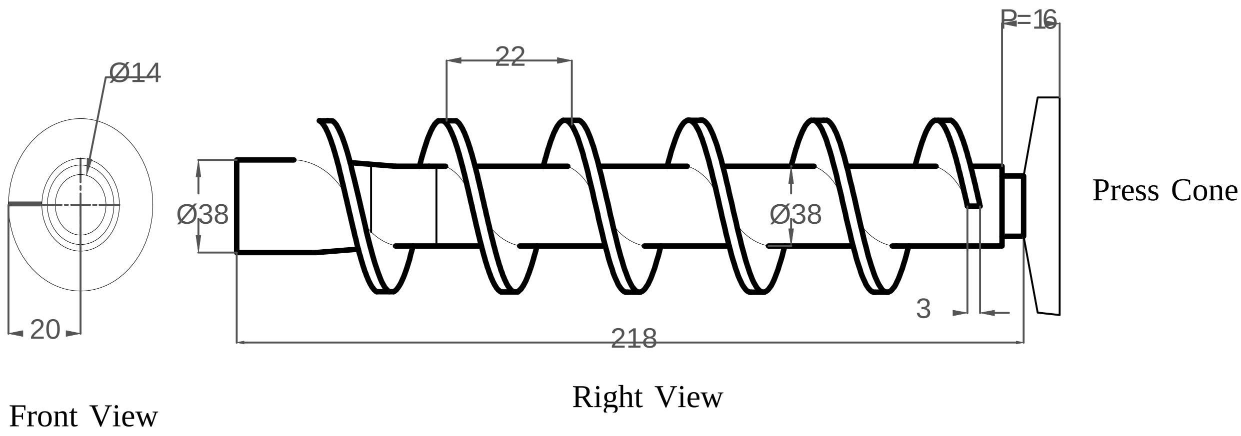


Figure 3.3: **Schematic Diagram of a Straight Screw Press**

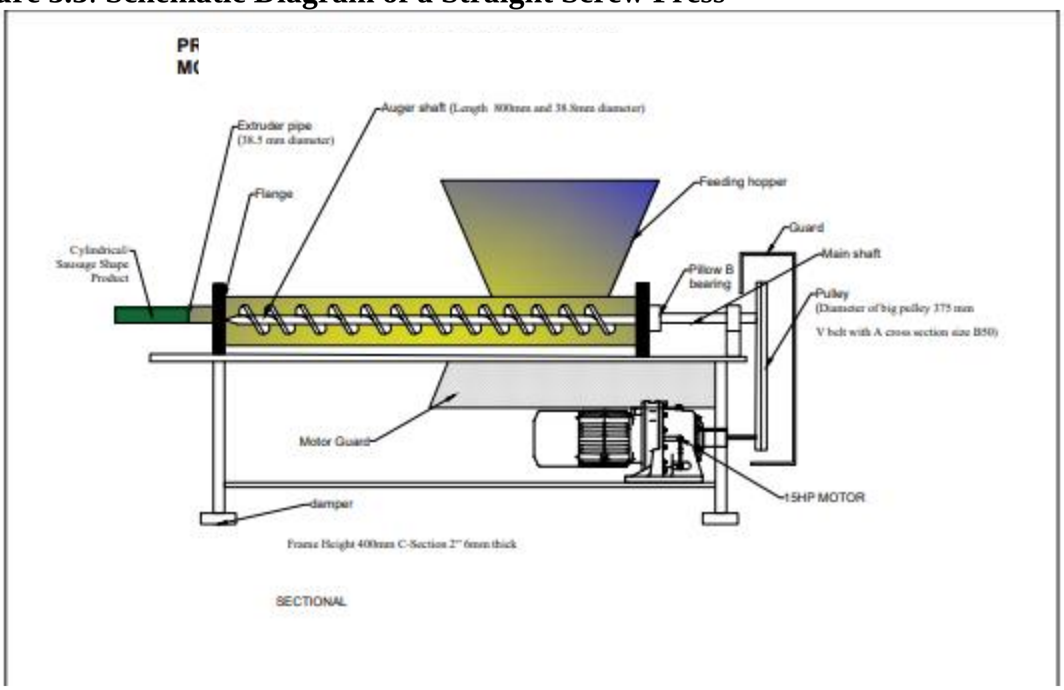


Figure 3.4: Improved Egerton Screw Press Machine

A 3 hp (horsepower) single-phase motor was used to drive rotating drum agglomerator. The design result data from calculations (Equations 2.14 - 2.19) and basic Agglomerator dimensions are presented in Table 3.2 while schematic diagram is shown in Figures 3.5.

Table 3.2: Drum Agglomerator Design Dimensions and Data

Drum Features	**Results and Units**
Drum diameter	1.2 m

Drum height	0.3 m
Angle of repose	45^0
Inclination angle	1.5^0
Rotating speed	45 rpm
Torque on rotating drum	13.5 Nm
Power required to run the drum	2.5 kN

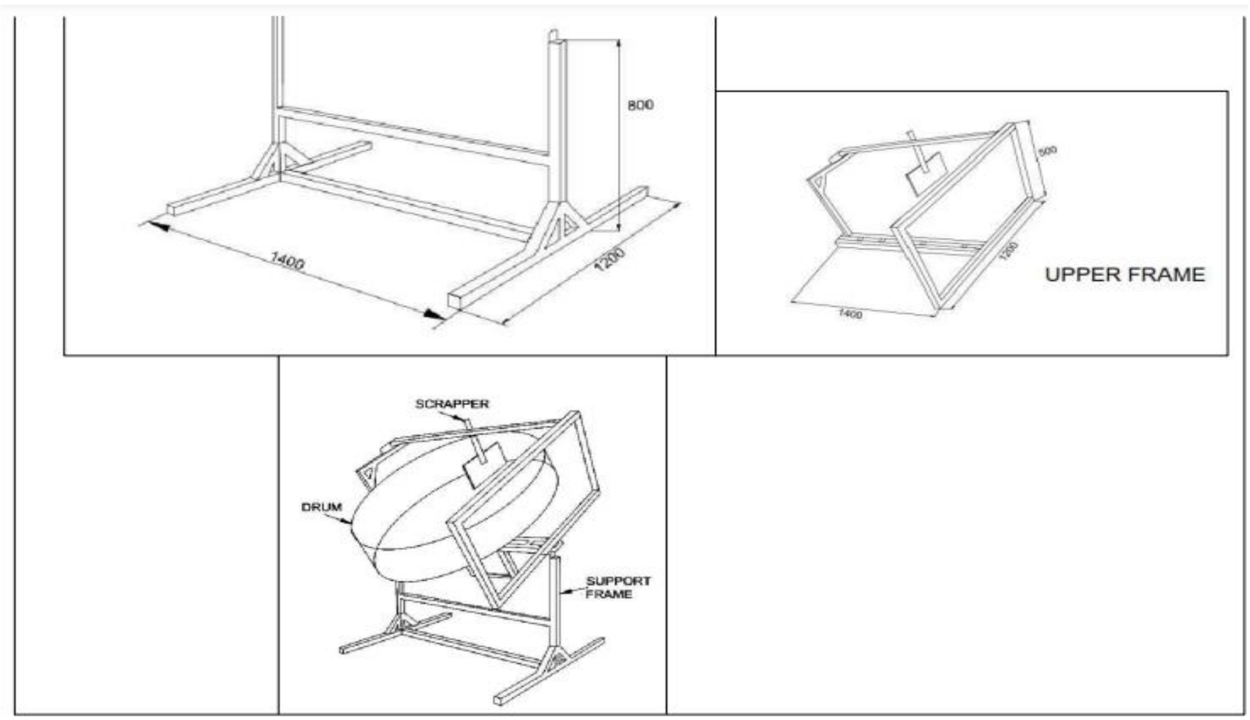


Figure 3.5: **Drum Agglomerator**

3.1.4 Material Preparation

Feedstocks to be used included rice husks, corncobs and sugarcane bagasse. Materials were sun-dried for 4 consecutive days, 6 hours per day during the sunny days of May 2021 with an average air temperature and relative humidity of 24^{o}C and 66% respectively to a moisture content of 10 - 14% in line with the recommendations by Ajimotokan et al. (2019) and Kenya Briquettes Manufacturers Authority (KBMA). Each dried feedstock was carbonized in a drum kiln.

During carbonization, a fireplace of the kiln was set and vents (intake and exhaust) opened to draw in enough oxygen for firing for about 30 minutes. It was closed for at least 1 hour 30 minutes for rice husks and corncobs and 2 hours for sugarcane bagasse without oxygen for carbonization. Temperature variation was monitored using a thermometer mounted on the kiln. The process output was char of each feedstock. Ajimotokan et al. (2019) recommended a size of <2 mm for easy densification and therefore the product was milled. Char was then mixed at different ratios.

3.1.5 Mix Ratios

Mix ratios used were adopted from a study by Arellano et al. (2015). Rice husks-corncobs and sugarcane bagasse milled carbonized materials were well blended and mixed with molasses binder during agglomeration and densification processes.

3.2 Effect of Briquetting Techniques on Performance Properties of Briquettes

Five kilograms (5 kg) of milled carbonized feedstock were mixed, and the binder (1 part to 6 parts of feedstock as recommended by Jamradloedluk and Wiriyaumpaiwong (2007) was sprinkled before being hand-fed into a screw press and agglomerator machines. The mixture was agglomerated into briquette molds and fireballs using a screw press (Appendix C.3) and drum Agglomerator (Appendix C.1). The briquettes were sun dried for three-five days to attained 8-10% moisture content recommended by Onaji and Siemons (1993) and Kenya Briquettes Manufacturers Authority. Similarly, fifty (50) grams of each milled carbonized material were mixed with a binder in the ratio of 6:1 beforehand molding.

Briquettes were sampled from the three techniques for further analysis considering their performance characteristics using Water Boiling Test (WBT version 4.2.3) using an improved cooking stove (called "Jiko Okoa", Appendix B.10). The local boiling point (Tb) at the Egerton Energy Laboratory room at an altitude of h = 1800 m giving a value of 94^{o}C asl, was determined using Equation 3.1 adopted from a study by Osei Bonsu et al. (2020)

$$Tb = [100 - {}^{h}/_{300}]^{\circ}C \quad (3.1)$$

Where;

Tb – Local boiling point

h – Altitude in meters

The high-power phase (including cold and hot start) was determined during the assessment. Further assessment on the performance, considering the Simmering-lower power phase in line with recommendation by Berrueta et al. (2008). Procedures for conducting WBT are outlined in (Appendix A.1).

Performance characteristics of the briquettes were determined using protocols recommended by Onukak et al. (2017) as briefly outlined. Specific fuel consumption (amount of solid fuel equivalent used in achieving a defined task divided by the weight of the task), power output (available amount of energy released from the fuel in a given time), burning rate (rate at which a certain mass of fuel is combusted in air), burning time (average time taken for the briquette to bring the water to the boiling point), were determined by weighing, firing the briquettes and taking time for the various parameters. Specific fuel consumption, power output, burning rate, and ignition time were calculated using Equations 3.2, 3.3, 3.4 and 3.5.

$$Specific\ Fuel\ Consumption = \frac{mass\ of\ fuel\ burnt\ (kg)}{mass\ of\ boiled\ water\ in\ the\ pot\ (kg)} \qquad (3.2)$$

$$Power\ Output\ (Kj/\text{sec}) = \frac{mass\ of\ fuel\ burnt (kg) x\ calorific\ value\ of\ the\ fuel\ (Kj/Kg)}{time\ take\ to\ burn\ fuel\ (\text{sec})} \qquad (3.3)$$

$$Burning\ Rate\ (Kg/\text{sec}) = \frac{mass\ of\ the\ fuel\ burnt\ (kg)}{time\ taken\ to\ burn\ the\ fuel\ (sec)} \qquad (3.4)$$

$$Ignition\ Time\ (\text{min}) = T_1 - T_0 \qquad (3.5)$$

Where;

T_1 = time that the briquette is ignited

T_o = time briquette was lighted

3.3 Effect of Mix Ratios of Husk: Corncobs: Bagasse on Briquettes' Physical and Combustion Properties

The physical and combustion characteristics of briquettes with the best performance characteristics were determined. The properties investigated are outlined in Table 3.3.

Table 3.3: Briquettes Physical and Combustion Properties

SN		Briquettes Properties
1	**Physical**	Moisture content, Density
2	**Combustion**	Calorific value, Volatile matter, Ash content, Fixed carbon

3.3.1 Physical Properties of Briquettes

Physical properties were determined using methods adopted from a study by Kpalo et al. (2020). The moisture content of the briquette was determined according to the ASTM D2444-16 specification and was calculated using Equation 3.6. The density of briquettes was determined according to ASTM D2395-17 standards and calculated as per Equation 3.7. Procedures to determine the physical properties of briquettes are outlined in (Appendix A.2).

$$Moisture\ Content = \frac{Wet\ basis - Dry\ basis}{Wet\ basis} \times 100\% \qquad (3.6)$$

$$\text{Density, } \rho = \frac{m}{v} \qquad (3.7)$$

Where;

ρ is density (kg/m^3)

m is briquette mass (kg)

v is volume (m^3)

3.3.2 Combustion Properties of Briquettes

Calorific value was determined using a method adapted from a study by Sotannde et al. (2010) using ASTM Standard E711-87 (2004) and calculated using Equation 3.8. Volatile matter, ash content and fixed carbon were determined using methods adopted from a study by Kpalo et al. (2020). The volatile matter was calculated using ASTM 872-82 standards and was determined using Equation 3.9. Also, ash content was determined following the ASTM E830-87 standards and was calculated using Equation 3.10. Fixed carbon was determined using Equation 3.11. Procedures for conducting combustion properties of briquettes is outlined in (Appendix A.3)

$$Calorific\ Value\ (Kcal/Kg) = \frac{(W+w)\ x\ (T1-T2)}{X} \qquad (3.8)$$

Where;

W = weight of calorimeter (Kg)

w = water equivalent of apparatus

T_1 = initial temperature of the water (˚c)

T_2 = final temperature of the water (˚c)

X = weight of fuel sample taken (kg)

$$\%\ volatile\ matter = \frac{w5-w6}{w5-w4}\ x\ 100 \quad (3.9)$$

Where;

W_4 = weight of empty crucible (gm)

W_5 = weight of empty crucible + sample (gm)

W_6 = weight of empty crucible + sample after heating (gm)

$$\%Ash\ Content = \frac{w9-w7}{w8-w7}\ x\ 100\% \quad (3.10)$$

Where;

W_7 = weight of empty crucible (gm)

W_8 = weight of crucible + sample (gm)

W_9 = weight of crucible + ash (gm)

$$\%fixed\ carbon = 100 - \%\ of\ (MC + VM + AC) \quad (3.11)$$

Where;

MC is moisture content (%)

VM is volatile matter (%)

AC is ash content (%)

3.4 Optimization of Briquette Properties Parameters.

Mix ratios were optimized using Taguchi method, where controllable variables were rice husk, corncobs and sugarcane bagasse varied at three (3) levels each. The Orthogonal Array determined the number of tests (Equation 2.20). The factors and levels are presented in Table 3.4

Table 3.4: Operation parameters and Levels

		LEVELS		
Parameters	**Labels**	**L1**	**L2**	**L3**

Rice husks (Kg)	A	1	2	3
Corncobs (Kg)	B	1	2	3
Bagasse (Kg)	C	1	2	3

For this experimental design, an L9 orthogonal array was suitable. Twenty-seven tests run were conducted since each trial was replicated three times. The design of the experiments for the L9 is shown in Table 3.5

Table 3.5: Optimization of Experimental Layout

	LEVELS		
Experimental runs	**A**	**B**	**C**
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

This experiment's design aimed to determine the feedstocks under which maximum mix ratios were achieved. Three experiments were conducted to determine the best mix ratio, drying method and particle sizes. Variable classes and fixed factors were selected for each of these ideal experiments. The variable classes were selected. Three machines were used for each variable class, and three replications were performed.

3.5 Data Analysis

The data obtained from the experiment was subjected to statistical analysis software (SAS). Analysis of Variance (ANOVA) was used to analyze data at a 5% significance level. The experimental design for this study was a factorial experiment. The degrees of freedom, sums of squares and mean sums of squares were calculated, and then the levels of significant difference between the factors were determined using the F-test

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Effect of Selected Briquetting Techniques on Performances Properties of Briquettes.

The performance values of briquettes from three techniques are presented as shown in Table 4.1. The mean values for briquettes' performance properties were significantly different ($p < 0.05$) among the different techniques. Tabulated values are presented in Appendix B.1

Table 4.1: Effect of Technique on Briquettes' Performance Parameters

TECHNIQUES	PARAMETERS				
	Ignition Time (Min)	**Time to Boil (Min)**	**Burning Rate (g/min)**	**S.F.C* (g/ml)**	**Power Output (kW)**
Screw Press Machine	1.3^{a}	14^{a}	0.8^{a}	0.11^{a}	1.8^{a}
Drum Agglomerator	1.0^{b}	12^{b}	1.1^{b}	0.13^{b}	1.4^{b}
Hand Made	0.9^{b}	11^{b}	1.3^{c}	0.15^{c}	0.75^{c}
Average	**1.07**	**12.33**	**1.07**	**0.13**	**1.32**

**S.F.C = specific fuel consumption*
Means within a column with the different superscript letters across column are statistically different p >0.05

4.1.1 Effect of Briquetting Techniques on Ignition Time

Ignition time (min) was taken as the average time taken to light a known fuel mass in line with Onuegbu et al. (2011). The longest ignition time of 4 min was obtained from pressurized technique (screw press) briquettes and shortest (3 min) from those made from non-pressurized (Table 4.1). Results from these studies are much higher than what was observed from individual feedstocks. For instance, Kpalo et al. (2020) reported an ignition time of 27.20 sec for corncobs, while rice husks had a value of 23.33 sec. Oyelaran (2015) reported a value of 96 sec for ignition time of briquettes made from sugarcane bagasse. Kabok et al. (2018) reported an ignition time of 2.7 min in a study where faecal sludge and sawdust were utilized as feedstocks. Values in this study compare well with 3 min and 3 - 4 min reported by Ndindeng et al. (2015) and Anggraeni et al. (2021), respectively, who used three feedstocks briquetting. A lower value (2.1 min) was reported by Abdulkareem et al. (2018) for briquettes made of charcoal, sawdust, and sugarcane bagasse using a hydraulic compression machine.

Ignition time increased with an increase in feedstocks and increased pressure. According to Davies (2013), highly compressed biomass or an increase in compaction reduces the void spaces of briquettes as particles are forced closer hence causing elongation of the ignition time. This explains why briquettes made using a screw press had the longest ignition time (Table 4.1). Dermirbas and Sahin (2004) recommend that briquettes for domestic use should be easily ignitable.

4.1.2 Effect of Briquetting Techniques on Time to Boil (min)

Time to boil water (minutes), which is the average time taken for the briquettes to bring water to the boiling point, was the longest (14 min) with the pressurized technique (screw press). The shortest time to boil, 12 and 11 minutes, was from low pressurized techniques. Time reduced from cold start to hot start (Table 4.1) since briquettes were still hot from the cold start phase. A range of 18 – 26 min was recorded by Kabok et al. (2018) for carbonized FS-sawdust briquettes. Abdulkareem et al. (2018) used a dial gauge hydraulic compression machine to produce briquettes from three feedstocks of charcoal, sawdust, and sugarcane bagasse and recorded a lower value of 5.1 - 7.3 minutes. Onuegbu et al. (2011), while using (manually operated hydraulic press – high pressurized) to produce briquettes from three feedstocks, reported a value of 8 - 26 min.

Therefore, it can be concluded that the number of feedstocks used in briquetting does not affect the time to boil. However, the technique used has a significant effect due to the pressure involved. An increase in density due to pressurized techniques inhibits the percolation of oxygen into the fuel; thus, briquettes from screw press had the longest time to boil. Lubwama et al. (2020) reported that the time to boil is attributed to the quantity of fuel and the type of cooking stove.

4.1.3 Effect of Briquetting Techniques on Burning Rate

The burning rate (g/min) was taken as the ratio of the mass of fuel burnt to the total time taken in line with Kpalo et al. (2020). Pressurized technique (screw press) briquettes gave 0.8 g/min the least value. In contrast, the highest values were obtained from non-pressurized techniques with 1.1 and 1.3 g/min values for drum agglomerator and hand briquetting, respectively. High burning rates in briquettes imply that more briquettes will be required in combustion as they burn off readily, as reported by Onukak et al. (2017). Two feedstocks (rice husks and cassava peels) were used with a high-pressure technique by Anggraeni et al. (2021) and reported a value of 2.81 g/min, higher than three feedstocks but lower than the value obtained from a single feedstock.

Compared to other briquettes in literature, the burning rates in this study compare well with the (1.1 - 2.1 g/min) range reported by Ndindeng et al. (2015) from three feedstocks using the locally fabricated multi-piston press. Also, Davis et al. (2013) reported a similar value of (0.97 - 2.49 g/min) from three feedstocks when a non-pressurized technique was used to produce briquettes.

The values in the study were lower than 2.85 g/min reported by Osei Bonsu et al. (2020) based on a non-pressurized technique (compressor box) from kernel shells briquettes but higher than 0.4 - 0.5 g/min from three feedstocks of charcoal, sawdust, and sugarcane bagasse reported by Abdulkareem et al. (2018) who used hydraulic compression machine. The 0.44 - 0.53 g/min obtained from coconut shells blended with charcoal dust briquettes by Kongprasert et al. (2019) were also lower.

Navalta et al. (2020) reported that the burning rate of briquettes depends on biomass type and density. Therefore, the burning rate was significantly affected by the number of feedstocks and techniques used to produce briquettes. In this study, the low burning rate in screw press is attributed to the high density of the briquettes from the pressurized technique. The effect of the technique on briquettes burning rate is shown in Figure 4.1a.

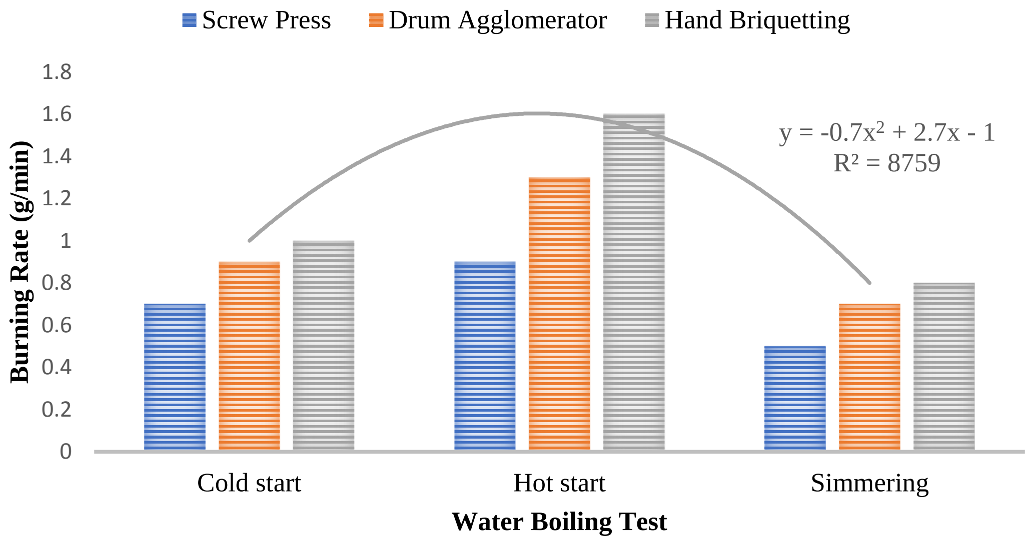


Figure 4.1a: Effect of Briquetting Techniques on Burning Rate

The graph obtained in Figure 4.1a has an R^2 = 87.59%. Short bars represent briquettes from screw press, indicating that a low amount of fuel was needed to bring water to boil for a pressurized technique.

4.1.4 Effect of Briquetting Techniques on Specific Fuel Consumption

Specific fuel consumption (SFC), in g/ml, was taken as the amount of fuel needed to bring a certain quantity of water to boiling point and was 0.11 for the pressurized technique. In contrast, low-pressure techniques gave 0.13 and 0.15 for drum agglomerator and handmade briquettes, respectively. More fuel consumption was in the cold start due to the heat required for warming the cookstove and the surrounding, as in Table 4.1. Considering two feedstocks, higher values (0.41 - 0.56 g/ml) were reported by Anggraeni et al. (2021) from rice husks and cassava peels using a high pressurized technique.

Values in the study are close to the range (0.14 - 0.17 kg/l) reported by Kpalo et al. (2020) while using a hydraulic piston press with three feedstocks. The values decreased with an increase in feedstock and applied pressure. Density has been reported as a factor affecting specific fuel consumption, explaining why screw press had a low value. SFC was, therefore, significantly affected by both numbers of feedstocks and the technique used to produce briquettes. The effect of the technique on briquettes SFC is shown in Figure 4.1b.

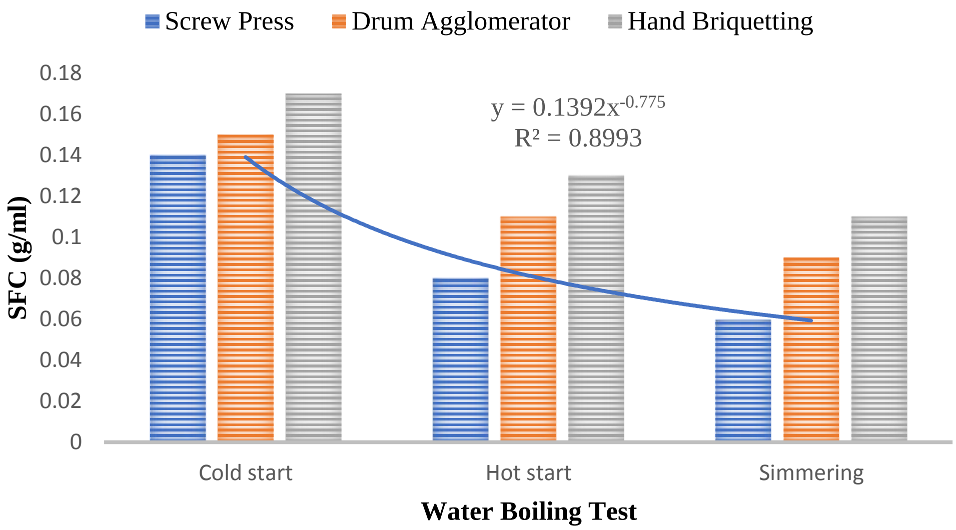


Figure 4.1b: **Effect of Briquetting Techniques on Specific Fuel Consumption**

The graph in Figure 4.2b has an R^2 = 89.9%. Short bars represent fuel from the screw press technique; hence, a low amount of fuel was needed for briquettes from the pressurized technique to bring water to boil.

4.1.5 Effect of Briquetting Techniques on Power Output

Power output (kW) was taken as the amount of energy released from the fuel in a given time in line with Sawadogo et al. (2018). It was 1.8, 1.4 and 0.75 for screw press, drum agglomerator and hand briquetting, respectively (Table 4.1). Power output increased in the high-power phase and decreased during simmering; pyrolysis was already complete, and less producer gas was available for combustion. The values (1.4 - 1.56 kW) obtained from a study by Ugwi and Agbo (2013) using a single feedstock of fruits bunches of oil palm plant and (1.3 - 1.5 kW) by Sawadogo et al. (2018) using cashew industry waste compares well to this study using non-pressurized and pressurized techniques respectively. The values for this study are slightly higher than 0.39 kW reported by Nwabue et al. (2017) for two feedstocks of bio-coal with plastic waste using hydraulic jack as the technique.

Power output was not significantly affected by the number of feedstocks used the type of biomass instead. However, the technique used to produce briquettes was a factor depending on applied pressure. This is why highly compressed briquettes from the pressurized technique (screw press) took more time to burn, and hence less amount was consumed to bring water to the boil. The effect of the technique on briquettes' power output is shown in Figure 4.1c.

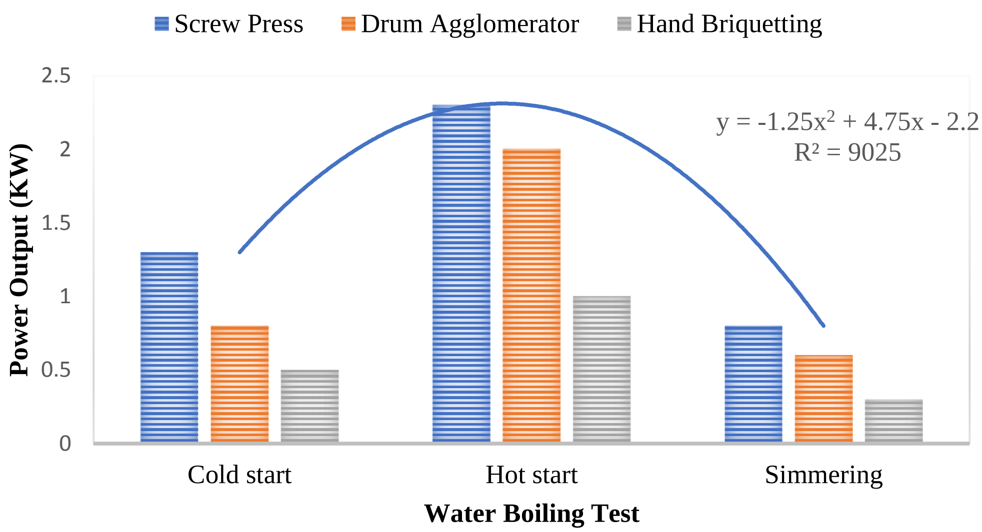


Figure 4.1c: Effect of Technique on Briquettes Power Output

The graph (Figure 4.1c) has an R^2 = 90.25%. The tall bars from the Water Boiling Test represent the pressurized technique (screw press) and indicate high power output was gotten from the fuel, while non-pressurized techniques are represented by short bars.

ANOVA showed a significant difference ($p < 0.05$) on ignition and time to boil between pressurized and non-pressurized techniques since p values (0.02/0.04) were less than 0.05. However, there was no significant difference between drum agglomerator and handmade (both are low-pressure techniques) as in Table 4.1, though briquettes from drum agglomerator took slightly more extended time than handmade to boil water. ANOVA showed a significant difference in burning rate, and specific fuel consumption of briquettes among the three techniques since p values (0.01) were less than 0.05 (Table 4.1). The power output was significantly different among the briquettes from the three techniques, with a p - value of 0.001.

4.2 Effect of Mix Ratios of Husk: Corncobs: Bagasse on Physical and Combustion Properties of Briquettes

From the results obtained for performance characteristics of the briquettes using different technologies, briquettes from different mix ratios were then subjected to study further where physical and combustion properties were evaluated. The effect and quality of the products obtained were then recorded and analyzed as shown in the following sub-sections.

4.2.1 Physical Properties of Briquettes

The two physical properties investigated in this study were moisture content (%) and density (kg/m^3). Values were tabulated and presented as in Table 4.2

Table 4.2: Effect of Mix Ratios of Rice husk: Corncob: Bagasse on Briquettes Moisture Content and Density

Mix Ratios Husk: Corncobs: Bagasse	Moisture Content (%)	Density (Kgm-^{3})
1:1:1	7.58	785
1:2:2	8.01	591
1:3:3	8.12	542
2:1:2	7.35	725
2:2:3	7.79	650
2:3:1	6.92	833
3:1:3	7.92	576
3:2:1	6.43	904
3:3:2	6.74	869
Average	**7.43**	**719.44**

Values obtained in this study ranged from 6.43% for a ratio of 3:2:1 to 8.12% (w.b) for the ratio of 1:3:3 briquette (Table 4.2). Yank et al. (2016) recommended briquettes to have an MC range of 5 – 10% before combustion. Briquettes with a higher percentage of sugarcane bagasse and corncobs material exhibited a higher moisture content than those with a higher percentage of rice husks. An increase in fuel MC lowers the heat of combustion and burning with excessive smoke emission (Magnago et al., 2020; Osei Bonsu et al., 2020). Higher moisture contents were recorded from individual biomasses. Efomah and Gbabo (2015) reported a value of 12.67% for rice husk briquettes. Oladeji (2012) got a value of 13.47% when maize cobs were used for briquettes. Values from two feedstocks blends are lower than values of individual feedstocks but higher than three mix blends. The 8.14% value was obtained by Jittabut (2015) for rice straw, and sugarcane leaves briquettes, Lela et al. (2015) reported a moisture content of 8.6% for cardboard/sawdust briquettes. Also, Brozek (2016) reported a moisture content of 5.7 to 15.7% for briquettes from wood dust and sawdust. The relationship between moisture content and briquette's mix ratios is shown in Figure 4.2a.

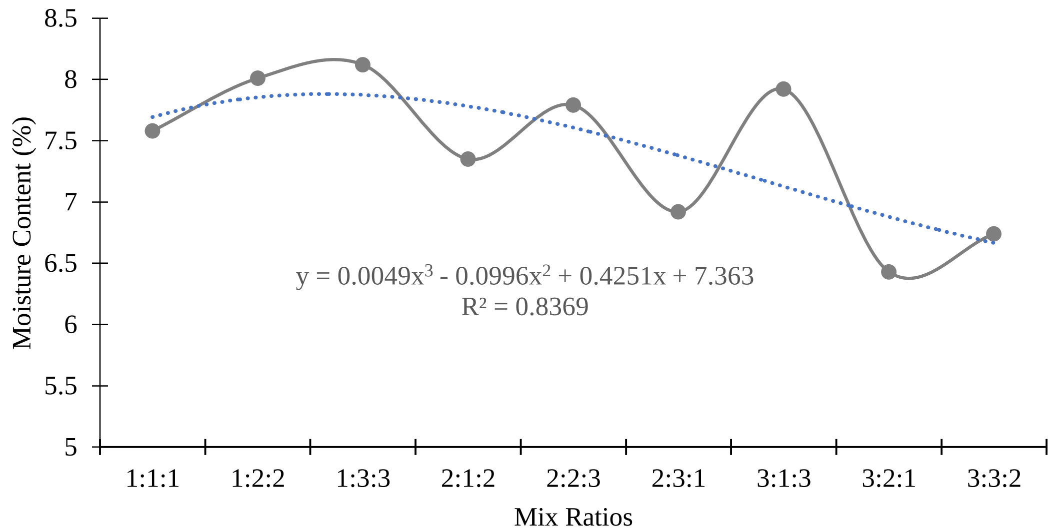


Figure 4.2a: Effect of Mix Ratios of Selected Feedstocks on Briquette's Moisture Content

The tolerance level of moisture content for briquettes may depend on the nature of the feedstocks. Studies have reported that moisture content of less than 5% will reduce the stability of briquettes, thus making them too dry leads to burning out quickly (Tumuluru et al., 2010). However, according to Miranda et al. (2021) high moisture content can make briquettes susceptible to poor combustion properties. A 3:2:1 mix ratio briquettes in this study are good enough to burn and conform to the tolerant level. However, any mix ratio with a high % of bagasse will attract moisture.

The average moisture content for this study was calculated to be 7.43%. Mix ratios of 1:1:1, 1:2:2, 1:3:3, 2:2:3 and 3:1:3 showed high moisture contents beyond the average and should not be used. However, the remaining four mix ratios (Table 4.2) briquettes are allowable and suitable for domestic use. An increase in the number of feedstocks reduced moisture content values of resulting briquettes. However, different mix ratios recorded different values depending on the nature of biomass. Therefore, it can be concluded that moisture content was influenced by the number of feedstocks and mix ratio used for briquetting.

Density is an important parameter determined by the nature of the feedstock, binder and briquetting pressure (Tumuluru et al., 2010). According to Avelar et al. (2016), the higher the density, the more concentrated the energy in the fuel, thus, leading to a high energy/volume ratio that prolongs burning time. However, according to Erickson and Prior (2018), other combustion properties of such briquettes may be negatively affected. The 1:3:3 briquette displayed the lowest density of 502 kg/m^3, while the 3:2:1 briquette had the highest density at 904 kg/m^3 (Table 4.3). The average value among all mix ratios was 719.44 kg/m^3. However, ratios of 1:2:2, 1:3:3, 2:2:3 and 3:1:3, however, recorded low-density values, less than mean values and could therefore be discarded.

Single feedstock showed lower values of density. Onchieku et al. (2012) obtained (300 - 390 kg/m^3) from briquettes produced with a carbonized coffee husk, while Yank et al. (2016) reported 440 kg/m^3 from rice husk briquettes. A mix of two feedstocks slightly improved these values as 590 kg/m^3 was reported by Jittabat (2015) from rice straw and sugarcane leaves briquettes. A 580 kg/m^3 was reported by Navalta et al. (2020) when sugarcane bagasse and rice bran were used as feedstocks. Oladeji (2010), in a study to evaluate properties of corncobs and rice husk briquettes, obtained 524 kg/m^3 as density while 480 kg/m^3 was noted by Falemara et al. (2018) from corncobs and wood residues. The relationship between briquette’s mix ratios and density is indicated in Figure 4.2b.

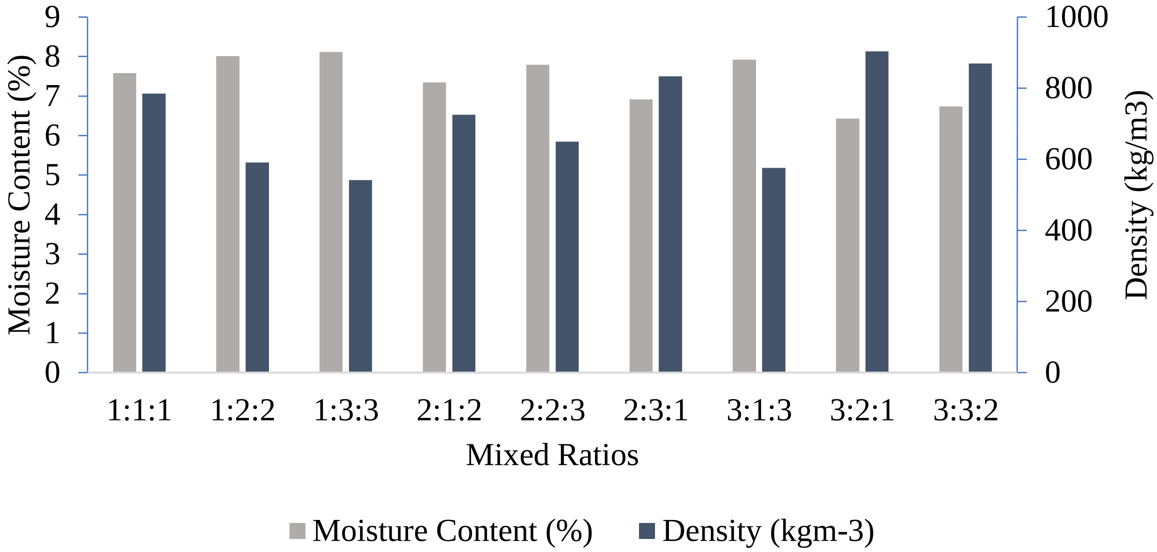


Figure 4.2b: **Effect of Mix Ratios of Selected Feedstocks on Briquettes Density**

The regression developed has an R^2 of 92.01%. Blending biomasses improved the density of the briquettes. Density increased but with a higher proportion of rice husk material. Comparing results from this study with literature, it can be said that density increased with an increase in the number of feedstocks. Also, mix ratios influenced density; mix with more rice husk and low value of bagasse recorded high-density value. Briquettes produced in this study have enough density suitable for transportation, handling and storage.

4.2.2 Combustion Properties of Briquettes

Calorific value (MJ/kg), ash content (%), fixed carbon (%) and volatile matter (%) were the four combustion properties investigated on the obtained briquettes in this study. Effect of the biofuels obtained was then recorded as shown in Table 4.3

Table 4.3: Effect of Mix Ratios of Husk: Corncob: Bagasse on Briquettes Combustion Properties

Mix Ratios Husk: Corncobs: Bagasse	Ash content (%)	Volatile matter (%)	Fixed carbon (%)	Calorific value (MJ/kg)
1:1:1	6.33	20.60	73.07	23.25
1:2:2	7.00	23.25	69.75	20.73
1:3:3	7.35	24.39	68.26	18.33
2:1:2	5.88	20.52	73.60	23.83
2:2:3	6.00	20.99	73.01	23.08
2:3:1	5.00	19.23	75.77	25.61
3:1:3	7.18	23.32	69.50	21.57
3:2:1	3.63	18.56	77.81	29.04
3:3:2	4.65	19.02	76.33	27.16
Average	**5.89**	**21.10**	**73.01**	**23.62**

The calorific value, which measures the briquettes' energy content in line with Kpalo et al. (2021), was found to range from 29.04 MJ/kg for 3:2:1 mix to 18.33 MJ/kg for 1:3:3 ratio briquettes, as shown in Table 4.3. The values obtained in the study meet the minimum recommended value of (16.0 MJ/kg) set by the Wood Pellet Association of Canada, as cited in Mitchual et al. (2014). Also, the values obtained in this study are higher than the minimum requirement of 14.5 MJ/kg recommended for non-woody briquettes by ISO 17225-7 (2021). Compared with other pieces of literature, individual feedstocks showed low calorific values. Kpalo et al. (2020) reported 17.78 MJ/kg and 16.54 MJ/kg for briquettes made of corncobs and oil palm trunks, respectively. Also, Oyelaran (2015) obtained calorific values as 18.64 MJ/kg and 17.12 MJ/kg when evaluating briquettes from sugarcane bagasse and groundnut shells, respectively. However, when a two feedstocks mix was used, values slightly improved but were lower than mean value of the current study. Chungcharoen and Srisang (2020) reported a range value of 18 – 22 MJ/kg for cashew nut shells and areca nuts. A 20.27 MJ/kg was obtained by Osei Bonsu et al. (2020) from briquettes made of palm and kernel shells. Also, Onuegbu et al.

(2011) used bio-coal as feedstocks and reported a 20.39 MJ/kg calorific value. Effect of different mix ratios is presented in Figure 4.2c

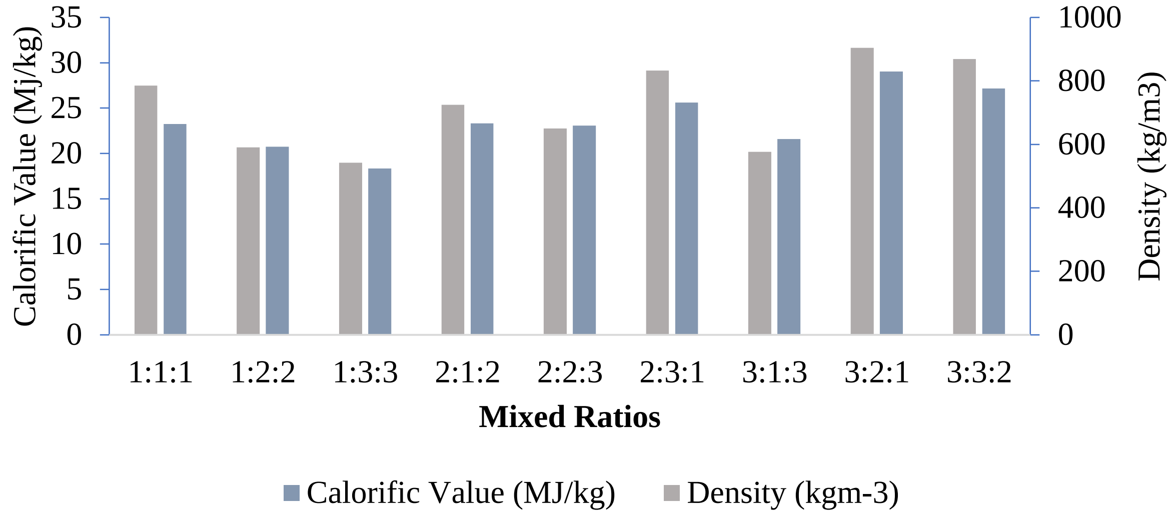


Figure 4.2c: **Effect of Mix Ratios and Density on Calorific Value of Briquettes**

The regression developed has an R^2 of 88.12%. The mean calorific value was obtained to be 23.62 MJ/kg. Tall bars represent high values of density. From Figure 4.2c, the higher the density, the higher the calorific value and vice versa. Production and adoption of briquettes from biomass wastes as alternative energy sources had enough calorific value to be used at the domestic level for energy. According to Idowu (2020); Kpalo et al. (2021) and Sawadogo et al. (2018), it has been reported that lower values of volatile matter with an associated high value of fixed carbon will lead to a high calorific value.

Mix from two feedstocks showed high calorific value than individual feedstocks. Also, a three mix of feedstocks had a higher value than two feedstocks. Therefore, an increase in feedstocks increased the calorific value of briquettes. Calorific value, however, varied depending on individual feedstocks in mix ratios. Mix ratios with a high mass of rice husk, 3:2:1, 3:3:2 and 2:3:1 showed high calorific values (Table 4.3)

According to Falemara et al. (2018), Ash content was taken as a percentage of impurity that does not burn during and after combustion or the inorganic matter left after complete combustion of the biomass. Ash content obtained in the study ranged from a minimum of 3.63% for a mix ratio of 3:2:1 to a maximum of 7.35%. for a ratio of 1:3:3. Minimum ash content value occurred at the low level of bagasse material since molasses used as a binder are a byproduct of bagasse. In contrast, maximum value occurred at a high level of bagasse material. Values reported from different pieces of literature using single feedstocks showed high ash content values. A 7% moisture content was obtained by Sawadogo et al. (2018) while using cashew industry waste briquettes. Lower values were obtained when two mixes were investigated. Onuegbu et al. (2011) reported a value of 6.09% from a mix of bio-coal briquettes, while 11.62% was recorded by Avelar et al. (2016) from bio sludge and cotton textile residues briquettes. Effect of different mix ratios on combustion properties is presented in Figure 4.2d

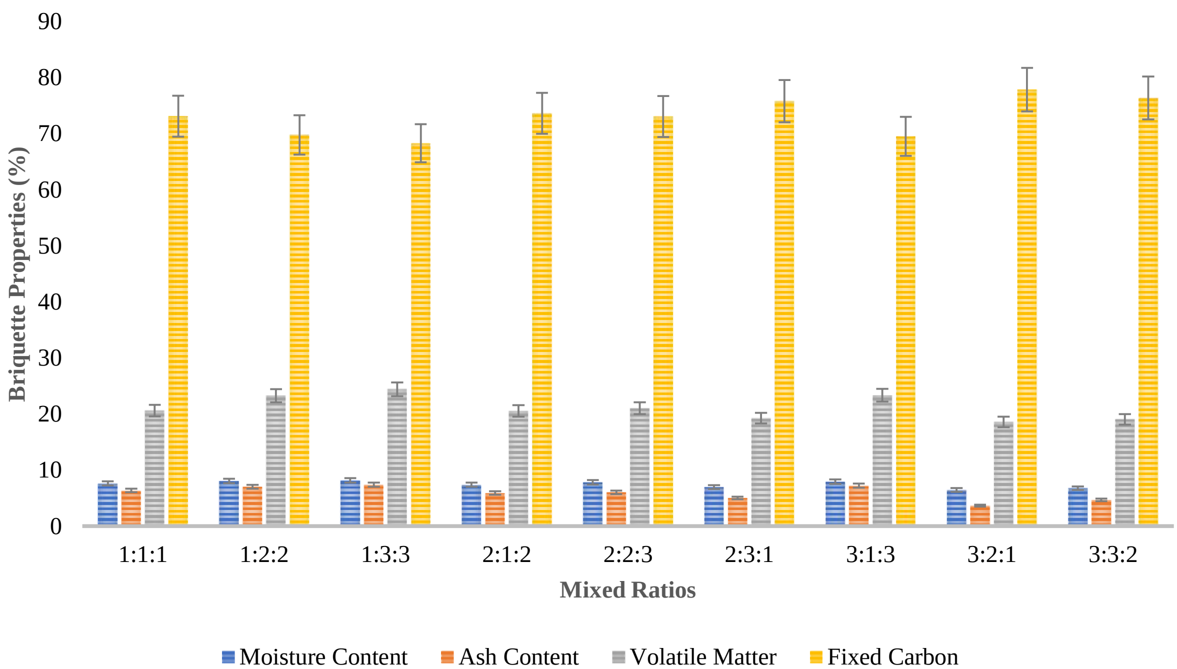


Figure 4.2d: **Effect of Feedstocks Mix Ratios on Briquettes Combustion Properties**

The mean value for ash content was obtained to be 5.89%. Mix ratios of 1:1:1, 1:2:2, 1:3:3, 2:2:3 and 3:1:3 had values more than mean values (Table 4.3) and therefore not considered suitable for use. Molasses has a high value of non-combustible elements, which remain as ash after combustion, and this is why briquettes with a high % of bagasse had high ash content. According to Loo et al. (2008), the higher ash content in fuels usually lowers calorific value. Ash content values of the studied briquettes ranged from 3.63 to 7.35%. According to Hahn (2014), any value lower than 6% is considered suitable for briquettes regarding the Austria ÖNORM M7135 standards. Ash content is influenced by a number of feedstocks used. An increase in the number of feedstocks corresponds to a decrease in ash content value. Also, the mix ratios of individual feedstocks are a key factor.

The volatile matter was taken as volatile gases released when biomass material is heated, as reported by Ajimotokan et al. (2019). Findings in the current study showed 3:2:1 briquette had the lowest value of 18.56%, while the 1:3:3 ratio had 24.39%, as shown in Table 4.3. According to Adetogun et al. (2014), although briquettes with lower volatile matter take longer to ignite than highly volatile matter, they burn smoothly with low ash content. The higher the volatile matter in the biomass, the higher the smoke emissions from the produced briquettes. Thus, good-quality briquettes should have a low volatile matter quantity. Individual feedstocks from different pieces of literature have shown high volatile matter content. Ajimotokan et al. (2019), in a study, stated a value of 82% and 77.7% for cassava peels and pine, respectively. Adetogun et al. (2014) obtained a range of 57.82 - 62.91% for maize cobs briquettes. However, relatively low values were reported from two mix ratios, Falamera et al. (2018) obtained (24.2 - 34.95%) for briquettes produced from agro-wastes and wood residues while (43 - 49%) was stated by Adegoke et al. (2010) for briquettes produced from mixed sawdust.

An increase in the number of feedstocks led to a decrease in the value of volatile matter. The value decreased from single feedstocks to two mix ratios to three mix ratios. However, different mix ratios have different values. The mean value of volatile matter was 21.10%, while ratios 1:2:2, 1:3:3 and 3:1:3 (Table 4.3) had values more than the current study mean.

Fixed carbon of fuel was taken as the percentage of carbon available for char combustion and gave a rough estimate of the heating value of fuel (Ajimotokan et al., 2019). From the study, values ranged from 77.81% for 3:2:1 to 68.26% for 1:3:3 ratio. These values compare well with 74 - 76% reported by Manyuchi et al. (2018) when evaluating the value addition of coal fines and sawdust to briquettes using molasses as a binder. Also, the almost similar value of 68 - 72.3% as stated by Kongprasert et al. (2019) from three feedstocks.

Compared to other pieces of literature with single feedstocks, low values of fixed carbon have been reported. Daniel et al. (2020) stated 29.87% and 45.16% values for rice husks and bagasse briquettes, respectively. Ajimotokan et al. (2019) reported a 15% value from pine feedstocks. 16.80 – 20.90% was quantified by Adetogun et al. (2014), who determined combustion properties of briquettes produced from maize cob. Pieces of literature with two mix ratios have reported improved values than single feedstocks. Falemara et al. (2018) stated a value of 62.4% for briquettes from agro-wastes and wood residues, while 50.13% was obtained by Jani (2016) from rice husks - charcoal briquettes. Navalta et al. (2020) stated a range of 60.5 - 74.3% for sugarcane bagasse and rice bran briquettes. Also, Sen et al. (2016) reported a 61.23% value for briquettes made of mixed wood charcoal. Effect of different mix ratios on fixed carbon against calorific value is presented in Figure 4.2e

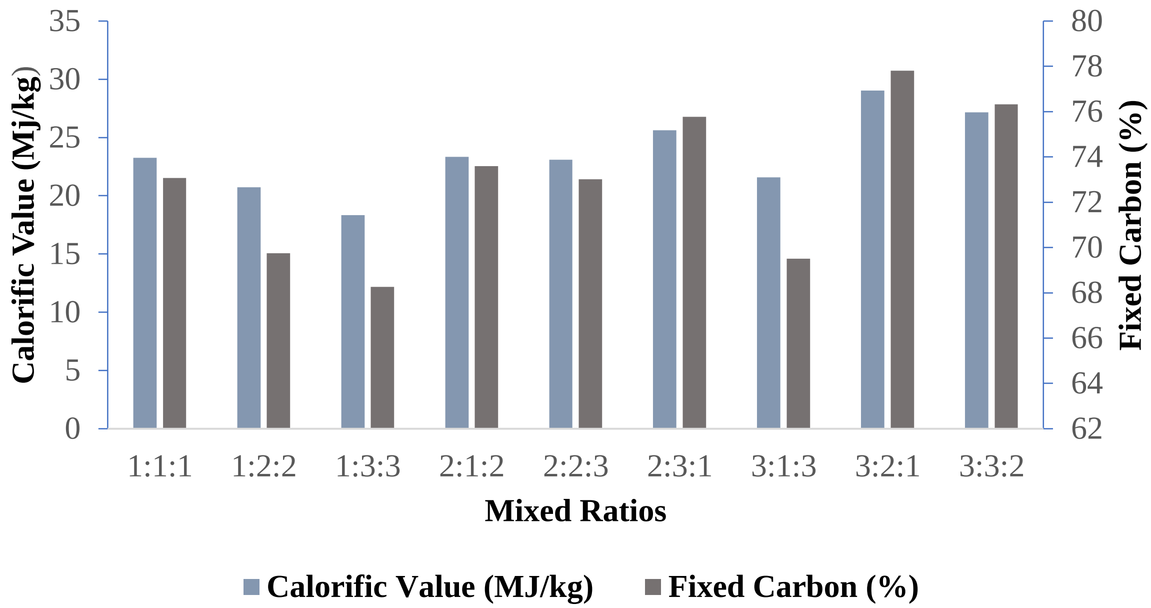


Figure 4.2e: Effect of Mix Ratios on Fixed Carbon and Calorific Value

Tall bars (Fig 4.2e) represent high fixed carbon corresponding to a high calorific value. According to Thabuot et al. (2015) fixed carbon content in briquettes is a critical factor influencing the calorific value of the fuel. High values of fixed carbon and the calorific value obtained in this study agree to the assertion of Onukak et al. (2017), who reported that high fixed carbon implies high calorific value. The mean value of this study was obtained as 73.01%, while mix ratios of 1:2:2, 1:3:3 and 3:1:3 had values lower than the mean (Table 4.3). Fixed carbon was influenced by the number of feedstocks used. The % value increased with an increase in the number of feedstocks. Also, individual feedstocks in the mix ratio influenced % fixed carbon. Mix ratios with the high quantity of rice husks showed high fixed carbon values, while those with high content of sugarcane bagasse showed low fixed carbon values (Table 4.3).

4.2.3 Analysis of Variance for Physical and Combustion Properties of Briquettes

Analysis of Variance (ANOVA) showed that for moisture content, all the nine mix ratios were significantly different apart from two mix ratios which were 2:3:1 and 3:3:2 that showed no difference. Similarly, mix ratios of 2:3:1 and 3:3:2 for density were the only ones that were not significantly different; otherwise, all the remaining mix ratios were significantly different from each other ($p > 0.05$). ANOVA showed that for all nine mix ratios for ash content, all values were significantly different from each other since $F_{calc} > F_{crit}$ at $\alpha = 0.05$. The statistical significance of the volatile matter was examined using *p*-values at $\alpha = 0.05$ using ANOVA. The analyzed data observed that mix ratios 1:1:1, 2:1:2 and 2:2:3 were not significantly different. Similarly, 1:2:2 and 3:1:3 mix ratios were not significantly different from each other. Also, 2:3:1 and 3:3:2 were not significantly different from each other. Otherwise, the remaining mix ratios were significantly different from each other. Using $\alpha = 0.05$, ANOVA showed that all mix ratios for fixed carbon were significantly different apart from three that included 1:1:1, 2:1:2 and 2:2:3. Finally, when the calorific value was subjected to ANOVA using $\alpha = 0.05$, all the nine mix ratios were significantly different from each other. Calculation of F, P-value and F-critical is shown in the appendix from Table B.10 to B.14.

4.3 Optimization of Briquette Properties Parameters

Minimizing variances of the experiments for optimal process parameters settings was achieved by the Taguchi technique (Taguchi L9 OA). Also, in consideration of multiple responses, Taguchi Grey relational analysis was used to optimize briquettes' physical and combustion properties for multi-objective optimization. Table 4.6 shows experimental runs that were carried out using three technologies. For the Signal to Noise ratio (S/N), the quality with "smaller the better "was used to minimize the means for moisture content, ash content and volatile matter. Further, "larger is better" quality was used to maximize the means for density, fixed carbon and calorific value.

4.3.1 Analysis of results for Taguchi based single objective optimization

The loss function “smaller the better” characteristics were selected for MC, AC, and VM, while “larger the better” was chosen for ρ , FC, and CV. The signal to noise (S/N) ratio was calculated from the means of parameters. The lower for “smaller the better” and greater signal to noise ratio for “larger the better” indicates better performance, and their related technology and mix ratio that delivers it were regarded as optimal settings. Table 4.4 displays the standard transformed into signal-to-noise ratios for each physical and combustion characteristic.

Table 4.4: Signal to Noise Ratios for Physical and Combustion Properties

Exp. No.	**Mix Ratios**	**Tech.**	**Parameters**						**Rank**	**GRG**
			MC	ρ	AC	VM	FC	CV		
1	1:1:1	SP	21.78	53.90	16.82	26.39	35.89	25.48	8	0.36
2	2:1:2	SP	21.32	55.13	16.41	25.13	36.56	26.00	6	0.44
3	2:3:1	DA	21.56	55.01	16.65	26.99	36.02	25.85	7	0.42
4	2:3:1	SP	20.97	57.00	16.12	22.05	37.67	26.58	4	0.50
5	3:2:1	HM	21.90	53.13	17.04	27.00	35.00	25.04	9	0.33
6	3:2:1	DA	20.84	57.23	15.87	24.82	37.78	26.99	3	0.60
7	3:2:1	SP	20.15	59.70	15.33	23.46	38.22	27.72	1	0.98
8	3:3:2	DA	21.00	56.59	16.17	24.87	36.96	26.14	5	0.49
9	3:3:2	SP	20.31	58.00	15.49	24.00	38.01	27.24	2	0.87

Abbreviations: Tech - Technology; MC- Moisture content; ρ - Density; AC - Ash content; VM - Volatile matter; FC - Fixed carbon; CV - Calorific value; GRG - Grey Relational Grade

From (Table 4.4), S/N ratios for MC, AC, and VM were calculated using Equation (2.21) since "smaller is better" was desired. In contrast, S/N ratios for D, FC, and CV were calculated using Equation (2.22) since "larger is better" was intended. The results obtained the best quality characteristics of moisture content at a mix ratio of 3:2:1 RH: CC: SB when using screw press as the technology. However, technology was responsible for deviation in moisture content due to pressure used during briquetting and not the number of feedstocks in the mix ratios. On the other hand, density was maximum when screw press was used at the same mix ratio of 3:2:1. Both technology and individual feedstock were responsible for changes in density. An increase in pressure increased compaction, thus increasing density, while for mix ratio, each feedstock has its bulk density, and mixing them led to different densities. However, feedstock material has the highest impact in determining the energy density of the briquettes. Ash content was minimized when a small amount of bagasse was used. Both technology and mix ratios affected ash content; however, individual feedstock bulk density contributed most to ash content.

Technique had the most negligible influence on volatile matter, fixed carbon, and calorific value. All these three combustion properties were highly affected by the mix ratios of individual feedstock material. Depending on the type of feedstock, combustion properties kept changing. However, a mix ratio of 3:2:1 of feedstock material gave the highest values when the volatile matter was minimized while fixed carbon and calorific values maximized.

4.3.2 Multi-objective Optimization using Taguchi-Grey Relational Analysis

Nine mix ratios with the best qualities were chosen from the twenty-seven from a single objective analysis. However, further analysis was needed to determine the influence of the selected mix ratios and their corresponding technologies for best quality briquettes. Taguchi-Grey relational analysis was thus used to determine the briquettes' best physical and combustion properties. Mean values from single-objective optimization were normalized and converted into Grey relational coefficients using grey relational analysis Equations (2.23- 2.26) and results tabulated in Table 4.5

Table 4.5: Optimal Physical and Combustion Properties

Mix Ratios	Tech.	Parameters						S/N for GRG	Rank
		MC	ρ	AC	VM	FC	CV		
1:1:1	SP	8.01	576	7.18	23.32	69.50	21.57	-8.04	8
2:1:2	SP	7.79	650	6.33	20.60	73.01	23.02	-7.10	6
2:3:1	DA	7.92	591	7.00	23.25	69.75	20.73	-7.42	7
2:3:1	SP	7.58	785	5.88	20.58	73.60	23.83	-6.64	4
3:2:1	HM	8.12	542	7.35	24.39	68.26	18.33	-8.87	9
3:2:1	DA	6.92	833	5.00	19.23	75.77	25.61	-5.00	3
3:2:1	SP	6.43	904	3.63	18.56	77.81	29.04	-0.08	1
3:3:1	DA	7.35	725	6.00	20.99	73.07	23.08	-6.91	5
3:3:1	SP	6.74	869	4.65	19.02	76.33	27.16	-3.05	2

Abbreviations: Tech- Technology; MC- Moisture content; ρ - Density; AC- Ash content; VM- Volatile matter; FC- Fixed carbon; CV- Calorific value; GRG- Grey relational grade

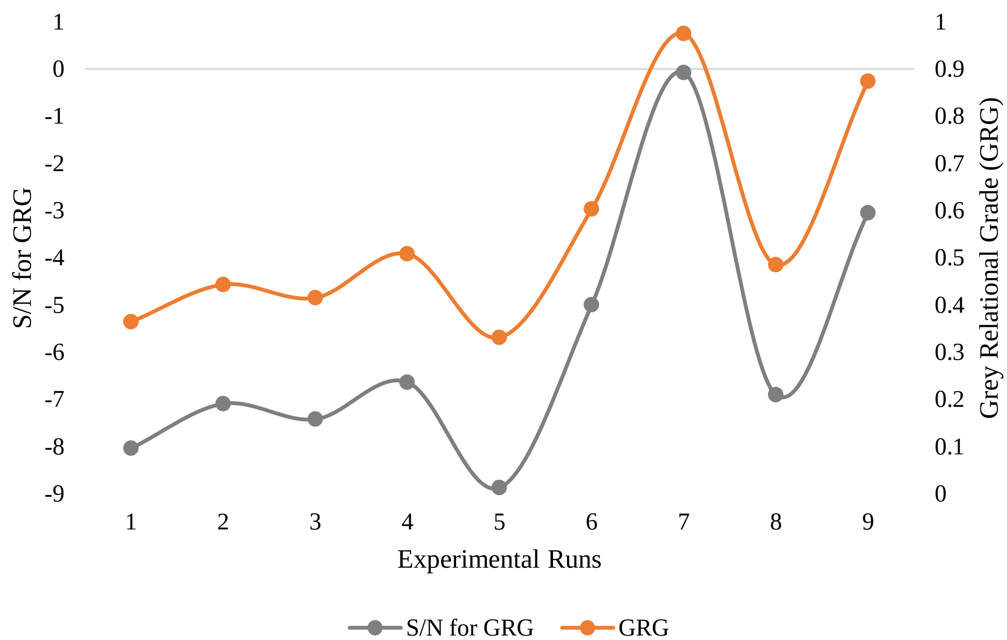


Figure 4.3: **A Graph showing S/N Ratios and its Corresponding GRG in Multi Objective Optimization**

Table 4.5 and Fig. 4.3a show that experimental run No.7 has the highest Grey relational grade value corresponding to the highest S/N ratio. The higher the GRG number and S/N ratio, the better the experimental run. The optimal condition was obtained at a mixed ratio of 3:2:1 when using screw press as the technique. The predicted value was 0.9879, which is close to 1.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

From the specific objectives, the following are the conclusions drawn from the findings. Briquetting techniques and the number of feedstocks influence the performance characteristics of briquettes. An increase in the number of feedstocks raised ignition time. Also, ignition time varied depending on the technique used as the pressurized technique (Screw press) registered high value. Also, the burning rate and specific fuel consumption were significantly influenced by the number of feedstocks and techniques used. An increase in feedstocks or pressure resulted in a corresponding decrease in performance values. However, time to boil and power output were not affected by a number of feedstocks but rather the technique used during production. The pressurized technique produced higher density briquettes that led to an increase in time to boil and power output. Therefore, the technique and number of feedstocks significantly influenced the properties investigated.

Number of feedstocks used and mix ratios affected physical and combustion characteristics. An increase in feedstocks led to a decrease in moisture content, ash content, and volatile matter. However, an increase in feedstocks led to a corresponding increase in briquettes density, calorific value, and fixed carbon. Also, the properties were influenced by the individual value of the feedstock in the mix ratio. Ratios with high values of husks showed improved characteristics, while poor characteristics were obtained when bagasse was high in the mix. ANOVA showed a significant influence from the number of feedstocks used and among all mix ratios investigated at $p = 5\%$.

Taguchi technique (Taguchi L9 OA) using multi-response optimization showed that type of feedstocks, technique, and feedstocks mix ratios affected briquettes characteristics. However, analyses using ANOVA showed that the significant influence on briquettes' properties was in the order of the number of feedstocks > mix ratios > technique. A confirmatory test was carried out to compare with analysis and agreed with the results where optimal physical and combustion properties were reached when screw press was used as the technique with mix ratio of 3:2:1 of husks: cobs: bagasse.

5.2 Recommendations

From these research findings, the following are the recommendations for practitioners and further research:

a) For practitioners:

   i. Screw press should be used during briquetting for improved briquettes performance characteristics.

   ii. Three feedstocks should be preferred for optimal energy from the briquettes.

b) For further research, there is need to study the effect of:

   i. Emission levels from briquettes to environment compared to firewood, charcoal and fossil fuels.

   ii. Different pressures in screw press during briquetting and their effect on final briquettes performance characteristics.

   iii. Binder quantity with drum agglomerator and the effect on briquettes properties.

REFERENCES

Abdoli, M. A., Golzary, A., Hosseini, A., & Sadeghi, P. (2018). Wood Pellet as a Renewable Source of Energy. *Springer International Publishing*, *9*, 161-184. https://doi.org/10.1007/978-3-319-74482-7

Abdulkareem, S., Hakeem, B. A., Ahmed, I. I., Ajiboye, T. K., Adebisi, J. A., & Yahaya, T. (2018). Combustion Characteristics of Bio-Degradable Biomass Briquettes. *Journal of Engineering Science and Technology*, *13*(9), 2779-2791.

Adeleke, A. A., Ikubanni, P. P., Orhadahwe, T. A., Christopher, C. T., Akano, J. M., Agboola, O. O., Adegoke, S. O., Balogun, A. O., & Ibikunle, R. A. (2021). Sustainability of multifaceted usage of biomass: A review. *Heliyon*, *7*(9), 1-19. https://doi.org/10.1016/j.heliyon.2021.e08025

Adeniyi, A. G., & Ighalo, J. O. (2020). Computer-Aided Modeling of Thermochemical Conversion Processes for Environmental Waste Management. In C. M. Hussain (Ed.), *Handbook of Environmental Materials Management*. *Springer International Publishing*, 1-16. https://doi.org/10.1007/978-3-319-58538-3_185-1

Adetogun, A.C., Ogunjobi, K.M., & Are, D.B. (2014). Combustion properties of briquettes produced from maize cob of different particle sizes. *Journal of Research in Forestry, Wildlife and Environmental*, *6*(1), 28-38.

Agomuo, U. C., Evuti, A. M., Ozigis, I. I., & Abba, A. H. (2019). Optimization of Calorific Value of Briquettes from Mixture of Rice Husk and Sawdust Biomass Using Taguchi Approach. *Nigeria Journal of Engineering Science and Technology Research*, *5*(2), 103-110.

Ajimotokan, H. A., Ehindero, A. O., Ajao, K. S., Adeleke, A. A., Ikubanni, P. P., & Shuaib-Babata, Y. L. (2019). Combustion characteristics of fuel briquettes made from charcoal particles and sawdust agglomerates. *Scientific African*, *6*, 1-15. https://doi.org/10.1016/j.sciaf.2019.e00202

Akbar, A., Aslam, U., Asghar, A., & Aslam, Z. (2021). Effect of binding materials on physical and fuel characteristics of bagasse-based pellets. *Biomass and Bioenergy*, *150*, 1-14. https://doi.org/10.1016/j.biombioe.2021.106118

Akolgo, G. A., Awafo, E. A., Essandoh, E. O., Owusu, P. A., Uba, F., & Adu-Poku, K. A. (2021). Assessment of the potential of charred briquettes of sawdust, rice and coconut husks: Using water boiling and user acceptability tests. *Scientific African*, *12*, 1-20. https://doi.org/10.1016/j.sciaf.2021.e00789

Akpenpuun, T. D., Salau, R. A., Adebayo, A. O., Adebayo, O. M., Salawu, J., & Durotoye, M. (2020). Physical and combustible properties of briquettes produced from a combination of groundnut shell, rice husk, sawdust and wastepaper using starch as a binder. *Journal of Applied Sciences and Environmental Management*, *24*(1), 171-177. https://doi.org/10.4314/jasem.v24i1.25

Anggraeni, S., Hofifah, S. N., & Nandiyanto, A. B. D. (2021). Effects of Particle Size and Composition of Cassava Peels and Rice Husk on the Briquette Performance. *Journal of Engineering Science and Technology*, *16*(1), 527-542.

Aransiola, E. F., Oyewusi, T. F., Osunbitan, J. A., & Ogunjimi, L. A. O. (2019). Effect of binder type, binder concentration and compacting pressure on some physical properties of carbonized corncob briquette. *Energy Reports*, *5*, 909–918. https://doi.org/10.1016/j.egyr.2019.07.011

Arellano, G. M. T., Kato, Y. S., & Bacani, F. T. (2015). Evaluation of Fuel Properties of Charcoal Briquettes Derived from Combinations of Coconut Shell, Corn Cob and Sugarcane Bagasse. *Proceedings of the DLSU Research Congress, 3*, 1-6.

Athreya & Venkatesh (2012). Application Of Taguchi Method for Optimization of Process Parameters in Improving the Surface Roughness of Lathe Facing Operation. .*International Refereed Journal of Engineering and Sciences*, *1*(3), 13-19.

Avelar, N. V., Rezende, A. A. P., Carneiro, A. de C. O., & Silva, C. M. (2016). Evaluation of briquettes made from textile industry solid waste. *Renewable Energy*, *91*, 417–424. https://doi.org/10.1016/j.renene.2016.01.075

Awasthi, M. K., Sarsaiya, S., Patel, A., Juneja, A., Singh, R. P., Yan, B., Awasthi, S. K., Jain, A., Liu, T., Duan, Y., Pandey, A., Zhang, Z., & Taherzadeh, M. J. (2020a). Refining biomass residues for sustainable energy and bio-products: An assessment of technology, its importance, and strategic applications in circular bio-economy. *Renewable and Sustainable Energy Reviews*, *127*, 1-18. https://doi.org/10.1016/j.rser.2020.109876

Bailis, R., Ghosh, E., O'Connor, M., Kwamboka, E., Ran, Y., & Lambe, F. (2020). Enhancing clean cooking options in peri-urban Kenya: A pilot study of advanced gasifier stove adoption. *Environmental Research Letters*, *15*(8), 1-12. https://doi.org/10.1088/1748-9326/ab865a

Bazargan, A., Rough, S. L., & McKay, G. (2014). Compaction of palm kernel shell biochars for application as solid fuel. *Biomass and Bioenergy*, *70*, 489–497. https://doi.org/10.1016/j.biombioe.2014.08.015

Bazargan, A., Rough, S. L., & McKay, G. (2018). Fine tuning of process parameters for improving briquette production from palm kernel shell gasification waste. *Environmental Technology*, *39*(7), 931–938. https://doi.org/10.1080/09593330.2017.1317835

Behling, R., Valange, S., & Chatel, G. (2016). Heterogeneous catalytic oxidation for lignin valorization into valuable chemicals: What results? What limitations? What trends? *Green Chemistry*, *18*(7), 1839–1854. https://doi.org/10.1039/C5GC03061G

Bello, R. S., & Onilude, M. A. (2020). Physico-mechanical Characteristics of High-Density Briquettes produced from Composite Sawdust. *Journal of Applied Sciences and Environmental Management*, *24*(5), 779–787. https://doi.org/10.4314/jasem.v24i5.8

Bembenek, M. (2020). The Influence of the Use of Polymer Lining within the Roller Press Gravity Feeder on Briquette Quality. *Polymers*, *12*(11), 1-14. https://doi.org/10.3390/polym12112489

Bembenek, M., Krawczyk, J., & Pańcikiewicz, K. (2020). The Wear on Roller Press Rollers Made of 20Cr4/1.7027 Steel under Conditions of Copper Concentrate Briquetting. *Materials*, *13*(24), 1-17. https://doi.org/10.3390/ma13245782

Berrueta, V. M., Edwards, R. D., & Masera, O. R. (2008). Energy performance of wood-burning cookstoves in Michoacan, Mexico. *Renewable Energy*, *33*(5), 859–870. https://doi.org/10.1016/j.renene.2007.04.016

Borowski, G. (2021). An Overview of Particle Agglomeration Techniques to Waste Utilization. *Journal of Ecological Engineering*, *22*(9), 263–271. https://doi.org/10.12911/22998993/141884

Brožek, M. (2016). The Effect of Moisture of the Raw Material on the Properties Briquettes for Energy Use. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, *64*(5), 1453–1458. https://doi.org/10.11118/actaun201664051453

Brunerová, A., Roubík, H., Brožek, M., Van Dung, D., Phung, L. D., Hasanudin, U., Iryani, D. A., & Herák, D. (2020). Briquetting of sugarcane bagasse as a proper waste management technology in Vietnam. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *38*(11), 1239–1250. https://doi.org/10.1177/0734242X20938438

Cardil, A., de-Miguel, S., Silva, C. A., Reich, P. B., Calkin, D., Brancalion, P. H. S., Vibrans, A. C., Gamarra, J. G. P., Zhou, M., Pijanowski, B. C., Hui, C., Crowther, T. W., Hérault, B., Piotto, D., Salas-Eljatib, C., Broadbent, E. N., Almeyda Zambrano, A. M., Picard, N., Aragão, L. E. O. C., Liang, J. (2020). Recent deforestation drove the spike in Amazonian fires. *Environmental Research Letters*, *15*(12), 1-5. https://doi.org/10.1088/1748-9326/abcac7

Chirchir, D. K., Nyaanga, D. M., & Githeko, J. M. (2013). Effect of Binder Types and Amount on Physical and Combustion Characteristics. *International Journal of Engineering Research and Science & Technology*, *2*(1) 11-20.

Chungcharoen, T., & Srisang, N. (2020). Preparation and characterization of fuel briquettes made from dual agricultural waste: Cashew nut shells and areca nuts. *Journal of Cleaner Production*, *256*, 1-43. https://doi.org/10.1016/j.jclepro.2020.120434

Costa, E. V. S., Pereira, M. P. de C. F., Silva, C. M. S. da, Pereira, B. L. C., Rocha, M. F. V., & Carneiro, A. de C. O. (2019). Torrefied Briquettes of Sugar Cane Bagasse and Eucalyptus. *Revista Árvore*, *43*(1), 1-9. https://doi.org/10.1590/1806-90882019000100001

da Silva, S. B., Arantes, M. D. C., de Andrade, J. K. B., Andrade, C. R., Carneiro, A. de C. O., & Protásio, T. de P. (2020). Influence of physical and chemical compositions on the properties and energy use of lignocellulosic biomass pellets in Brazil. *Renewable Energy*, *147*, 1870–1879. https://doi.org/10.1016/j.renene.2019.09.131

Davies, R. (2013). Ignition and Burning Rate of Water Hyacinth Briquettes. *Journal of Scientific Research and Reports*, *2*(1), 111–120. https://doi.org/10.9734/JSRR/2013/1964

Davies, R. M., & Davies, O. A. (2013). Physical and Combustion Characteristics of Briquettes Made from Water Hyacinth and Phytoplankton Scum as Binder. *Journal of Combustion*, *2013*, 1–7. https://doi.org/10.1155/2013/549894

De Filippo, D., & Serrano-López, A. E. (2018). From academia to citizenry. Study of the flow of scientific information from projects to scientific journals and social media in the field of "Energy saving." *Journal of Cleaner Production*, *199*, 248–256. https://doi.org/10.1016/j.jclepro.2018.07.177

Demirbas, A. (2004). Combustion characteristics of different biomass fuels. *Progress in Energy and Combustion Science*, *30*(2), 219–230. https://doi.org/10.1016/j.pecs.2003.10.004

Demirbas, A., & Sahin- Demirbas, A. (2004). Briquetting Properties of Biomass Waste Materials. *Energy Sources*, *26*(1), 83–91. https://doi.org/10.1080/00908310490251918

Demirel, C., Gürdil, G. A. K., Kabutey, A., & Herak, D. (2020). Effects of Forces, Particle Sizes, and Moisture Contents on Mechanical Behaviour of Densified Briquettes from Ground Sunflower Stalks and Hazelnut Husks. *Energies*, *13*(10), 1-19. https://doi.org/10.3390/en13102542

Demirel, C., Gurdil, G. A. K., Kabutey, A., & Wasserbauer, M. (2019). Comparing energy demand of densified briquettes of ground and unground hazelnut husks under compression loading. *IOP Conference Series: Earth and Environmental Science*, *260*(1), 1-5. https://doi.org/10.1088/1755-1315/260/1/012028

Dinesha, P., Kumar, S., & Rosen, M. A. (2019). Biomass Briquettes as an Alternative Fuel: A Comprehensive Review. *Energy Technology*, *7*(5), 1-22. https://doi.org/10.1002/ente.201801011

Djangba, R. M., Ohene-Akoto, J., Addo, S. G., & Issah, A.-M. (2021). Techno-Economic Assessment of Briquetting: A Case Study of The Sokoban Wood Village. *2021 International Conference on Advance Computing and Innovative Technologies in Engineering (ICACITE)*, 550–554. https://doi.org/10.1109/ICACITE51222.2021.9404704

Dulal, S., & Singh, R. M. (2021). Fuel Briquettes from Sal (Shorea robusta) Forest Litter as an Alternative Cooking Fuel. *Nepal Journal of Science and Technology*, *19*(2), 68–74. https://doi.org/10.3126/njst.v20i1.39433

Efomah, A. N., & Gbabo, A. (2015). The Physical, Proximate and Ultimate Analysis of Rice Husk Briquettes Produced from a Vibratory Block Mould Briquetting Machine. *International Journal of Innovative Science, Engineering & Technology*, *2*(5), 814-822.

Falemara, B., Joshua, V., Aina, O., & Nuhu, R. (2018). Performance Evaluation of the Physical and Combustion Properties of Briquettes Produced from Agro-Wastes and Wood Residues. *Recycling*, *3*(3), 1-13. https://doi.org/10.3390/recycling3030037

Fei, N. C., Mehat, N. M., & Kamaruddin, S. (2013). Practical Applications of Taguchi Method for Optimization of Processing Parameters for Plastic Injection Moulding: A Retrospective Review. *ISRN Industrial Engineering*, *2013*, 1–11. https://doi.org/10.1155/2013/462174

Felfli, F. F., Mesa P, J. M., Rocha, J. D., Filippetto, D., Luengo, C. A., & Pippo, W. A. (2011). Biomass briquetting and its perspectives in Brazil. *Biomass and Bioenergy*, *35*(1), 236–242. https://doi.org/10.1016/j.biombioe.2010.08.011

García, R., Pizarro, C., Lavín, A. G., & Bueno, J. L. (2012). Characterization of Spanish biomass wastes for energy use. *Bioresource Technology*, *103*(1), 249–258. https://doi.org/10.1016/j.biortech.2011.10.004

Garcia-Freites, S., Welfle, A., Lea-Langton, A., Gilbert, P., & Thornley, P. (2020). The potential of coffee stems gasification to provide bioenergy for coffee farms: A case study in the Colombian coffee sector. *Biomass Conversion and Biorefinery*, *10*(4), 1137–1152. https://doi.org/10.1007/s13399-019-00480-8

Gilvari, H., Cutz, L., Tiringer, U., Mol, A., de Jong, W., & Schott, D. L. (2020). The Effect of Environmental Conditions on the Degradation Behavior of Biomass Pellets. *Polymers*, *12*(4), 1-15. https://doi.org/10.3390/polym12040970

Gupta, A., Mulukutla, A. N. V., Gautam, S., TaneKhan, W., Waghmare, S. S., & Labhasetwar, N. K. (2020). Development of a practical evaluation approach of a typical biomass cookstove. *Environmental Technology & Innovation*, *17*, 1-33. https://doi.org/10.1016/j.eti.2020.100613

Gwenzi, W., Ncube, R. S., & Rukuni, T. (2020). Development, properties and potential applications of high-energy fuel briquettes incorporating coal dust, biowastes and postconsumer plastics. *SN Applied Sciences*, *2*(6), 1-14. https://doi.org/10.1007/s42452-020-2799-8

Husain, Z., Zainac, Z., & Abdullah, Z. (2002). Briquetting of palm ÿbre and shell from the processing of palm nuts to palm oil. *Biomass and Bioenergy*, *22*, 505-509.

Ibitoye, S. E., Jen, T.-C., Mahamood, R. M., & Akinlabi, E. T. (2021). Densification of agro-residues for sustainable energy generation: An overview. *Bioresources and Bioprocessing*, *8*(1), 1-19. https://doi.org/10.1186/s40643-021-00427-w

Idowu, A. (2020). Combustion Quality Evaluation of Briquettes Produced from Sesame Hull as Source of Sustainable Energy. *Asian Journal of Energy Transformation and Conservation*, *4*(1), 30-39. https://doi.org/10.18488/journal.81.2020.41.30.39

Ikubanni, P. P., Agboola, O. O., Olabamiji, T. S., Adediran, A. A., Anisere, T., & Oladimeji, S. (2020). Development and performance assessment of piston-type briquetting machine. *IOP Conference Series: Earth and Environmental Science*, *445*(1), 1-13. https://doi.org/10.1088/1755-1315/445/1/012005

Jackson, R. B., Le Quéré, C., Andrew, R. M., Canadell, J. G., Korsbakken, J. I., Liu, Z., Peters, G. P., & Zheng, B. (2018). Global energy growth is outpacing decarbonization. *Environmental Research Letters*, *13*(12), 1-7. https://doi.org/10.1088/1748-9326/aaf303

Jacobson, M., & Ciolkosz, D. (2020). Plantation forestry and pellet production in Kenya. *Biomass and Bioenergy*, *135*, 1-4. https://doi.org/10.1016/j.biombioe.2020.105519

Jamradloedluk, J., & Wiriyaumpaiwong, S. (2007). Production and Characterization of Rice Husk Based Charcoal Briquettes. *KKU Engineering Journal*, *34*(4), 391-398.

Jani, S. M. (2016). The proximate analysis and mechanical properties of rice husk charcoal briquette. *Journal of Tropical Agriculture and Food Science*, *44*(2), 243-251.

Jiao, W., Tabil, L. G., Xin, M., Song, Y., Chi, B., Wu, L., Chen, T., Meng, J., & Bai, X. (2020). Optimization of process variables for briquetting of biochar from corn stover. *BioResources*, *15*(3), 6811–6825. https://doi.org/10.15376/biores.15.3.6811-6825

Jittabut, P. (2015). Physical and Thermal Properties of Briquette Fuels from Rice Straw and Sugarcane Leaves by Mixing Molasses. *Energy Procedia*, *79*, 2–9. https://doi.org/10.1016/j.egypro.2015.11.452

Ju, X., Zhang, K., Chen, Z., & Zhou, J. (2020). A Method of Adding Binder by High-Pressure Spraying to Improve the Biomass Densification. *Polymers*, *12*(10), 1-14. https://doi.org/10.3390/polym12102374

Kabok, A. P., Nyaanga, D. M., Mbugua, J. M., & Eppinga, R. (2018). Effect of Shapes, Binders and Densities of Faecal Matter—Sawdust Briquettes on Ignition and Burning Times. *Journal of Petroleum & Environmental Biotechnology*, *9*(2), 1-5. https://doi.org/10.4172/2157-7463.1000370

Kaliyan, N., & Morey, R. V. (2015). Strategies to Improve Durability of Switchgrass Briquettes. *American Society of Agricultural and Biological Engineers*, *52*(6), 1943-1953.

Kaliyan, N., & Morey, R. V. (2010). Natural binders and solid bridge type binding mechanisms in briquettes and pellets made from corn stover and switchgrass. *Bioresource Technology*, *101*(3), 1082–1090. https://doi.org/10.1016/j.biortech.2009.08.064

Kashif, M., Awan, M. B., Nawaz, S., Amjad, M., Talib, B., Farooq, M., Nizami, A. S., & Rehan, M. (2020). Untapped renewable energy potential of crop residues in Pakistan: Challenges and future directions. *Journal of Environmental Management*, *256*, 1-10. https://doi.org/10.1016/j.jenvman.2019.109924

Kaur, S., Kumar, D., Singla, M., & Dogra, R. (2020). Biogas to Bio-CNG from paddy straw: A review. *International Journal of Chemical Studies*, *8*(3), 1833–1838. https://doi.org/10.22271/chemi.2020.v8.i3y.9475

Kongprasert, N., Wangphanich, P., & Jutilarptavorn, A. (2019). Charcoal Briquettes from Madan Wood Waste as an Alternative Energy in Thailand. *Procedia Manufacturing*, *30*, 128–135. https://doi.org/10.1016/j.promfg.2019.02.019

Kpalo, S. Y., Zainuddin, M. F., Manaf, L. A., & Roslan, A. M. (2020). Production and Characterization of Hybrid Briquettes from Corncobs and Oil Palm Trunk Bark under a Low-Pressure Densification Technique. *Sustainability*, *12*(6), 1-16. https://doi.org/10.3390/su12062468

Kpalo, S. Y., Zainuddin, M. F., Manaf, L. A., & Roslan, A. M. (2020). A Review of Technical and Economic Aspects of Biomass Briquetting. *Sustainability*, *12*(11), 1-30. https://doi.org/10.3390/su12114609

Kpalo, S. Y., Zainuddin, M. F., Manaf, L. A., & Roslan, A. M. (2021). Evaluation of hybrid briquettes from corncob and oil palm trunk bark in a domestic cooking application for rural communities in Nigeria. *Journal of Cleaner Production*, *284*, 1-10. https://doi.org/10.1016/j.jclepro.2020.124745

Križan, P., Šooš, Ľ., Matúš, M., Beniak, J., & Svátek, M. (2014). Research of Significant Densification Parameters influence on Final Briquettes Quality. *Wood Research*, *60*(2), 301-316.

Kumar, R., Strezov, V., Weldekidan, H., He, J., Singh, S., Kan, T., & Dastjerdi, B. (2020). Lignocellulose biomass pyrolysis for bio-oil production: A review of biomass pre-treatment methods for production of drop-in fuels. *Renewable and Sustainable Energy Reviews*, *123*, 1-31. https://doi.org/10.1016/j.rser.2020.109763

Kwon, G., Bhatnagar, A., Wang, H., Kwon, E. E., & Song, H. (2020). A review of recent advancements in utilization of biomass and industrial wastes into engineered biochar. *Journal of Hazardous Materials*, *400*, 1-44. https://doi.org/10.1016/j.jhazmat.2020.123242

Latterini, F., Stefanoni, W., Suardi, A., Alfano, V., Bergonzoli, S., Palmieri, N., & Pari, L. (2020). A GIS Approach to Locate a Small Size Biomass Plant Powered by Olive Pruning and to Estimate Supply Chain Costs. *Energies*, *13*(13), 1-17. https://doi.org/10.3390/en13133385

Li, Y., Xing, B., Ding, Y., Han, X., & Wang, S. (2020). A critical review of the production and advanced utilization of biochar via selective pyrolysis of lignocellulosic biomass. *Bioresource Technology*, *312*, 1-51. https://doi.org/10.1016/j.biortech.2020.123614

Liu, X., Liu, Z., Fei, B., Cai, Z., Jiang, Z., & Liu, X. (2013.). Comparative Properties of Bamboo and Rice Straw Pellets. *BioResources*, *8*(1), 638-647.

Lubwama, M., Yiga, V. A., Muhairwe, F., & Kihedu, J. (2020). Physical and combustion properties of agricultural residue bio-char bio-composite briquettes as sustainable domestic energy sources. *Renewable Energy*, *148*, 1002–1016. https://doi.org/10.1016/j.renene.2019.10.085

Lunguleasa, A., Ayrilmiş, N., Sova, D., & Spirchez, C. (2021). Selected properties of briquettes made from blends of bamboo and beech biomass. *Turkish Journal of Agriculture and Forestry*, *4*(5), 389-401.

MacCarty, N., Still, D., & Ogle, D. (2010). Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. *Energy for Sustainable Development*, *14*(3), 161–171. https://doi.org/10.1016/j.esd.2010.06.002

Magnago, R. F., Costa, S. C., Assunção Ezirio, M. J. de, Godoy Saciloto, V. de, Cremona Parma, G. O., Gasparotto, E. S., Gonçalves, A. C., Tutida, A. Y., & Barcelos, R. L. (2020). Briquettes of citrus peel and rice husk. *Journal of Cleaner Production*, *276*, 1-9. https://doi.org/10.1016/j.jclepro.2020.123820

Mamvura, T. A., & Danha, G. (2020). Biomass torrefaction as an emerging technology to aid in energy production. *Heliyon*, *6*(3), 1-17. https://doi.org/10.1016/j.heliyon.2020.e03531

Mangla, S. K., Luthra, S., Jakhar, S., Gandhi, S., Muduli, K., & Kumar, A. (2020). A step to clean energy—Sustainability in energy system management in an emerging economy context. *Journal of Cleaner Production*, *242*, 1-12. https://doi.org/10.1016/j.jclepro.2019.118462

Mani, S., Tabil, L. G., & Sokhansanj, S. (2006). Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. *Biomass and Bioenergy*, *30*(7), 648–654. https://doi.org/10.1016/j.biombioe.2005.01.004

Manyuchi, M. M., Mbohwa, C., & Muzenda, E. (2018). Value addition of coal fines and sawdust to briquettes using molasses as a binder. *South African Journal of Chemical Engineering*, *26*, 70–73. https://doi.org/10.1016/j.sajce.2018.09.004

Matúš, M., Križan, P., Šooš, Ľ., & Beniak, J. (2015). Effects of Initial Moisture Content on the Physical and Mechanical Properties of Norway Spruce Briquettes. *International Journal of Environmental and Ecological Engineering*, *9(*10), 1227-1233.

Matyjewicz, B., Świechowski, K., Koziel, J. A., & Białowiec, A. (2020). Proof-of-Concept of High-Pressure Torrefaction for Improvement of Pelletized Biomass Fuel Properties and Process Cost Reduction. *Energies*, *13*(18), 1-27. https://doi.org/10.3390/en13184790

Mitra, R. K. S., Nagaraju, N., & Sekhar, C. (2015). Optimization of Process Parameters in Repititive Corrugation & Straightening (Rcs) of Mild Steel Using Taguchi Based Fuzzy Logic. *South Asian Journal of Engineering and Technology*, *2*(1), 134-138.

Nanda, S., Azargohar, R., Dalai, A. K., & Kozinski, J. A. (2015). An assessment on the sustainability of lignocellulosic biomass for biorefining. *Renewable and Sustainable Energy Reviews*, *50*, 925–941. https://doi.org/10.1016/j.rser.2015.05.058

Navalta, C. J. L. G., Banaag, K. G. C., Raboy, V. A. O., Go, A. W., Cabatingan, L. K., & Ju, Y.-H. (2020). Solid fuel from Co-briquetting of sugarcane bagasse and rice bran. *Renewable Energy*, *147*, 1941–1958. https://doi.org/10.1016/j.renene.2019.09.129

Ndindeng, S. A., Mbassi, J. E. G., Mbacham, W. F., Manful, J., Graham-Acquaah, S., Moreira, J., Dossou, J., & Futakuchi, K. (2015). Quality optimization in briquettes made from rice milling by-products. *Energy for Sustainable Development*, *29*, 24–31. https://doi.org/10.1016/j.esd.2015.09.003

Ngusale, G. K., Luo, Y., & Kiplagat, J. K. (2014). Briquette making in Kenya: Nairobi and peri-urban areas. *Renewable and Sustainable Energy Reviews*, *40*, 749–759. https://doi.org/10.1016/j.rser.2014.07.206

Nguyen, Q. A., Smith, W. A., Wahlen, B. D., & Wendt, L. M. (2020). Total and Sustainable Utilization of Biomass Resources: A Perspective. *Frontiers in Bioengineering and Biotechnology*, *8*(546), 1-7. https://doi.org/10.3389/fbioe.2020.00546

Nielsen, S. K., Mandø, M., & Rosenørn, A. B. (2020). Review of die design and process parameters in the biomass pelleting process. *Powder Technology*, *364*, 971–985. https://doi.org/10.1016/j.powtec.2019.10.051

Niño, A., Arzola, N., & Araque, O. (2020). Experimental Study on the Mechanical Properties of Biomass Briquettes from a Mixture of Rice Husk and Pine Sawdust. *Energies*, *13*(5), 1-20. https://doi.org/10.3390/en13051060

Nunes, L. J. R., Causer, T. P., & Ciolkosz, D. (2020). Biomass for energy: A review on supply chain management models. *Renewable and Sustainable Energy Reviews*, *120*, 1-8 https://doi.org/10.1016/j.rser.2019.109658

Nurek, T., Gendek, A., Roman, K., & Dąbrowska, M. (2019). The effect of temperature and moisture on the chosen parameters of briquettes made of shredded logging residues. *Biomass and Bioenergy*, *130*, 1-7. https://doi.org/10.1016/j.biombioe.2019.105368

Nwabue, F. I., Unah, U., & Itumoh, E. J. (2017). Production and characterization of smokeless bio-coal briquettes incorporating plastic waste materials. *Environmental Technology & Innovation*, *8*, 233–245. https://doi.org/10.1016/j.eti.2017.02.008

Obi, O. F., Ezeoha, S. L., & Okorie, I. C. (2016). Energetic performance of a top-lit updraft (TLUD) cookstove. *Renewable Energy*, *99*, 730–737. https://doi.org/10.1016/j.renene.2016.07.060

Ochola, G. O. (2018). Urbanization and Environmental Stress: A Review of Impacts of Urban Development on the Environment in Kenya. *International Journal of Environmental Sciences & Natural Resources*, *14*(3), 68-72. https://doi.org/10.19080/IJESNR.2018.14.555889

Okot, D. K., Bilsborrow, P. E., & Phan, A. N. (2018). Effects of operating parameters on maize COB briquette quality. *Biomass and Bioenergy*, *112*, 61–72. https://doi.org/10.1016/j.biombioe.2018.02.015

Okot, D. K., Bilsborrow, P. E., & Phan, A. N. (2019). Briquetting characteristics of bean straw-maize cob blend. *Biomass and Bioenergy*, *126*, 150–158. https://doi.org/10.1016/j.biombioe.2019.05.009

Oladeji, J. T. (2010). Fuel Characterization of Briquettes Produced from Corncob and Rice Husk Resides. *The Pacific Journal of Science and Technology*, *11*(1), 101-106.

Oladeji, J. T., & Enweremadu, C. C. (2012). The Effects of Some Processing Parameters on Physical and Densification Characteristics of Corncob Briquettes. *International Journal of Energy Engineering*, *2*(1), 22–27. https://doi.org/10.5923/j.ijee.20120201.04

Olatunde Ajani Oyelaran. (2015). Evaluating the bio-energy potential of groundnut shell and sugarcane bagasse waste composite. *KKU Engineering Journal*, *42*(4), 306-310. https://doi.org/10.14456/KKUENJ.2015.36

Onaji, P. B., & Siemons, R. V. (1993). Production of charcoal briquettes from cotton stalk in malawi: Methodology for feasibility studies using experiences in Sudan. *Biomass and Bioenergy*, *4*(3), 199–211. https://doi.org/10.1016/0961-9534(93)90059-D

Onchieku, J. M., Chikamai, B. N., & Rao, M. S. (2012). Optimum Parameters for the Formulation of Charcoal Briquettes Using Bagasse and Clay as Binder. *European Journal of Sustainable Development*, *1*(3), 477-492. https://doi.org/10.14207/ejsd.2012.v1n3p477

Onuegbu, T. U., Ekpunobi, U. E., Ogbu, I. M., Ekeoma, M. O., & Obumselu, F. O. (2011). Comparative Studies of Ignition Time and Water Boiling Test of Coal and Biomass Briquettes Blend. *International Journal of Recent Research and Applied Studies*, *7*(2), 153-159.

Onukak, I., Mohammed-Dabo, I., Ameh, A., Okoduwa, S., & Fasanya, O. (2017). Production and Characterization of Biomass Briquettes from Tannery Solid Waste. *Recycling*, *2*(4), 1-19. https://doi.org/10.3390/recycling2040017

Orisaleye, J. I., Jekayinfa, S. O., Adebayo, A. O., Ahmed, N. A., & Pecenka, R. (2018). Effect of densification variables on density of corn cob briquettes produced using a uniaxial compaction biomass briquetting press. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *40*(24), 3019–3028. https://doi.org/10.1080/15567036.2018.1516007

Orisaleye, J. I., Ojolo, S. J., & Ajiboye, J. S. (2020). Mathematical modelling of die pressure of a screw briquetting machine. *Journal of King Saud University - Engineering Sciences*, *32*(8), 555–560. https://doi.org/10.1016/j.jksues.2019.09.004

Osei Bonsu, B., Takase, M., & Mantey, J. (2020). Preparation of charcoal briquette from palm kernel shells: Case study in Ghana. *Heliyon*, *6*(10), 1-8. https://doi.org/10.1016/j.heliyon.2020.e05266

Ozoh, O., Okwor, T., Adetona, O., Akinkugbe, A., Amadi, C., Esezobor, C., Adeyeye, O., Ojo, O., Nwude, V., & Mortimer, K. (2018). Cooking Fuels in Lagos, Nigeria: Factors Associated with Household Choice of Kerosene or Liquefied Petroleum Gas (LPG). *International Journal of Environmental Research and Public Health*, *15*(4), 1-13. https://doi.org/10.3390/ijerph15040641

Pachauri, S. (2013). Pathways to achieve universal household access to modern energy by 2030. *Environmental Research Letters*, *8*, 1-7

Panwar, V., Prasad, B., & Wasewar, K. L. (2011). Biomass Residue Briquetting and Characterization. *Journal of Energy Engineering*, *137*(2), 108–114. https://doi.org/10.1061/(ASCE)EY.1943-7897.0000040

Plaza, D., Artigas, J., Ábrego, J., Gonzalo, A., Sánchez, J. L., Dro, A. D., & Richardson, Y. (2019). Design and operation of a small-scale carbonization kiln for cashew nutshell valorization in Burkina Faso. *Energy for Sustainable Development*, *53*, 71–80. https://doi.org/10.1016/j.esd.2019.10.005

Prasityousil, J., & Muenjina, A. (2013). Properties of Solid Fuel Briquettes Produced from Rejected Material of Municipal Waste Composting. *Procedia Environmental Sciences*, *17*, 603–610. https://doi.org/10.1016/j.proenv.2013.02.076

Rahaman, S. A., & Salam, P. A. (2017). Characterization of cold densified rice straw briquettes and the potential use of sawdust as binder. *Fuel Processing Technology*, *158*, 9–19. https://doi.org/10.1016/j.fuproc.2016.12.008

Rodrigues, T., & Braghini Junior, A. (2019). Charcoal: A discussion on carbonization kilns. *Journal of Analytical and Applied Pyrolysis, 143,* 1-46. https://doi.org/10.1016/j.jaap.2019.104670

Roman, K., Roman, M., Wojcieszak-Zbierska, M., & Roman, M. (2021). Obtaining Forest Biomass for Energy Purposes as an Enterprise Development Factor in Rural Areas. *Applied Sciences*, *11*(12), 1-18. https://doi.org/10.3390/app11125753

Saeed, A. A. H., Yub Harun, N., Bilad, M. R., Afzal, M. T., Parvez, A. M., Roslan, F. A. S., Abdul Rahim, S., Vinayagam, V. D., & Afolabi, H. K. (2021). Moisture Content Impact on Properties of Briquette Produced from Rice Husk Waste. *Sustainability*, *13*(6), 1-14. https://doi.org/10.3390/su13063069

Saptoadi, H. (2008). The Best Biobriquette Dimension and its Particle Size. *Asian Journal of Energy and Environment, 9*(3), 161-175.

Sawadogo, M. (2018). Cleaner production in Burkina Faso: Case study of fuel briquettes made from cashew industry waste. *Journal of Cleaner Production,* 1-23.

Seco, A., Espuelas, S., Marcelino, S., Echeverría, A. M., & Prieto, E. (2020). Characterization of Biomass Briquettes from Spent Coffee Grounds and Xanthan Gum Using Low Pressure and Temperature. *Bioenerg. Res.*, 1-9.

Sen, R., Wiwatpanyaporn, S., & Annachhatre, A. P. (2016). Influence of binders on physical properties of fuel briquettes produced from cassava rhizome waste. *International Journal of Environment and Waste Management*, *17*(2), 158-175. https://doi.org/10.1504/IJEWM.2016.076750

Shankar Tumuluru, J., Sokhansanj, S., Hess, J. R., Wright, C. T., & Boardman, R. D. (2011). REVIEW: A review on biomass torrefaction process and product properties for energy applications. *Industrial Biotechnology*, *7*(5), 384–401. https://doi.org/10.1089/ind.2011.7.384

Sharma, D., Ravindra, K., Kaur, M., Prinja, S., & Mor, S. (2020). Cost evaluation of different household fuels and identification of the barriers for the choice of clean cooking fuels in India. *Sustainable Cities and Society*, *52*, 1-8. https://doi.org/10.1016/j.scs.2019.101825

Sherwood, J. (2020). The significance of biomass in a circular economy. *Bioresource Technology*, 1-47.

Singla, M., Singh, M., & Dogra, R. (2020). Experimental investigation of imbert downdraft gasifier using rice straw briquettes. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 1–11. https://doi.org/10.1080/15567036.2020.1771478

Soares, L. D. S., Maia, A. A. D., Moris, V. A. S., & De Paiva, J. M. F. (2020). Study of the Effects of the Addition of Coffee Grounds and Sugarcane Fibers on Thermal and Mechanical Properties of Briquettes. *Journal of Natural Fibers*, *17*(10), 1430–1438. https://doi.org/10.1080/15440478.2019.1578325

Sokhansanj, S., & Turhollow, A. F. (2004). Biomass Densification – Cubing Operations and Costs for Corn Stover. *American Society of Agricultural Engineers*, *20*(4), 495-499.

Song, B., & Hall, P. (2020). Densification of Biomass and Waste Plastic Blends as a Solid Fuel: Hazards, Advantages, and Perspectives. *Frontiers in Energy Research*, *8(58)*, 1-7. https://doi.org/10.3389/fenrg.2020.00058

Song, X., Zhang, S., Wu, Y., & Cao, Z. (2020). Investigation on the properties of the bio-briquette fuel prepared from hydrothermal pretreated cotton stalk and wood sawdust. *Renewable Energy*, *151*, 184–191. https://doi.org/10.1016/j.renene.2019.11.003

Sotannde, O. A., Oluyege, A. O., & Abah, G. B. (2010). Physical and combustion properties of briquettes from sawdust of Azadirachta indica. *Journal of Forestry Research*, *21*(1), 63–67. https://doi.org/10.1007/s11676-010-0010-6

Styks, J., Wróbel, M., Frączek, J., & Knapczyk, A. (2020). Effect of Compaction Pressure and Moisture Content on Quality Parameters of Perennial Biomass Pellets. *Energies*, *13*(8), 1-20. https://doi.org/10.3390/en13081859

Suluh, S., Bontong, Y., Baan, A., Labiran, R., Patintingan, M. L., & Silka. (2021). Effect of variations in the composition of additives on the performance of petung bamboo charcoal briquettes. *IOP Conference Series: Materials Science and Engineering*, *1088*(1), 1-6. https://doi.org/10.1088/1757-899X/1088/1/012115

Thabuot, M., Pagketanang, T., Panyacharoen, K., Mongkut, P., & Wongwicha, P. (2015). Effect of Applied Pressure and Binder Proportion on the Fuel Properties of Holey Bio-Briquettes. *Energy Procedia*, *79*, 890–895. https://doi.org/10.1016/j.egypro.2015.11.583

Thapa, S., & Engelken, R. (2020). Optimization of pelleting parameters for producing composite pellets using agricultural and agro-processing wastes by Taguchi-Grey relational analysis. *Carbon Resources Conversion*, *3*, 104–111. https://doi.org/10.1016/j.crcon.2020.05.001

Tolessa, A., Zantsi, S., Louw, T. M., Greyling, J. C., & Goosen, N. J. (2020). Estimation of biomass feedstock availability for anaerobic digestion in smallholder farming systems in South Africa. *Biomass and Bioenergy*, *142*, 1-10. https://doi.org/10.1016/j.biombioe.2020.105798

Toscano Miranda, N., Lopes Motta, I., Maciel Filho, R., & Wolf Maciel, M. R. (2021). Sugarcane bagasse pyrolysis: A review of operating conditions and products properties. *Renewable and Sustainable Energy Reviews*, *149*, 1-20. https://doi.org/10.1016/j.rser.2021.111394

Tran, K.-Q., Werle, S., Trinh, T. T., Magdziarz, A., Sobek, S., & Pogrzeba, M. (2020). Fuel characterization and thermal degradation kinetics of biomass from phytoremediation plants. *Biomass and Bioenergy*, *134*, 1-7. https://doi.org/10.1016/j.biombioe.2020.105469

Trigueiro, W. R. (2020). Uncovering the spatial variability of recent deforestation drivers in the Brazilian Cerrado. *Journal of Environmental Management*, 275, 1-10.

Trubetskaya, A., Grams, J., Leahy, J. J., Johnson, R., Gallagher, P., Monaghan, R. F. D., & Kwapinska, M. (2020). The effect of particle size, temperature and residence time on the yields and reactivity of olive stones from torrefaction. *Renewable Energy*, *160*, 998–1011. https://doi.org/10.1016/j.renene.2020.06.136

Tryner, J., Willson, B. D., & Marchese, A. J. (2014). The effects of fuel type and stove design on emissions and efficiency of natural-draft semi-gasifier biomass cookstoves. *Energy for Sustainable Development*, *23*, 99–109. https://doi.org/10.1016/j.esd.2014.07.009

Tumuluru, J. S. (2018). Effect of pellet die diameter on density and durability of pellets made from high moisture woody and herbaceous biomass. *Carbon Resources Conversion*, *1*(1), 44–54. https://doi.org/10.1016/j.crcon.2018.06.002

Tumuluru, J. S. (2019). Effect of Moisture Content and Hammer Mill Screen Size on the Briquetting Characteristics of Woody and Herbaceous Biomass. *KONA Powder and Particle Journal*, *36*(0), 241–251. https://doi.org/10.14356/kona.2019009

Tumuluru, J. S., & Fillerup, E. (2020). Briquetting characteristics of woody and herbaceous biomass blends: Impact on physical properties, chemical composition, and calorific value. *Biofuels, Bioproducts and Biorefining*, *14*(5), 1105–1124. https://doi.org/10.1002/bbb.2121

Tumuluru, J. S., Tabil, L. G., Song, Y., Iroba, K. L., & Meda, V. (2015). Impact of process conditions on the density and durability of wheat, oat, canola, and barley straw briquettes. *BioEnergy Research*, *8*(1), 388–401. https://doi.org/10.1007/s12155-014-9527-4

Tumuluru, Christopher T Wright, Kevin L Kenney, & Richard J Hess. (2010). A Technical Review on Biomass Processing: Densification, Preprocessing, Modeling and Optimization. *An ASABE Meeting Presentation, 1009401,* 1-32. https://doi.org/10.13031/2013.29874

Usmani, Z., Sharma, M., Awasthi, A. K., Sivakumar, N., Lukk, T., Pecoraro, L., Thakur, V. K., Roberts, D., Newbold, J., & Gupta, V. K. (2021). Bioprocessing of waste biomass for sustainable product development and minimizing environmental impact. *Bioresource Technology*, *322*, 1-12. https://doi.org/10.1016/j.biortech.2020.124548

Vivek, C. P., Rochak, P. V., Suresh, P. S., & Raghavendra Ravi Kiran, K. (2019). Comparison Study on Fuel Briquettes Made of Eco-Friendly Materials for Alternate Source of

Energy. *IOP Conference Series: Materials Science and Engineering*, *577*(1), 1-8. https://doi.org/10.1088/1757-899X/577/1/012183

Wang, Q., Han, K., Gao, J., Li, H., & Lu, C. (2017). The pyrolysis of biomass briquettes: Effect of pyrolysis temperature and phosphorus additives on the quality and combustion of bio-char briquettes. *Fuel*, *199*, 488–496. https://doi.org/10.1016/j.fuel.2017.03.011

Ward, B. J., Yacob, T. W., & Montoya, L. D. (2014). Evaluation of Solid Fuel Char Briquettes from Human Waste. *Environmental Science & Technology*, *48*(16), 9852–9858. https://doi.org/10.1021/es500197h

Welfle, D. A., Chingaira, S., & Kassenov, A. (2020). Decarbonising Kenya's domestic & industry Sectors through bioenergy: An assessment of biomass resource potential & GHG performances. *Biomass and Bioenergy*, *142*, 1-10. https://doi.org/10.1016/j.biombioe.2020.105757

Welker, C., Balasubramanian, V., Petti, C., Rai, K., DeBolt, S., & Mendu, V. (2015). Engineering Plant Biomass Lignin Content and Composition for Biofuels and Bioproducts. *Energies*, *8*(8), 7654–7676. https://doi.org/10.3390/en8087654

Wilaipon, P. (2009). The Effects of Briquetting Pressure on Banana-Peel Briquette and the Banana Waste in Northern Thailand. *American Journal of Applied Sciences, 6(*1), 167-171.

Yahaya, D. B., & Ibrahim, T. G. (2012). Development of Rice Husk Briquettes for Use as Fuel. *Research Journal in Engineering and Applied Sciences*, *1*(2), 130-133.

Yanfen, L., & Xiaoqian, M. (2010). Thermogravimetric analysis of the co-combustion of coal and paper mill sludge. *Applied Energy*, *87*(11), 3526–3532. https://doi.org/10.1016/j.apenergy.2010.05.008

Yang, Y. B., Newman, R., Sharifi, V., Swithenbank, J., & Ariss, J. (2007). Mathematical modelling of straw combustion in a 38MWe power plant furnace and effect of operating conditions. *Fuel*, *86*(1–2), 129–142. https://doi.org/10.1016/j.fuel.2006.06.023

Yank, A., Ngadi, M., & Kok, R. (2016). Physical properties of rice husk and bran briquettes under low pressure densification for rural applications. *Biomass and Bioenergy*, *84*, 22–30. https://doi.org/10.1016/j.biombioe.2015.09.015

Yilmaz, H., Topakci, M., Karayel, D., & Çanakci, M. (2020). Comparison of the physical properties of cotton and sesame stalk pellets produced at different moisture contents and combustion of the finest pellets. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 1–19. https://doi.org/10.1080/15567036.2020.1850931

Yumak, H., Ucar, T., & Seyidbekiroglu, N. (2010). Briquetting soda weed (Salsola tragus) to be used as a rural fuel source. *Biomass and Bioenergy*, *34*(5), 630–636. https://doi.org/10.1016/j.biombioe.2010.01.006

Yun, X., Shen, G., Shen, H., Meng, W., Chen, Y., Xu, H., Ren, Y., Zhong, Q., Du, W., Ma, J., Cheng, H., Wang, X., Liu, J., Wang, X., Li, B., Hu, J., Wan, Y., & Tao, S. (2020). Residential solid fuel emissions contribute significantly to air pollution and associated health impacts in China. *Science Advances*, *6*(44), 1-7. https://doi.org/10.1126/sciadv.aba7621

Yusuff, A. S., Ajayi, O. A., & Popoola, L. T. (2021). Application of Taguchi design approach to parametric optimization of adsorption of crystal violet dye by activated carbon from poultry litter. *Scientific African*, *13*, 1-13. https://doi.org/10.1016/j.sciaf.2021.e00850

Z. Colley, O. O. Fasina, D. Bransby, & Y. Y. Lee. (2006). Moisture Effect on the Physical Characteristics of Switchgrass Pellets. *Transactions of the ASABE*, *49*(6), 1845–1851. https://doi.org/10.13031/2013.22271

Zhang, F., Wang, M., & Yang, M. (2021). Successful application of the Taguchi method to simulated soil erosion experiments at the slope scale under various conditions. *Catena*, *196*, 1-14. https://doi.org/10.1016/j.catena.2020.104835

APPENDICES

Appendix A: Design Calculations and Procedures

A.1: Design Calculations of Kiln Development

Density of maize cob = 815 Kgm^{-3}

$$V = \frac{\pi D^2 h}{4} = \frac{m}{\rho}$$

But; D = 0.5m

h = 1, for carbonization, 0.75m was used.

V = $\frac{\pi}{4} x(0.5)^2 x0.75 = 0.147 \approx 0.15m^3$

V = $\frac{m}{\rho}; 0.15m^3 = \frac{m}{815kg/m^3}$

m = 122.25 kg

m = 120 kg was chosen from the study.

Volume of the kiln, $\frac{\pi D^2 h}{4}$

= $\frac{\pi}{4}(0.5)^2 x0.75 = 0.196$

0.15 = $\frac{\pi D^2}{4} x0.75$

$D^2 = 0.2546$

D = 0.5046 $\approx$ 0.5m

A.2: Design Calculations of Screw Press Development

Torque on Rotating Shaft

$$T = \frac{63000*5}{1400} = 22.5$$

Diameter of the Screw Shaft

$$D^3 = \frac{\sqrt{(K_b\, xM_b)^2 + (1\, x\, M_t)^2}}{n400}$$

$$Permissable\ Stress = \frac{0.5\ x\ 400}{3} = 66.67$$

Assuming, Maximum tension driven by the belt, P_1 = 2.5 kN,

μ = 0.24,

$\theta = 180^{\circ}$

Now, $\frac{2.5}{P_2} = e^{0.24*180}$ = 1175 N ≈ 1.2 kN

Torque, $M_t = (P_1 - P_2)$ x radius

Or, M_t = 330882.5 Nmm

For the bending moment, $M_{t=}$ $(P_3 - P_4)$ x R_2

Or, $(P_3 - P_4)$ x 125 = 330882.5

So, P_3 = 5000 N

P_4 = 2352.94 N

From the Bending Moment Diagram, M_b = 1185625.45 Nmm

Load Lifted by Screw

$$W_e = \frac{\frac{D_m}{2}\tan\theta + \frac{\mu}{\cos\alpha}}{1 - \mu\tan\theta\cos\alpha}$$

Pressure Lifted by Screw Thread

$$P_r = \frac{W_e}{A_p}$$

But, $A_p = \pi D_m 4*0.85$

Briquette Capacity

$$Q_e = 60\frac{\pi}{4}0.07493 * 0.07493\ x\ 0.031_1^2 * 1.6 * 137 * 0.8 * 0.815 = 15.35$$

Power and Torque on the Screw Shaft

$$P = Ts\ x\ 14.66$$

But, $T_s = F_{180}\frac{\tan\theta + \frac{f}{\cos\theta_n}}{1 - \frac{f tan\ \theta}{\cos\theta_n}}$

Longitudinal and Hoop Stress

Hoop stress is always taken as double than longitudinal stress. Therefore, design is based on hoop stress.

Assuming, σ_H = 50 Mpa, P = 15 Mpa

Given, D_m = 50 mm

Thus, a reasonable value of extruder chamber thickness was obtained, t = 15 mm

$$\sigma_1 = \frac{15*50}{4*15} = 12.5$$

$$\sigma_H = \frac{15*50}{2*15} = 25$$

A.3: Procedure for Carrying out Water Boiling Test (WBT)

a) Cold start - high power phase

- Two liters of water at room temperature was poured into a pot and the briquettes were stacked in the combustion chamber of the cook stove.
- Initial water temperature was determined using a digital thermometer at a depth of about 1cm above the bottom of the pot.
- The initial weight of pot with water and cook stove with briquettes was determined by a weighing balance of 1g accuracy.
- Briquettes were given time to kindle and ignition time noted using a stopwatch.
- Once the briquettes had ignited, the pot with water was placed on the cook stove.
- The starting and stopping time were recorded and the water heated until the boiling point.
- Finally, the final water temperature, weights of; pot with remaining water, cook stove with remaining briquettes (after shaking it to allow the ash to fall on the ash tray), ash and the time to boil were determined and recorded.

b) Hot Start - High Power Phase

- The pot containing two litres of water at room temperature was placed on the cook stove with the remaining hot briquettes from cold start phase. The starting and stopping time was noted when the water reached the boiling point of 94^oC.
- The final water temperature; weights of pot with remaining water, cook stove with remaining briquettes, (after shaking it to allow the ash to fall on the ash tray), and time to boil was determined and recorded.
- The weight of ash is assumed to be the same as that of cold start phase.

c) **Simmering - Low Power Phase**

- A known weight of briquettes was added to fill the cook stove.
- The pot with the remaining hot water from the hot start phase was simmered for 45 minutes whereby, the water temperature is maintained at 3^{o}C below the boiling point.
- The ash tray port was opened and closed to regulate the air flowing into the combustion chamber hence controlling the water temperature.
- After 45 minutes, the final water temperature; weights of pot with remaining water, cook stove with remaining briquettes, (after shaking it to allow the ash to fall on the ash tray), ash and time to boil were determined and recorded.
- The shift from one phase to another was conducted within two minutes.

A.4: Procedures for Determining Physical Properties

i. Moisture Content

- Empty crucibles were cleaned and weighed.
- Two grams (2g) of samples were weighed using an electronic mass balance, poured on crucibles and placed in an oven.
- Oven was turned on and set to a temperature of 105 ^{o}C.
- Samples were allowed in the oven for 3 hours before being removed and placed in a desiccator to cool for 20 minutes to a room temperature.
- The final mass of the sample was then determined.

ii. Density

- Diameter and height of spherical briquettes were measured at six (6) positions at 90^{o} to each other by a vernier caliper.
- Volume (v) was then calculated from the average of the measurements which was computed and assumed as diameter (d) and height (h).
- Mass of the briquettes was measured using an electronic mass balance.

A.5: Procedures for Determining Combustion Properties

1) Calorific Value

- Approximately 1g of the sample was carefully weighed and placed directly into the crucible. Sample was weighed the to the nearest 0.1mg. Some form of compaction was done to ensure satisfactory ignition and complete combustion.
- 1.0ml of water was added to the bomb by a pipet.
- A measured length of firing wire was connected to the ignition terminals and maintained contact with the sample.
- The bomb calorimeter was charged with oxygen to a consistent pressure between 20 and 30 atm (2.03 and 3.04 MPa).
- Calorimeter water was adjusted before weighing as follows: Isothermal Jacket Method (1.6 to 2.0°C / 3.0 to 3.5°F below jacket temperature).
- Calorimeter in the jacket was assembled and stirrer started. 5 min was allowed for attainment of equilibrium; then calorimeter temperatures recorded at 1min intervals for 5 min.
- The charge was fired at the start of the sixth minute and time and temperature recorded.
- The time at which the 60% point is reached was recorded.
- Temperatures was also recorded (after the rapid-rise period (about 4 to 5 min), at 1 min intervals on the minute until the difference between successive readings remained constant for 5 min.
- Temperature rise in the water jacket was used by the calorimeter to calculate the heating value of the sample and tests on each sample replicated five times then average calculated.

2) Volatile Matter

- As specified in standards E-872, 1g of grounded sample was measured and put in a covered crucible
- The covered crucible was placed in a maffle furnace maintained at 950+_ 20°C.

- The volatile released were detected by luminous flame observed from the top of furnace.
- The heating was done for 7 min after which the crucible was removed and cooled in a desiccator.
- Mass of the sample was immediately weighed to determine weight loss due to devolatilization

3) Ash Content

- As specified in ASTM test protocol E-1755-01, a 1g of sample fully crushed and grounded was dried and placed into a muffle furnace with uncovered crucible.
- The temperature of the furnace was set at 575+_ 25°C and sample heated for 3 hours.
- The sample was removed, cooled in a desiccator and weighed.

Appendix B: Experimental Data and Statistical Analysis

i. Screw Press Machine

Table B.1: General Performance during High Power- Cold Start

		TRIALS			
Parameter	**Units**	**1**	**2**	**3**	**Mean**
Ignition Time	Min	4.00	3.80	4.30	4.03
Time to Boil	Min	15.20	15.10	14.80	15.03
Burning Rate	g/min	18.40	18.20	17.85	18.15
S.F.C	J/g	0.135	0.138	0.133	0.135
Power Output	KW	6.7	6.5	6.80	6.67

Table B.2: General Performance during High Power- Hot Start

		TRIALS			
Parameter	**Units**	**1**	**2**	**3**	**Mean**
Ignition Time	Min	0	0	0	0.00
Time to Boil	Min	12.10	12.30	11.80	12.07
Burning Rate	g/min	21.00	21.40	21.10	21.17
S.F.C	J/g	0.106	0.104	0.102	0.104
Power Output	KW	7.9	7.6	7.8	7.77

Table B.3: General Performance during Low Power- Simmer Phase

		TRIALS			
Parameter	**Units**	**1**	**2**	**3**	**Mean**
Ignition Time	Min	0	0	0	0.00
Time to Boil	Min	45	45	45	45.00
Burning Rate	g/min	11.00	11.30	11.20	11.17
S.F.C	J/g	0.085	0.087	0.085	0.086
Power Output	KW	4.50	4.45	4.52	4.49

ii. Drum Agglomerator

Table B.4: General Performance during High Power- Cold Start

		TRIALS			
Parameter	**Units**	**1**	**2**	**3**	**Mean**
Ignition Time	Min	3.00	3.20	3.00	3.07
Time to Boil	Min	13.00	13.25	12.80	13.02
Burning Rate	g/min	21.00	20.80	21.50	21.10
S.F.C	J/g	0.137	0.135	0.137	0.136
Power Output	KW	5.90	6.00	5.80	5.90

Table B.5: General Performance during High Power- Hot Start

		TRIALS			
Parameter	**Units**	**1**	**2**	**3**	**Mean**
Ignition Time	Min	0	0	0	0.00
Time to Boil	Min	11.00	10.80	10.90	10.90
Burning Rate	g/min	23.10	22.75	23.00	22.95
S.F.C	J/g	0.109	0.110	0.107	0.109
Power Output	KW	6.50	6.43	6.45	6.46

Table B.6: General Performance during Low Power- Simmer Phase

		TRIALS			
Parameter	**Units**	**1**	**2**	**3**	**Mean**
Ignition Time	Min	0	0	0	0.00
Time to Boil	Min	45	45	45	45.00
Burning Rate	g/min	12.80	13.00	12.90	12.90
S.F.C	J/g	0.087	0.088	0.087	0.087
Power Output	KW	4.20	4.15	4.15	4.17

iii. Hand Made

Table B.7: General Performance during High Power- Cold Start

		TRIALS			
Parameter	**Units**	**1**	**2**	**3**	**Mean**
Ignition Time	Min	3.00	3.10	2.85	2.98
Time to Boil	Min	12.00	11.90	11.90	11.93
Burning Rate	g/min	26.00	26.00	25.80	25.93
S.F.C	J/g	0.141	0.143	0.141	0.142
Power Output	KW	4.10	4.00	4.10	4.07

Table B.8: General Performance during High Power- Hot Start

		TRIALS			
Parameter	**Units**	**1**	**2**	**3**	**Mean**
Ignition Time	Min	0	0	0	0.00
Time to Boil	Min	11.00	11.30	10.90	11.07
Burning Rate	g/min	28.70	29.00	29.20	28.97
S.F.C	J/g	0.113	0.112	0.113	0.113
Power Output	KW	5.50	5.30	5.50	5.43

Table B.9: General Performance during Low Power- Simmer Phase

		TRIALS			
Parameter	**Units**	**1**	**2**	**3**	**Mean**
Ignition Time	Min	0	0	0	0.00
Time to Boil	Min	45	45	45	45.00
Burning Rate	g/min	14.00	14.30	14.10	14.13
S.F.C	J/g	0.090	0.091	0.088	0.089
Power Output	KW	3.90	3.85	3.92	3.89

Table B.10: ANOVA for cold, hot and simmering phases (Power Output)

Source	DF	Sum of Squares	Mean Square	F-Value	Pr>F
Model	4	40.88717778	10.22179444	53.39	<.001
Error	22	4.21182222	0.19144646		
Corrected Total	26	45.09900000			
	R-Square	*Coeff Var*	*Root MSE*	*PO Mean*	
	0.906609	*8.062886*	*0.437546*	*5.426667*	

Source	DF	Type I SS	Mean Square	F Value	Pr>F
Tech	2	15.40015556	7.70007778	40.22	<.001
Phases	2	25.48702222	12.74351111	66.56	<.001

Table B.11: ANOVA for cold, hot and simmering phases (S.F.C)

Source	DF	Sum of Squares	Mean Square	F-Value	Pr>F
Model	4	0.01164081	0.00291020	1026.52	<.001
Error	22	0.00006237	0.00000284		
Corrected Total	26	0.01170319			
	R-Square	*Coeff Var*	*Root MSE*	*SFC Mean*	
	0.994671	*1.513358*	*0.001684*	*0.111259*	

Source	DF	Type I SS	Mean Square	F Value	Pr>F
Tech	2	0.00018363	0.00009181	32.39	<.001
Phases	2	0.01145719	0.00572859	2020.66	<.001

Table B.12: ANOVA for cold, hot and simmering phases (Burning Rate)

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	4	846.4281481	211.6070370	156.66	<.01
Error	22	29.7153704	1.3506987		
Corrected Total	26	876.1435185			

	R-Square	*Coeff Var*	*Root MSE*	*BR Mean*
	0.966084	*5.927329*	*1.162196*	*19.60741*

Source	DF	Type I SS	Mean Square	F Value	Pr>F
Tech	2	177.3090741	88.6545370	65.64	<.01
Phases	2	669.1190741	334.5595370	247.69	<.01

Table B.13: ANOVA for cold, hot and simmering phases (Ignition Time)

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	4	68.46370370	17.11592593	243.31	<.02
Error	22	1.54759259	0.07034512		
Corrected Total	26	70.01129630			

	R-Square	*Coeff Var*	*Root MSE*	*IT Mean*
	0.977895	*23.67311*	*0.265227*	*1.120370*

Source	DF	Type I SS	Mean Square	F Value	Pr>F
Tech	2	0.68129630	0.34064815	4.84	<.02
Phases	2	67.78240741	33.89120370	481.78	<.02

Table B.14: ANOVA for cold, hot and simmering phases (Time to Boil)

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	4	6428.540370	1607.135093	4205.92	<.04
Error	22	8.406481	0.382113		
Corrected Total	26	6436.946852			
	R-Square	*Coeff Var*	*Root MSE*	*TB Mean*	
	0.998694	*2.661689*	*0.618153*	*23.22407*	

Source	DF	Type I SS	Mean Square	F Value	Pr>F
Tech	2	0.68129630	0.34064815	4.84	<.04
Phases	2	67.78240741	33.89120370	481.78	<.04

Table B.15: Effect of Mix Ratios of Selected Feedstocks on Physical Properties

Variable	**Parameter**							
Mix Ratios	**Moisture Content**				**Density**			
RH:CC:SB	**1**	**2**	**3**	**Mean**	**1**	**2**	**3**	**Mean**
1:1:1	7.56	7.54	7.64	**7.58**	784	784	787	**785**
1:2:2	8	8.02	8.01	**8.01**	591	593	589	**591**
1:3:3	8.11	8.13	8.12	**8.12**	541	544	538	**542**
2:1:2	7.34	7.36	7.35	**7.35**	720	723	732	**725**
2:2:3	7.79	7.78	7.8	**7.79**	652	647	651	**650**
2:3:1	6.9	6.92	6.94	**6.92**	833	831	835	**833**
3:1:3	7.94	7.91	7.89	**7.92**	577	573	578	**576**
3:2:1	6.41	6.43	6.45	**6.43**	900	907	905	**904**
3:3:2	6.74	6.73	6.75	**6.74**	868	868	871	**869**

Table B.16: ANOVA for the effect of Mix Ratios on Moisture Content of the Briquettes

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	8	8.82234074	1.10279259	2096.86	<.0001
Error	18	0.00946667	0.00052593		
Corrected Total	26	8.83180741			

	R-Square	*Coeff Var*	*Root MSE*	*Moisture Mean*
	0.998928	*0.308732*	*0.022933*	*7.428148*

Table B.17: Density ANOVA for the effect of Mix Ratios on Density of the Briquettes

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	8	442170.0000	55271.2500	5589.23	<.0001
Error	18	178.0000	9.8889		
Corrected Total	26	442348.0000			

	R-Square	*Coeff Var*	*Root MSE*	*Density Mean*
	0.998928	*0.308732*	*0.022933*	*7.428148*

Table B.18: ANOVA for the effect of Mix Ratios on Ash Content of the Briquettes

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	8	38.01266667	4.75158333	4915.43	<.0001
Error	18	0.01740000	0.00096667		
Corrected Total	26	38.0300667			

	R-Square	*Coeff Var*	*Root MSE*	*Ash Mean*
	0.999542	*0.527766*	*0.031091*	*5.891111*

Table B.19: ANOVA for the effect of Mix Ratios on Volatile Matter of the Briquettes

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	8	106.2569185	13.2821148	357.12	<.0001
Error	18	0.6694667	0.0371926		
Corrected Total	26	106.9263852			
	R-Square	*Coeff Var*	*Root MSE*	*Volatile Mean*	
	0.993739	*0.915703*	*0.192854*	*21.06074*	

Table B.20: ANOVA for the effect of Mix Ratios on Fixed Carbon of the Briquettes

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	8	262.6256667	32.8282083	8741.24	<.0001
Error	18	0.0676000	0.0037556		
Corrected Total	26	262.6932667			
	R-Square	*Coeff Var*	*Root MSE*	*Fixed Mean*	
	0.999743	*0.083936*	*0.061283*	*73.01111*	

Table B.21: ANOVA for the effect of Mix Ratios on Calorific Value of the Briquettes

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	8	260.6380667	32.5797583	40166.8	<.0001
Error	18	0.0146000	0.0008111		
Corrected Total	26	260.6526667			
	R-Square	*Coeff Var*	*Root MSE*	*CV Mean*	
	0.999944	*0.120564*	*0.028480*	*23.6222*	

Table B.22: Experimental output corresponding to Technologies and Mix Ratios

Exp. No	Technology	Mix Ratios	MC (%)	D (Kg/m^3)	AC (%)	VM (%)	FC (%)	CV (MJ/Kg)
1	SP	1:1:1	7.58	785	6.33	20.60	73.07	23.25
2	SP	1:2:2	8.01	591	7.00	23.25	69.75	20.73
3	SP	1:3:3	8.12	542	7.35	24.39	68.26	18.33
4	SP	2:1:2	7.35	725	5.88	20.52	73.60	23.83
5	SP	2:2:3	7.79	650	6.00	20.99	73.01	23.08
6	SP	2:3:1	6.92	833	5.00	19.23	75.77	25.61
7	SP	3:1:3	7.92	576	7.18	23.32	69.50	21.57
8	SP	3:2:1	6.43	904	3.63	18.56	77.81	29.04
9	SP	3:3:2	6.74	869	4.65	19.02	76.33	27.16
10	DA	1:1:1	8.45	753	8.25	22.51	69.24	21.15
11	DA	1:2:2	9.21	531	8.92	25.16	65.92	18.53
12	DA	1:3:3	9.42	502	9.27	26.30	64.43	16.13
13	DA	2:1:2	8.60	700	7.80	22.43	69.77	21.63
14	DA	2:2:3	8.89	637	7.92	22.90	69.18	20.88
15	DA	2:3:1	7.82	801	6.92	21.14	71.94	23.41
16	DA	3:1:3	9.00	516	9.10	25.23	65.67	19.37
17	DA	3:2:1	7.47	875	5.55	20.47	73.98	26.84
18	DA	3:3:2	7.64	839	6.57	20.93	72.50	24.96
19	HM	1:1:1	9.69	702	9.86	24.12	66.02	19.03
20	HM	1:2:2	10.45	500	10.53	26.77	62.70	16.41
21	HM	1:3:3	10.66	471	10.88	27.91	61.21	14.01
22	HM	2:1:2	9.84	669	9.41	24.04	66.55	19.51
23	HM	2:2:3	10.13	606	9.53	24.51	65.96	18.76
24	HM	2:3:1	9.06	750	8.53	22.75	68.72	20.29
25	HM	3:1:3	10.24	485	10.71	26.84	62.45	17.25
26	HM	3:2:1	8.71	824	7.16	22.08	70.76	22.72
27	HM	3:3:2	8.88	788	8.18	22.54	69.28	21.84

Table B.23: ANOVA for means from multi objective optimization

Process Parameters	DF	MS	SS	F-value	p-value
Technology	2	0.0582	0.1390	41.23	0.005
Mix Ratio	2	0.0214	0.0528	35.21	0.035
Error	6	0.0307	0.0061		
Total	10				

Appendix C: Research Photos

Figure C.1: Drum Agglomerator

Figure C.2: Briquettes from Drum Agglomerator

Figure C.3: Screw Press

Figure C.4: Briquettes from Screw Press

Figure C.5: Drum Kiln

Figure C.6: Carbonized Corncobs

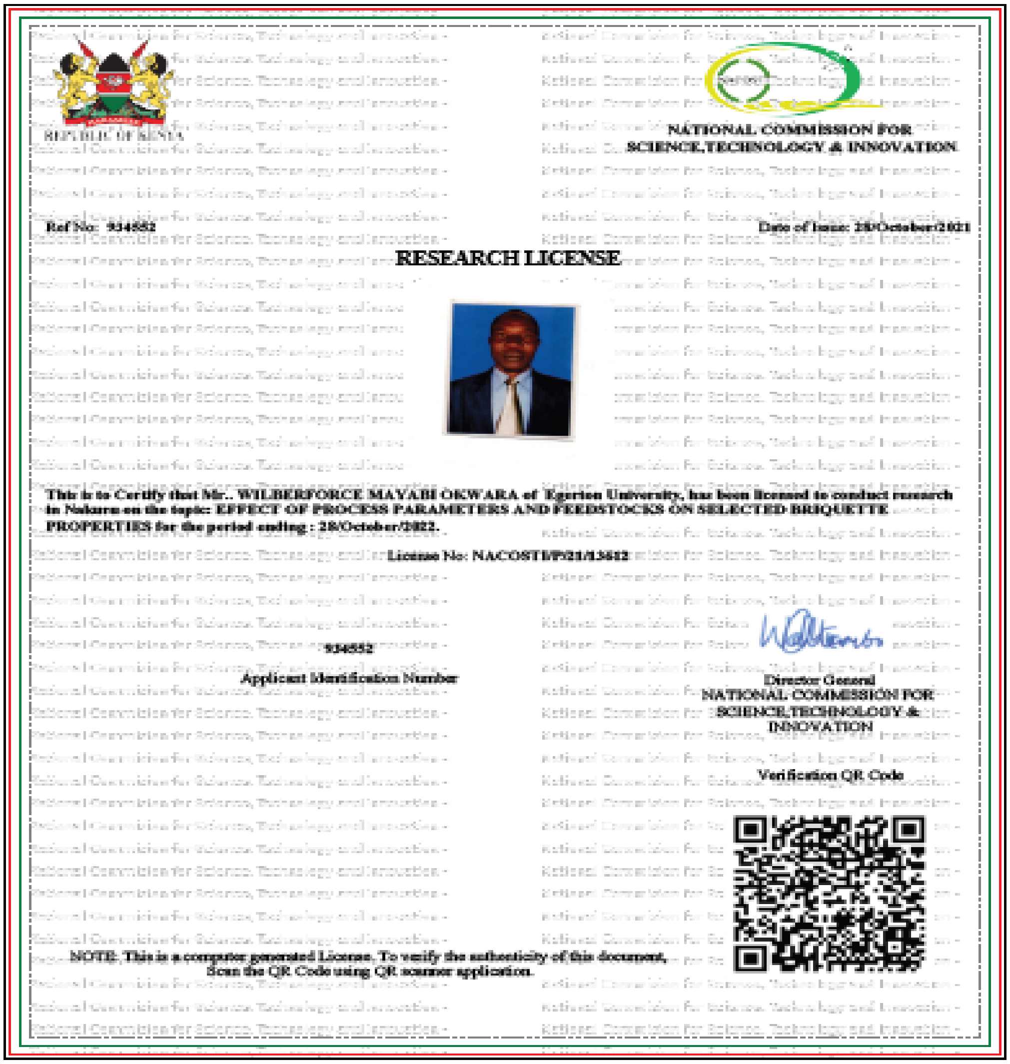
Figure C.7: Oven Drier (Dairy)

Figure C.8: Combustion analysis of briquettes in a muffle furnace

Figure C.9: Cooling in a Desiccator

Figure C.10: Burning briquettes in improved jiko

Appendix D: Research Permit (NACOSTI)


REPUBLIC OF KENYA

NATIONAL COMMISSION FOR SCIENCE,TECHNOLOGY & INNOVATION

Ref No: 934552

Date of Issue: 28/October/2021

RESEARCH LICENSE

This is to Certify that Mr.. WILBERFORCE MAYABI OKWARA of Egerton University, has been licensed to conduct research in Nakuru on the topic: EFFECT OF PROCESS PARAMETERS AND FEEDSTOCKS ON SELECTED BRIQUETTE PROPERTIES for the period ending : 28/October/2022.

License No: NACOSTI/P/21/13842

934552

Applicant Identification Number

Director General
NATIONAL COMMISSION FOR SCIENCE,TECHNOLOGY & INNOVATION

Verification QR Code

NOTE: This is a computer generated License. To verify the authenticity of this document, Scan the QR Code using QR scanner application.

Appendix E: Relevant Publications Based on the Study

Journal of Energy, Environmental & Chemical Engineering
2022; 7(1): 1-8
http://www.sciencepublishinggroup.com/j/jeece
doi: 10.11648/j.jeece.20220701.11
ISSN: 2637-4331 (Print); ISSN: 2637-434X (Online)

SciencePG
Science Publishing Group

Effect of Process Techniques on Three Feedstocks Mix on Briquette Performance Properties

Wilberforce Okwara[1, *], Daudi Nyaanga[1], Peter Kabok[2], Jane Nyaanga[3]

[1]Department of Agricultural Engineering, Egerton University, Nakuru, Kenya

[2]Department of Agricultural Engineering and Renewable Energy, Jaramogi Oginga Odinga University of Science and Technology (JOOUST), Siaya, Kenya

[3]Department of Crops, Horticulture and Soils, Egerton University, Nakuru, Kenya

Email address:
okwaramayabi@gmail.com (W. Okwara), dmnyaanga@egerton.ac.ke (D. Nyaanga), kabpaguko@yahoo.com (P. Kabok), jgnyaanga@egerton.ac.ke (J. Nyaanga)

*Corresponding author

To cite this article:
Wilberforce Okwara, Daudi Nyaanga, Peter Kabok, Jane Nyaanga. Effect of Process Techniques on Three Feedstocks Mix on Briquette Performance Properties. *Journal of Energy, Environmental & Chemical Engineering*. Vol. 7, No. 1, 2022, pp. 1-8.
doi: 10.11648/j.jeece.20220701.11

Received: January 13, 2022; **Accepted**: February 4, 2022; **Published**: February 16, 2022

Abstract: Energy availability at domestic level is a challenge across the world and especially in Africa. Firewood is the major source of energy for cooking for households in Kenya and there is need for a friendly sustainable environmental fuel. Carbonized biomass materials (briquettes) are considered a substitute. This study thus evaluated effect of selected briquetting techniques on briquettes' performance properties. Milled charcoal dusts mixed in a ratio of 1:1:1 (Rice husk, maize cob, and sugarcane bagasse) with molasses binder in the ratio of 6:1 was hence ready for densification and agglomeration. The Water Boiling Test was used in determination of the briquette's performance characteristics for various parameters. High (screw press); and low (drum agglomerator and hand making) pressure briquetting techniques were distinctly different in ignition time (minutes), time to boil (minutes) burning rate (g/min), specific fuel consumption (g/ml) and power output (kW) values as (4, 3, 3; 14, 12, 11: 0.8, 1.1, 1.3; 0.11, 0.13, 0.15; and 1.8, 1.4, 0.75). Diversified briquetting techniques, number and type of feedstocks are thus factors that influence performance characteristics of briquettes in converting the agricultural and or other wastes for useful energy application. This knowledge should enable users to make choices on techniques for optimum efficiency towards realization of Sustainable Development Goal Number #7 on affordable and clean energy.

Keywords: Energy, Feedstock, Carbonization, Technique, Briquettes, Performance Properties

1. Introduction

Energy is one of the components of sustained development and poverty eradication for basic human needs and it is both vital and key for social economic growth [24]. Its availability at domestic level is a challenge across the world and especially in Africa where deforestation and high cost of Liquid Petroleum Gas (LPG) or cooking gas, electricity, and kerosene is experienced [9, 42, 40]. In developing countries demand for charcoal is expected to rise [33] due to urbanization rate. Fossil fuels all over the world though is limited, demand for developed industries' energy consumption has extremely increased [19]. As ecological issues demand priority for conserved natural resources, high usage of these limited available fossil fuels has led to undesirable outcomes [19]. Thus, to avoid dependence on fossil fuel, waste biomass has been considered as a substitute fuel source.

Significant quantities of biomass are available in Sub-Saharan Africa for conversation into domestic energy sources [3, 4]. Biomassare however underutilized due to poor combustion characteristics [10]. Handling, utilizing, transporting, and storing biomass in original form is also not easy [30, 31]. According to da Silva et al. [11] it has been reported that biomass in its original form has high moisture content, low bulky density, irregular shapes and sizes. To improve on handling and reliability of biomass energy, densification should then be undertaken [23]. Kenya is one

EFFECT OF THREE FEEDSTOCKS MIX ON BRIQUETTES' PHYSICAL AND COMBUSTION PROPERTIES

W.M. Okwara[1] *, D.M. Nyaanga[1], P. Kabok[2]

1. Department of Agricultural Engineering, Egerton University, Nakuru, Kenya
2. Department of Agricultural Engineering and Renewable Energy, Jaramogi Oginga Odinga University of Science and Technology (JOOUST), Siaya, Kenya

DOI: https://doi.org/10.37017/jeae-volume8-no2.2022-6
Publication Date: 11 May 2022

ABSTRACT:

Significant quantities of biomass are available in Africa for conversion into domestic energy sources. However, they are underutilized due to poor physical and combustion properties. Knowledge about the effect of briquettes with three feedstocks has not been fully studied. Thus, the main objective of this study was to assess effect of three feedstocks mix on briquettes' physical and combustion properties. The feedstocks; rice husk- maize cobs and bagasse were carbonized in a drum kiln and mixed at different ratios (1:1:1, 1:2:2, 1:3:3, 2:1:2, 2:2:3, 2:3:1, 3:1:3, 3:2:1 and 3:3:2) before densification using screw press technique. Briquettes were sampled for Laboratory testing. At the optimal ratio, 3:2:1, physical properties; moisture content and density values were 6.43% and 904 kg/m^3 respectively. Results showed values of 3.63% for ash content, 18.56% for volatile matter, 77.81% for fixed carbon and 29.04 MJ/kg for calorific value. Number and type of feedstocks are thus factors influencing physical and combustion characteristics of briquettes in converting agricultural wastes to useful energy application. Findings from this study are therefore useful to briquettes users, as a source of clean energy, in making right choices on feedstocks mix ratios during densification thus realization of Sustainable Development Goal (SDGs #7).

Keywords: *Energy, Feedstocks, Briquettes, Physical Properties, Combustion Properties.*