

**DETERMINATION OF COMBUSTION PROPERTIES OF BLENDED  
BRIQUETTES OF SAWDUST, MAIZE STALKS, AND COFFEE HUSKS**

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Engineering in Partial Fulfilment of the Requirements for the Award of the  
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**NOVEMBER, 2025**

**DECLARATION**

This thesis is my original work prepared with no other than the indicated sources. It has not been presented for a degree or any award for a degree or any other award in any other university or institution.

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**CERTIFICATION**

We, the undersigned, certify that we have read and hereby recommend for acceptance of Masinde Muliro University of Science and Technology a thesis entitled: **“Determination of combustion properties of blended briquettes of sawdust, maize stalks, and coffee husks.”**

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## ABSTRACT

The tea industry in Kericho is among the main consumers of firewood for its intensive thermal energy demand used in industrial steam boilers. Concerns over firewood depletion have led tea producers to switch to alternate fuels for boilers. Briquettes made from biomass leftovers are among the possible options; however, they are not yet widely adopted and implemented. This study found a potential source of briquettes for fire boilers that will use agricultural byproducts produced in Kericho. The combustion properties of blended briquettes made from sawdust, maize stalks, and coffee husks were used to determine the optimal ratio. Among the primary reasons is the depletion of firewood, with a rise in the number of tea industry projects in Kericho County, resulting in an 8% reduction in forest cover. Blended briquettes have gained attention as a sustainable alternative to traditional fuels due to their potential for reducing environmental impact by utilizing agricultural and forestry residues and reducing the dependency on wood pellets. The physical properties investigated in this research included gross calorific value, moisture content, fixed carbon, and volatile matter of the blended briquettes. Experiment design and analysis were done using Design-Expert® Software Version 10-Stat-Ease. The response surface methodology was utilized to investigate how burning affects the physical properties of mixed briquettes manufactured from coffee husks, maize stalks, and sawdust. The interaction of the parameters was also explored. Blended briquettes were developed from coffee husks, maize stalks, and sawdust, measuring 45mm by 45mm by 35mm. From the analysis of individual briquettes, Individual briquettes' moisture content ranges from 10.01 % and 12.59%. Coffee husks gave 10.01%, Maize stalks briquettes 12.59% and coffee husks 10.01. The volatile matter is between 71.25% and 78.30% where sawdust gave 77.05%, coffee husks 78.30% and maize stalks 71.25%. The fixed carbons range between 8.58% and 13.08%. Sawdust gave 9.36%, coffee husks 8.58% and maize stalks at 13.08%. The Calorific Value is between 3.8652 kCal/g and 4.2149 kCal/g. Sawdust generated 4.1589 kCal/g, Coffee Husks 4.2129 kCal/g and maize stalks 3.8652 kCal/g. The optimal mix ratio of sawdust: coffee husks: maize stalks is 350:169.142:150. This ratio gives a moisture content of 9.65%, a gross calorific value of 4.356 kCal/g, a fixed Carbon of 6.986%, and a volatile matter of 79.115%. This has verified that blended briquette fuel has better combustion properties than individual samples. The knowledge gained from this research has contributed to the development of renewable energy technologies and supports the transition towards a more environmentally friendly and resource-efficient society.

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## **DEDICATION**

I dedicate this work to my family for their moral support during this period. I thank them for their endless support and encouragement as I undertook my master's program. May God bless them.

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## TABLE OF CONTENTS

<b>DECLARATION</b> .....	ii
<b>ABSTRACT</b> .....	iii
<b>COPYRIGHT</b> .....	iv
<b>DEDICATION</b> .....	v
<b>ACKNOWLEDGMENTS</b> .....	vi
<b>TABLE OF CONTENTS</b> .....	vii
<b>LIST OF FIGURES</b> .....	xi
<b>LIST OF TABLES</b> .....	xiii
<b>LIST OF ABBREVIATIONS AND ACRONYMS</b> .....	xiv
<b>CHAPTER ONE: INTRODUCTION</b> .....	<b>1</b>
1.1 Background .....	1
1.2 Statement of the Problem .....	10
1.3 Objectives.....	11
1.3.1 Main Objective.....	11
1.3.2 Specific Objectives.....	11
1.4 Research Questions .....	11
1.5 Justification .....	11
1.6 Scope .....	12
1.7 Conceptual Framework .....	13
<b>CHAPTER TWO: LITERATURE REVIEW</b> .....	<b>14</b>
2.1 Introduction .....	14
2.2 Maize Growing in Kericho.....	20
2.3 Coffee Farming .....	22

2.3.1 Coffee production in Kericho .....	23
2.4 Eucalyptus Sawdust Generation.....	24
2.5 Molasses.....	26
2.6 Briquetting Technologies. ....	27
2.6.1 High-pressure technologies.....	27
2.6.2 Screw press techniques. ....	29
2.6.3 Medium pressure compaction with heating Mechanism.....	30
2.6.4 Manual Press with compaction. ....	31
2.7 Factors Affecting Briquettes Making. ....	33
2.8 Large-scale production of briquettes.....	34
2.8.1 Raw Material Preparation .....	35
2.8.2 Procedure of making briquettes .....	37
2.9 Response Surface Methodology.....	38
2.10 Experiment design.....	44
2.10.1 Design of Experiments .....	45
2.10.2 General practical steps and directions for designing DOE. ....	45
2.10.3 The principal applications of the design of experiments. ....	48
2.11 Analysis of variance. ....	48
2.11.1 Choice of Design Factors. ....	50
2.11.2 Box-Behnken Designs.....	51
2.11.3 Benefits of using Box Behnken Designs.....	52
<b>CHAPTER THREE: MATERIALS AND METHODS .....</b>	<b>54</b>
3.1 Preparation of Materials.....	54
3.1.1 Preparation of eucalyptus sawdust.....	56
3.1.2 Coffee Husk Preparation .....	57

3.1.3 Maize stalks Preparation .....	57
3.1.4 Molasses preparation.....	58
3.1.5 Preparation of briquettes Sample .....	58
3.2 Determination of physical properties of Briquettes .....	59
3.2.1 Density .....	59
3.2.2 Moisture Content.....	59
3.2.3 Calorific Value of Briquettes.....	61
3.2.5 Ash Content:.....	62
3.2.6 Volatile Matter Analysis. ....	62
3.2.7 Determination of Fixed Carbon .....	63
3.3 Briquetting Mold.....	63
3.4 Design of Experiments.....	64
<b>CHAPTER FOUR: 4. RESULTS AND DISCUSSION.....</b>	<b>66</b>
4.1.1 Combustion and physical properties of eucalyptus sawdust, coffee husk, and Maize stalks Molasses.....	66
4.1.2 Combustion and physical properties of Blended briquettes as per the design of experiments. ....	67
4.2 Effects of mix ratios on the Gross Calorific Value of blended briquettes using the 2FI Model.....	68
4.2.1 ANOVA for 2FI Model Gross Calorific Value.....	68
4.2.2 Final Equation in Terms of Actual Factors.....	69
4.3 Effects of mix ratios on the Fixed Carbons on blended briquette using Reduced Cubic Model.....	74
4.3.1 ANOVA for Reduced Cubic model .....	74
4.3.2 Fit Statistics.....	75

4.3.3 Final Equation in Terms of Actual Factors.....	75
4.4 Effects of mixing ratios on the moisture content of blended briquettes using Reduced Quadratic Equation. ....	81
4.4.1 ANOVA for Reduced Quadratic model.....	81
4.4.2 Fit Statistics.....	82
4.4.3 Final Equation in Terms of Actual Factors.....	82
4.5 Effects of mix ratios on the Volatile Matter of blended briquettes Using Reduced Cubic Model.....	87
4.5.1 ANOVA for Reduced Cubic model.....	87
4.5.2 Fit Statistics.....	88
4.5.3 Final Equation in Terms of Actual Factors.....	88
4.6 Optimization of combustion properties of blended briquettes.....	93
<b>CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS.....</b>	<b>96</b>
5.1 Conclusion.....	96
5.2 Recommendations.....	97
<b>REFERENCES.....</b>	<b>98</b>
<b>APPENDICES.....</b>	<b>111</b>

## LIST OF FIGURES

Figure 1-1: Conceptual Framework for briquetting technology and materials being used. ....	13
Figure 2-1: Maize Growing in Kenya in million bags. ....	21
Figure 2-2 : Images of Coffee husk varieties in Kericho County.....	24
Figure 2-3: Image of Blue gam by-product from Londiani sawmill.....	26
Figure 2-4: Piston Press Machine . ....	28
Figure 2-5: Image of screw press Machine . ....	30
Figure 2-6: Image of Medium Pressure machine with a Heater . ....	31
Figure 2-7: Image of a Low-pressure Machine . ....	33
Figure 2-8: Schematic illustration of the briquette production scheme . ....	37
Figure 3-1: Image of eucalyptus Sawdust sample.....	54
Figure 3-2: Image of Coffee husk sample.....	55
Figure 3-3: Image of Maize stalks sample . ....	55
Figure 3-4: Image of Mixing Equipment. ....	56
Figure 3-5: Image of Crusher Machine.....	57
Figure 3-6: Image of drying process of prepared briquettes. ....	59
Figure 3-7: Image of Hot Air furnace. ....	60
Figure 3-8: Images of Bomb Calorimeter . ....	62
Figure 3-9: Briquetting Mold . ....	64
Figure 4-1: A graph of projected calorific value verses experimental results.....	70
Figure 4-2: A graph of externally studentized residuals versus the run number. ....	71
Figure 4-3: A graph of two factor interaction plots between coffee husks and eucalyptus sawdust.....	72
Figure 4-4: A graph of a two-factor interaction between maize stalks and eucalyptus sawdust.....	73

Figure 4-5: A graph of two-factor interaction plots for Maize stalks and coffee husks. .....	73
Figure 4-6: A graph of Predicted Fixed verses Actual fixed Carbon of blended briquettes.....	76
Figure 4-7: A graph of two factor interaction plots between coffee husk and eucalyptus sawdust.....	77
Figure 4-8: A graph of two factor interaction between maize stalks and eucalyptus sawdust.....	78
Figure 4-9: A graph of two factor interaction between maize stalks and coffee husks .....	79
Figure 4-10: A plot of Expected moisture content verses Experimental results of blended briquettes. ....	83
Figure 4-11: A plot of externally studentized residual verses run number in blended briquettes.....	84
Figure 4-12: A graph of two factor interaction for Maize stalks and coffee husks....	85
Figure 4-13: A plot of Predicted verse Actual Volatile Matter for Blended Briquettes .....	89
Figure 4-14: A plot of two-factor interaction on volatile matter between coffee husks and eucalyptus sawdust.....	90
Figure 4-15: A plot of two factor interaction of Volatile Matter between Maize stalks and Eucalyptus Sawdust.....	91
Figure 4-16: A plot of two factor interaction of Volatile Matter between Maize stalks and Coffee Husks .....	92
Figure 4-17: Schematic representation of Numerical optimization for Combustion properties.....	94

## LIST OF TABLES

Table 2-1: Distribution of Maize in Kericho.....	22
Table 2-2 : Gazzetted forest covers in Kericho, 2019 .....	25
Table 2-3: Choosing model order. ....	41
Table 3-1: Design of experiments for blended briquettes .....	65
Table 4-1: Individual briquettes sample analysis .....	66
Table 4-2: Combustion properties of blended briquette.....	67
Table 4-3: Gross Calorific value of blended briquettes .....	68
Table 4-4: ANOVA for Reduced cubic model for Fixed carbon .....	74
Table 4-5: ANOVA for reduced Quadratic equation for moisture content.....	81
Table 4-6: ANOVA for reduced Cubic model for Volatile Matter .....	87
Table 4-7: Optimization matrix .....	94
Table A-5-1: Design of Experiments Weight Calculation.....	110
Table A-5-2: Table optimization starting points.....	111
Table A-5-3: Optimizations solutions. ....	115

## LIST OF ABBREVIATIONS AND ACRONYMS

<b>Abbreviation</b>	<b>Meaning</b>
ANOVA	Analysis of Variance
BBD	Box Behnken Design
CBM	Cubic Metre
CV	Calorific Value
CCDs	Central Composite Designs
DoE	Design of Experiments
DoF	Degree of Freedom
FC	Fixed Carbon
GCV	Gross Calorific Value
KFS	Kenya Forestry Service
KTDA	Kenya Tea Development Agency
MC	Moisture Content
MSTr	Treatment mean Squares
MSQ	Error Means Squares
MPa	Mega Pascals
NEMA	National Environmental Management Authority
OFAT	One Factor at a Time
RSM	Response Surface Methodology
SST	Sum of Squares
SSTr	Sum of squares of Treatments
SSQ	Sum of Squares of Error

## CHAPTER ONE

### INTRODUCTION

#### 1.1 Background

Kericho's tea business is a big user of firewood due to its high thermal energy requirement for use in industrial steam boilers(Suryani *et al.*, 2022). Kericho's tea business is handled by large plantation-based tea estates and small-scale holder farmers affiliated with the Kenya Tea Development Agency (KTDA). KTDA serves more than 635,000 farmers who own shares in factories and private holding company, which oversees 70 facilities in total. In Kenya, tea is grown in 19 counties in the West and East of the Rift Valley, with KTDA running facilities and plantations in 16 counties (Githiomi and Oduor, 2012). KTDA accounts for more than 60% of the nation's tea production. Because of the high thermal energy demand for steam drying, Kericho's tea sector is one of the largest consumers of firewood (Suryani *et al.*, 2022). KTDA is a private holding company that manages 70 factories on behalf of almost 635,000 farmers who possess a stake in them. Tea is farmed in 19 counties in the West and East of Rift in Kenya, with KTDA operating plantations and factories in 16 of them (Githiomi and Oduor, 2012). KTDA produces more than 60% of the country's tea. As a result, this study focused on tea factories controlled by the KTDA and multinational corporations. In this study, energy demand is defined as the thermal energy required for the withering and drying processes, which is produced by burning firewood in boilers (Suryani *et al.*, 2022).The amount of firewood required in tea factories varies according on output capacity. This analysis assumed an average annual firewood consumption per factory of 1000 cubic metre (CBM) per month for an 80-ton capacity plant.

The manufacturing of briquettes from sawdust and other agro-residues shows the potential of adequate technology for exploiting biomass residues, which are abundantly available in poor nations. However, compared to developed countries where successful briquette operations are mostly found, briquettes have not been widely adopted in developing countries due to the high cost of production, lack of awareness of its sustainability, lack of ready market (Emerhi, 2011), and poor packaging and distribution systems for the product.

Blended briquettes have unique physical and combustion properties. Densification of biomass waste materials has significantly increased the application of wood and agricultural waste for home and industrial fuel (Mitchual *et al.*, 2013).

The global energy supply is currently in critical condition. Energy resources are numerous yet depleted under current conditions. The search for alternative energy sources has become increasingly popular around the world. Solar and wind energy are currently in demand due to their low investment costs. However, research emphasizes the importance of using trash as an alternative source of energy. Making fuel briquettes from naturally occurring biodegradable waste items is advantageous. The moisture content, volatile matter, fixed carbon, and calorific value are all determined (Raju *et al.*, 2021). The waste materials are mixed in various ratios. The calorific value is determined through the final analysis. Data was collected to analyze the influence of various variables such as fuel briquettes on power production. Analysis of materials and estimation of attributes for fuel briquettes (Raju *et al.*, 2021).

Bio-briquettes, created from green byproducts and organic materials, are used to generate steam in boilers as an alternative for wood logs and pellets. With increasing energy needs and a constantly growing population, as a result, agriculture generates

a lot of waste and requires more energy to operate. Agricultural byproducts are frequently discarded after harvesting. Using agricultural waste to make bio-briquettes reduces reliance on forests and addresses rising energy demands (Sivakumar and Mohan, 2010).

Historically, biomass has been considered as among the top three source of energy used. Furthermore, biomass can be defined as any organic matter that is available on a renewable or recurring basis, such as energy crops and trees, agricultural food and feed crops, agricultural crop wastes, and wood wastes, which is recognized as one of the major potential sources of energy production.

Kenya's tea business is the largest consumer of fuel wood, accounting for around 33% of overall industrial consumption. At the same time, it is the top electricity and fuel consumer (Suryani *et al.*, 2022). Wood fuel and thermal energy demand fuelwood is required in the tea industry for the following purposes: producing hot air for withering, fermentation and drying operations. Harvested tea leaves have a moisture content of between 71 to 86%, and withering methods reduce moisture content to a level suitable for unit operations such as rolling and roll breaking. At this stage the accepted level of moisture depends on the method of manufacture adopted being  $68 \pm 1.5\%$  (wet basis) for high/mid-grown teas having liquoring characteristics;  $59 \pm 2\%$  (wet basis) for low-grown manufactured for leaf style to suit markets in the Middle East; and  $70 \pm 2\%$  (wet basis) for CTC teas to suit markets requiring small leaf grades having thick coloury liquors (De Silva, 1996).

Biomass energy provides 68% of Kenya's national energy requirements and is expected to be the primary energy source for the foreseeable future (Mugo and Gathui, 2010). In 2000, Kenya was reported to use 31.6 million tons of biomass for

fuel, of which 15.1 million tons were fuelwood and 16.5 million tons were wood for charcoal production treated in kilns at a mere 10% efficiency.

With increasing concerns about firewood depletion, tea makers have been moving to alternative fuels to power their boilers. The rise in global oil prices forced tea manufacturers to switch from oil burners to firewood-based boilers (Dillon and Barrett, 2016). This shift has had its challenges, including the loss of forest cover and significant expenditures on firewood. The loss of trees has exacerbated the effects of climate change, leading to a decrease in tea production. Diversification is crucial for ensuring a steady supply of biomass energy while reducing tea factory drying costs. One alternative is to employ locally accessible organic byproducts as a source of energy (Njenga *et al.*, 2015). Briquettes generated from biomass leftovers are one of the promising alternatives; nonetheless, they are not yet commonly used (Ngusale *et al.*, 2014). This study was conducted to investigate alternative sources of briquettes for use in boiler combustion. The physical and combustion properties of blended briquettes of sawdust, maize stalks, and coffee husks were assessed to determine the substitution potential and the optimal ratio. Among the primary reasons is the dwindling availability of firewood, with a loss of forest cover in Kericho to 8% due to an increase in the number of tea sector developments (Maina *et al.*, 2017). Biomass energy accounts for 68% of Kenya's total energy consumption and is among the primary energy sources for the foreseeable future. In 2000, Kenya was reported to use 34.3 million tons of biomass for fuel, with 15.1 million tons being fuel wood (Suryani *et al.*, 2022).

There is an alarming decline in the proportion of forest area to the world's total land area from 31.9% in 2000 to 31.2% in 2020 (Nikiema *et al.*, 2022). Between 2002 and 2020, Kenya lost 7.6% of its primary forests, primarily driven by the demand for

inexpensive electricity. As the world's third-largest producer of black tea, the Kenyan tea business uses around one million tons of firewood each year, primarily to lower the moisture level of the tea leaves (Langat, 2019).

Lack of sustainable wood energy production planning has led to scarcity and over-exploitation of natural resources and environmental degradation as supported by past studies by Akinga (1980) and the Ministry of Energy (2002), which, despite being two decades apart showed a widening gap between supply and demand in wood fuel. The wood fuel shortfall resulted from a higher rate of tree cutting than replacement. Strategies must be put in place to ensure the sustainability of wood fuel production. A comprehensive biomass study undertaken in Kenya in 2000 revealed that the principal sources of fuel wood are the farmlands with a production of 84% of the total wood fuel requirement. Kenya has 3.467 million hectares of forest cover, which is comparable to 5.9% of the land surface, of which 1.417 million ha are indigenous closed-canopy forests, mangroves, and plantations (Kenya Forest Service Strategic Plan, 2009). Much of the closed canopy forest has been lost owing to internal and external forces. Continued losses of forests and associated resources have had far-reaching negative impacts on the country's economy and the welfare of Kenyans. Some of the consequences include an inadequate supply of wood fuel and timber which leads to the overharvesting of trees leading to environmental degradation and loss of biodiversity among others (Githiomi and Oduor, 2012).

The increased demand for firewood among rural populations and industry has resulted in deforestation and the depletion of trees as a natural resource (Ha and Ha). Tea companies, which rely on firewood for production, faced increased costs and, as a result, a decrease in revenues. They therefore wish to make investments in

alternate energy sources. Several research have already looked into alternative energy sources for the tea industry (Petursson *et al.*, 2013).

The potential of biomass leftovers as a firewood substitute in their operations was recognized by Kenyan tea companies. Crop waste from existing agricultural production, such as sawdust, maize stalks, and coffee husks, presents a significant bioenergy opportunity for Kenya. Briquettes have been incorporated into several tea firms through co-firing, which combines firewood and briquettes in boilers. However, this potential is not being completely realized. Recent research implies that operational challenges, cost intensity, and the distance from briquette factories to tea factories are some of the factors inhibiting briquette utilization (Deshannavar *et al.*, 2018; Suryani *et al.*, 2022).

Briquettes made from biomass leftovers may help to provide a sustainable supply of biomass energy (Ngusale *et al.*, 2014). Densifying agricultural leftovers and wood waste into fuel briquettes can provide a relatively high-quality alternative fuel source, especially in areas where solid wood fuel resources are rare (Wamukonya and Jenkins, 1995).

Optimal briquetting requires proper selection and setup of processing factors (Navalta *et al.*, 2020) such as pressure, temperature, particle size, type of binder, and characteristics of the chosen biomass have a big influence on the compression strength, density, and energy potential of the briquettes (Marreiro *et al.*, 2021).

Blended briquettes have gained popularity as a sustainable alternative to traditional fuels because of their promise to reduce environmental impact by utilizing agriculture and forestry leftovers hence decreasing reliance on wood pellets.

Analysis of the briquette sector in East Africa found various impediments to briquette adoption, including a lack of particular briquette rules, restricted access to finance options, insufficient marketing and distribution strategies, and an unreliable supply of raw materials. Furthermore, feedstock supply, lack of technical capacity, high briquette costs, lack of knowledge, inadequate fiscal incentives, and lack of an overall institutional framework can all be hurdles in implementation (Suryani *et al.*, 2022).

However, this study has alleviated the logistics and cost-related issues because each facility produced briquettes locally, allowing for co-firing and lowering reliance on forest cover. In light of this, the goal of this study was to find the appropriate ratios for creating high-quality briquettes with improved combustion properties.

These briquettes offer a promising solution to utilize agricultural and forestry residues effectively thereby lowering dependence on fossil fuels and addressing environmental challenges. These byproducts include corn stalks and coffee husks that come from numerous agricultural activities. These wastes are commonly left piled in the field to decompose or burn in open fires which consequently provide risks to the environment and animal and human health (Sanchez *et al.*, 2022). Byproducts such as maize stalks, sugarcane, and sawdust, are a promising source of energy that can be used to meet Kenya's increasing energy demand.

Briquettes, a high-density, energy-concentrated solid material created by compacting this biomass, can co-fire at industrial boilers to supplement current energy sources. The assessment of physical and combustion parameters is critical for evaluating the feasibility and performance of blended briquettes. Understanding these qualities provides vital insights into their potential as a fuel source, as well as assisting in the

optimization of the production process and combustion conditions for efficient energy conversion.

The physical properties of blended briquettes encompass several key aspects (Sotande *et al.*, 2010). The density of briquettes is essential because it impacts their storage, transportation, and combustion qualities. Handling and feeding qualities of briquettes in various combustion systems are heavily influenced by their size and form. Moisture content is another crucial factor affecting combustion efficiency, as excessive moisture can hinder ignition and cause incomplete combustion. Lastly, the mechanical strength of briquettes ensures their integrity during transportation and handling.

The combustion properties of blended briquettes are equally important for evaluating their energy potential and environmental impact. Calorific value, measured in terms of heat energy released during combustion, indicates the briquettes' energy content (Lubwama *et al.*, 2020). Ignition and combustion rates reflect the ease with which the briquettes can ignite and burn, impacting their overall performance in combustion devices. Ash content is an important metric because it influences residual ash formation, which has implications for ash disposal and combustion system maintenance. Furthermore, emissions such as carbon dioxide, carbon monoxide, and particulate matter must be assessed to ensure compliance with environmental regulations and to reduce air pollution.

By establishing these physical and combustion qualities, researchers can get insight into blended briquettes' potential as an alternative fuel source. This understanding contributes to the development of optimal production processes, formulation strategies, and combustion technologies that improve energy efficiency and reduce environmental consequences.

This work investigated and analyzed the physical and combustion features of briquettes manufactured from eucalyptus sawdust, maize stalks, and coffee husk waste. This study added to the expanding body of knowledge on biomass utilization for sustainable energy production, assisting the transition to a more environmentally friendly and resource-efficient energy sector. However, little information is available about the physical and combustion properties of blended briquettes made from sawdust, maize stalks, and coffee husks. Blended briquettes have attracted attention as a sustainable alternative to traditional fuels due to their potential for minimizing environmental impact, utilizing agriculture and forestry leftovers, and lowering reliance on wood pellets. The advantages of converting leftovers into a densified state are as follow, first the technique raises the net calorific value per unit volume and the densified products are easy to transport and store. This process helps to solve the problem of residue disposal and lastly the fuel produced is uniform in size and quality.

The usage of agricultural waste is usually troublesome due to its uneven and unpleasant qualities. Densification, also known as briquetting, is the process of compressing trash into a product that has a higher density than the original raw materials. Densification has recently attracted a lot of interest in developing countries throughout the world as a technology for converting waste into energy sources.

Mixed briquettes formed from coffee husks, sawdust, and maize stalks have distinct physical and combustion features. The general physical characteristics of these blended briquettes includes density, gross calorific value, Fixed carbon, ash content and volatile matter. Blended briquettes typically have a higher density compared to the individual components. The density depends on the proportion of each material

used in the blend. Blended briquettes can be mounded into various shapes and sizes depending on the requirements. Common shapes include cylindrical, rectangular, or pillow-shaped briquettes. Moisture Content is also critical in the use of briquettes. Properly dried sawdust, maize stalks, and coffee husks are usually used to ensure low moisture content in the briquettes. Low moisture content promotes effective burning.

Combustion properties of blended briquettes investigated included the calorific value which is significant in burning. It represents the amount of heat energy released when briquettes are burned. The composition of the blend determines its calorific value which can be influenced by factors like the carbon and moisture content of the materials used. Fixed Carbon and Volatile Matter determine the ignition and combustion rates. Briquettes with low moisture content ignite and burn more easily.

## **1.2 Statement of the Problem**

Most tea companies utilize wood biomass to power industrial boilers, but the rising number of factories in Kericho has led to increased energy demand. The decrease of forest cover necessitates the investigation of sustainable alternative energy sources. Kenya produces hundreds of tons of agricultural garbage each year. The majority of these agricultural residues have been assessed for their energy potential, while others have not. Converting leftovers into a densified form helps to reduce deforestation by substituting burning wood, therefore the demand for wood pellets is reduced (Sivakumar and Mohan, 2010). Studies on individual sawdust, maize stalk and coffee husks have been carried out. However, studies that focuses on combination of these three briquettes components have not been widely studied. Therefore, this study investigated the physical and combustion properties of blended briquettes made from sawdust, maize stalks, and coffee husk, assessing their potential as an

alternative industrial energy source and defining the ideal physical, mechanical, and combustion aspects for use in steam boilers.

### **1.3 Objectives**

#### **1.3.1 Main Objective**

The main objective was to determine the combustion properties of blended briquettes of sawdust, maize stalks, and coffee husks.

#### **1.3.2 Specific Objectives**

The following specific objectives guided this study:

- i. To make blended briquettes from sawdust, from maize stalks, and from coffee husks
- ii. Assess the physical and combustion qualities of blended briquettes.
- iii. To optimize ratios of sawdust, maize stalks, and coffee husks to produce blended briquettes

### **1.4 Research Questions**

- i. What are the effects of mixture ratios on the blended briquettes?
- ii. How do the blended briquettes formed from coffee husks, maize stalks, and sawdust on affect physical and combustion properties?
- iii. What are the effects of optimizing mix ratios on calorific value, fixed carbon, volatile matter, and moisture content of blended briquettes?

### **1.5 Justification**

Industrial operations are linked to increased forest depletion, necessitating the development of environmentally acceptable alternative fuels (Amirnejad et al., 2021). Sawdust, coffee husks, and maize stalks are examples of waste materials can be briquetted and used as an alternative fuel in industrial boilers. The briquettes will

supplement traditional sources of energy, putting less impact on the already diminishing forest canopy. Tea manufacturers have always relied on firewood to generate steam. As the tea industry grows, there is a need to seek other fuel sources. Every year, Kenya produces a considerable volume of agricultural waste that is not used. However, little has been done to alleviate the reliance on woods. Bio-briquettes made from agricultural waste, including coffee husk, maize stalks, and sawdust, have helped to meet the growing need for energy and minimize reliance on trees (Sivakumar and Mohan, 2010). Hence the necessity to diversify (Sanchez et al., 2022b).

### **1.6 Scope**

The experiment was used to investigate the effect of briquettes made from a mixture of coffee husks, eucalyptus sawdust, and maize stalks compressed under pressure with the same particle sizes. Briquettes were studied primarily for their physical and combustion qualities which included measurements of moisture content, gross calorific value, volatile matter, ash content, and fixed carbons of blended briquettes. Eucalyptus Sawdust were acquired from sawmills, whilst coffee husk and maize stalks are dry stalks collected as a byproduct of agricultural output.

## 1.7 Conceptual Framework

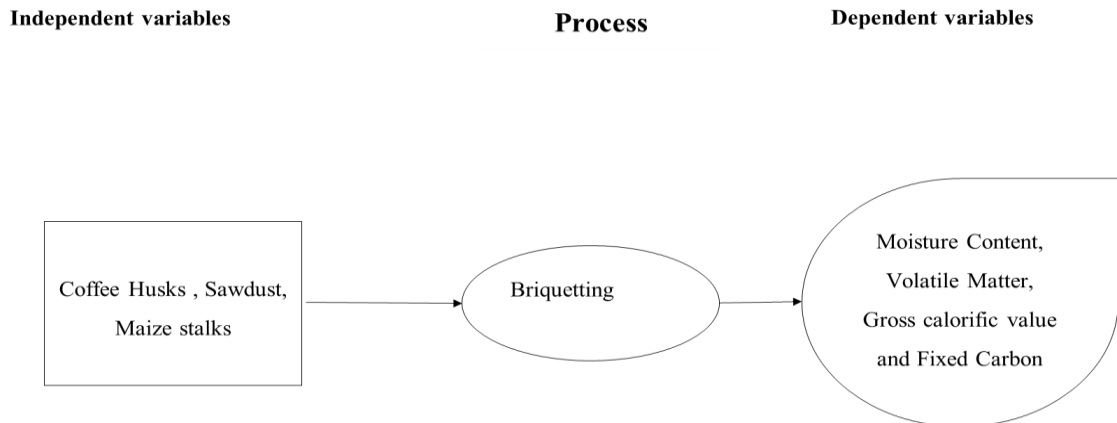


Figure 0-1: Conceptual Framework for briquetting technology and materials being used.

Figure 0-1 demonstrates the conceptual foundation of the study. Eucalyptus sawdust, maize stalks, and coffee husk are the independent variables employed in the creation of briquettes, which were sundried and pulverized to a diameter of 2mm. The dependent variables for obtained from blended briquettes and they included calorific value, fixed carbon, moisture content and volatile Matter using laboratory experiments. The process included the use of pre-fabricated mold and slight application of pressure.

## **CHAPTER TWO**

### **LITERATURE REVIEW**

#### **2.1 Introduction**

Briquetting is the process of compacting residues into a product that has a higher density than the original raw materials. It's also termed densification (Oladeji, 2015). Biomass densification is a set of technologies that transform biomass into fuel. The procedure improves the handling properties of materials for transportation, storage, and other uses. This technology contributes to the increased use of biomass in energy production since densification increases the volumetric and calorific value of a fuel, lowering transportation costs and perhaps improving the fuel situation in rural areas (Grover and Mishra, 1996).

Bio-briquetting has several benefits, including creating a bond within the particles to form a solid fuel, lowering the moisture content of the biomass, increasing the net caloric value per unit volume by removing volatile matter, producing uniform size and quality fuel, making transportation and storage easier, and addressing the residue disposal problem.

Blended briquettes, which have distinct physical and combustion properties due to the densification of biomass waste materials, have greatly increased the use of wood and agricultural waste as residential and industrial fuel in industrial boilers (Mitchell et al., 2013).

The world's energy supply is currently in great demand due to rising industrial activity and manufacturing. Energy resources are considerable but have been depleted under current conditions. The hunt for alternative energy sources has grown worldwide, with solar and wind energies drawing special attention due to their low cost of investment. However, because of its availability and low cost, trash is a

valuable alternative source of energy in research. Creating fuel briquettes from readily available biodegradable waste sources has various advantages. This experiment was designed to assess moisture content, ash content, volatile matter, fixed carbon, and calorific value. Waste items are blended in a variety of ratios. Caloric value is determined by the final analysis. Data was collected to determine the effects of various qualities, such as fuel briquettes, on power production. Material Analysis (Proximate and Ultimate) and Property Estimation for Fuel Briquettes Calorific value, porosity, and water absorption (Ferronato *et al.*, 2022; Raju *et al.*, 2021). The technique of compressing loose biomass material under pressure to create compact, solid composites of different sizes is known as biomass briquetting. In order to create briquettes from leftovers, pressure, heat, and a binding agent are applied to the loose components. There are now two different kinds of densification technologies in use (Oladeji, 2015). Renewable energy from biomass is one of the few proven, cost-effective, and practicable technologies that can reduce carbon dioxide emissions (Kpalo *et al.*, 2020).

The uneven and demanding nature of the briquetting technology may make the use of agricultural byproducts difficult at times. The process of compressing waste into a product with a higher density than the original raw materials is known as densification or briquetting. As a method of converting waste into energy, densification has recently garnered significant attention from developing nations worldwide.

Utilising and applying biomass resources through briquetting reduces the risk of environmental harm, lowers the cost of reclamation and manufacturing, and alleviates the disposal issues caused by the large volume of agricultural and forestry waste produced annually.

The benefits of employing biomass bio-briquettes as a source of heat include cost-effectiveness and sustainable energy. It also has low sulfur levels and hence cannot contaminate the environment. Biomass briquettes have a larger caloric value than individual briquette sources. The ash concentration of Bio-briquettes burn uniformly since their percentage is lower than that of coal (2–10%). There is a good chance of a continuous energy supply because densified briquette products are portable and easy to store, and the fuel produced is consistent in size and quality. Finally, it contributes in the reduction of deforestation by offering an alternative for fuel wood for both households and industries (Bajwa *et al.*, 2018; Gbabo *et al.*, 2015).

Ash lumping and slag formation are issues with all fuel types. The operational efficiencies of different boiler technologies vary. Horse manure and maize contribute to Nitrogen oxides and particle emissions. Additional research and development are necessary to adapt current boilers to different fuels since agricultural biomass has a wide range of fuel characteristics and combustion behaviours. Developing countries face a significant challenge in waste management and agricultural residue disposal, with the majority of this agricultural waste being destroyed in the field or at disposal sites, leading to pollution and greenhouse gas emissions into the environment.

There is a strong desire to turn these leftovers into fuels and other energy-rich goods. However, these agricultural leftovers are extremely difficult to handle, store, especially if they are burned. Direct withering conversion has relatively low thermal efficiency and produces significant air pollution. All of this can be prevented by converting waste biomass into a useable form for energy generation. This has made biomass briquettes an alternative source of fossil fuels, improved waste management, reduced air pollution, and significantly cut the cost of manufacture (Emerhi, 2011).

Briquettes of biochar are another kind of fuel made from biomass. One type of renewable energy is biomass. The biomass used in this study was agricultural waste made from maize cobs, which farmers do not often use. The burning quality of briquettes is affected differently by changes in particle size and briquette pressure (Adegoke *et al.*, 2010).

The process of bio-briquetting involves compressing the initial free particles using mechanical force in order to increase the density of biomass. Among the advantages of bio-briquetting are creating a bond within the particles to form a solid fuel, decreasing the moisture content of the biomass, increasing the net caloric value per unit volume because of the removal of volatile matter, producing uniform size and quality fuel, making transportation and storage easier, and addressing the residue disposal problem (Sanchez *et al.*, 2022).

Densifying biomass can be done in a number of ways. The most often used densification technique that works well for small-scale applications is screw press briquetting. A screw press briquetting conveys and compresses the raw material from the hopper. Compared to other methods, this procedure creates briquettes that are denser and stronger (Bhattacharya *et al.*, 2002).

In addition, a hand-operated biomass briquetting mold was made from locally accessible materials to produce the charcoal briquettes for final examination. In the past, briquettes made of binding materials including paper pulp, wheat flour, and cow dung were utilized. These briquettes were evaluated for calorific value and compressive strength by altering the amount by volume of binder (Kumar *et al.*, 2016).

Extensive examination into the parameters that impact the robustness and longevity of biomass products like briquettes have been done (Kaliyan and Morey, 2009). Previous studies presented a range of ideas to explain particle bonding in biomass densification, including attraction forces between biomass particles, adhesion and cohesion forces, solid bridges and mechanical interlocking links, interfacial forces, and capillary pressure (Obi *et al.*, 2022). The study emphasized the significance of physical factors such density, size, and moisture content in determining briquette strength and handling characteristics. It underlined the importance of suitable drying processes to reduce moisture content and improve combustion efficiency (Kaliyan and Morey, 2009).

Several studies have been conducted on the briquetting of waste biomass for energy production. The research investigated the effect of various parameters, such as particle size, moisture content, and binder content, on the physical and combustion properties of briquettes (Shahapur *et al.*, 2017). The study emphasized the importance of optimizing these parameters to achieve briquettes with desirable properties for efficient combustion (Brunerová *et al.*, 2017). Solid biomass as an energy source has a significant influence in low-income communities due to its ease of access, low cost, and sustainability. Furthermore, biomass briquettes are a carbon-neutral energy source with minimum environmental impact. Deforestation can be prevented by producing loose biomass wastes from agricultural and forestry activities on an annual basis. There is a need to encourage off-grid populations to minimize their dependency on wood as an energy source and exploit the readily available loose biomass from agricultural wastes or by-products (Shuma and Madyira, 2017).

Taguchi approach was used to improve the process parameters for briquetting biomass. The study concentrated on the physical qualities of briquettes, such as

density, moisture content, and compressive strength, to discover the ideal combination of factors for improved briquette quality and combustion performance (Kandpal *et al.*, 2018; Shuma and Madyira, 2017).

The study of different biomass materials physical and combustion properties, including eucalyptus sawdust and agricultural residues like maize stalks and sugar cane waste were analyzed. It provided insights into the composition, density, moisture content, and calorific value of these materials, which are essential in determining the potential for briquette production and energy conversion (Obi *et al.*, 2022).

The physical and combustion properties of briquettes made using a variety of organic binders and eucalyptus sawdust from three hardwood species. The type of binders employed in the densification and preparation procedures affect the combustion properties. Most performance issues, such as low yield and energy content, can be significantly improved by using binders in the proper proportions and understanding how binder qualities affect combustion properties, energy content, mechanical durability, and density of fuel briquettes. The compatibility of binders and fuel briquettes is also investigated in order to get a larger yield, as well as the mechanical and combustion properties that result. The mechanical durability of fuel briquettes can be improved by lowering the percentage of lignin, fat, and other extractives in the binder while also enhancing its qualities such as particle size, texture, and quantity (Olugbade *et al.*, 2019). Although not expressly focused on maize stalks and sugar cane waste, the study provided insights into the impact of different materials and binders on briquette features, including as density, moisture content, compressive strength, and combustion properties (Emerhi, 2011).

These studies highlight the need of determining the physical and combustion properties of blended briquettes made from uncarbonized eucalyptus sawdust, maize stacks, and sugarcane garbage. These findings highlight the importance of density, size, moisture content, calorific value, and emissions in determining the viability and performance of these briquettes as renewable energy sources. The findings of these studies can inform continuing research and development initiatives aimed at optimizing the composition, manufacturing methods, and combustion technologies for blended briquettes (Marreiro *et al.*, 2021).

The physical and combustion properties of mixed briquettes made from sawdust, corn stacks, and other agricultural wastes have been the subject of several studies. This research provided vital insights into the features and performance of briquettes as an alternative fuel source.

## **2.2 Maize Growing in Kericho**

Maize is Kenya's principal crop and is wholly dependent on rainfall, while only about 17% of the country is suitable for rain-fed crop production (Wokabi, 2013). Maize production levels are determined by complex interplay between water and nutrient availability, weed competition, insect and disease prevalence, and management strategies. Increasing maize output in Kenya can be done at both the farm and national levels. At the farm level, several important measures are required: early and better land preparation, timely planting, planting of the most appropriate maize varieties, proper fertilization, efficient weeding, and improved pest and disease control, with family labor being used effectively to carry out weeding operations (Wokabi, 2013).

## Production volume of maize in Kenya from 2015 to 2021 (in million bags)

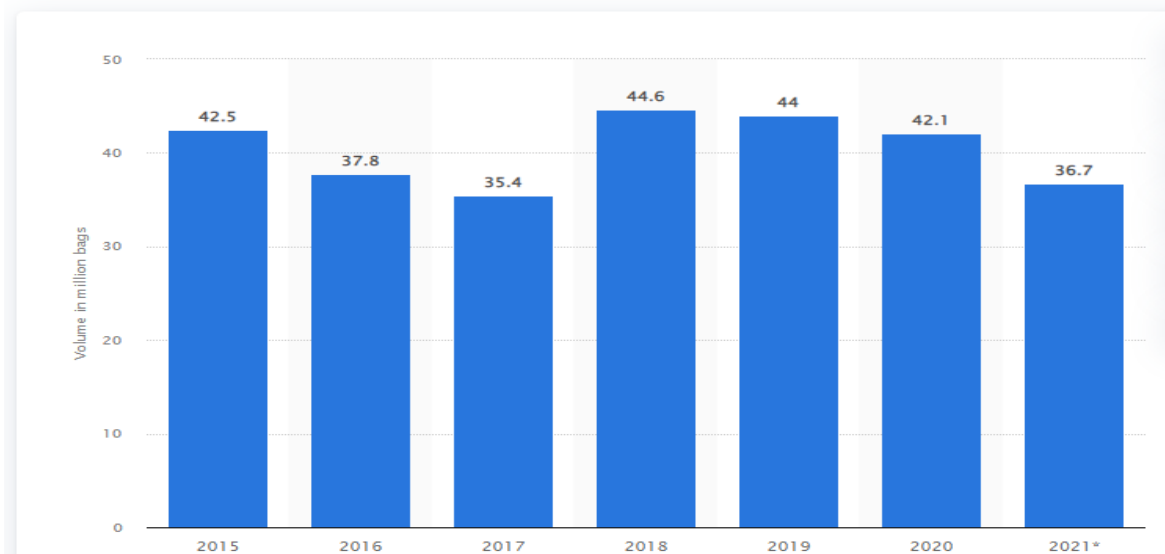


Figure 0-1: Maize Growing in Kenya in million bags.

Figure 0-1 illustrate maize production in Kenya from the year 2015 up to 2021 in million bags (Wokabi, 2013).

Kericho County is divided into three agricultural zones as high, medium, and low production zones. Kipkelion East and West Sub-counties are located in very productive agricultural zones, and they account for more than half of the county's total land area (Sang, 2021). These two sub counties rely largely on rainfall for maize cultivation, receiving an average of 1200mm per year spread out throughout the entire year. The two sub counties experience one short period of rain in March and April during the planting season, followed by long periods of rain from August to September. The soils are fertile loamy, which promotes maize cultivation while also retaining water and fertilizer, which are required for maize production. The two sub-counties are the primary dry maize growers in Kericho County, and they were chosen as the study location due to an abundance of maize stalks, which are essential

for the production of blended briquettes. Maize production throughout the county (Sang, 2021).

Table 2-1 shows the distribution of maize planting in Kericho County in the year 2021. There has been an increase in maize production over the last year due to an increase in fertiliser subsidies. Kipkelion East and West are the major producer of maize because of the larger area and favourable climatic conditions.

Table 0-1: Distribution of Maize in Kericho

<b>Zone</b>	<b>Tonnes</b>	<b>Total area (Hectares)</b>
Ainamoi	6700	2127
Belgut	3043	969
Bureti	16918	5438
Kipkelion East and west	69836	22170
Soin Sigowet	6846	2168
Totals	103343	32872

### **2.3 Coffee Farming**

Coffee manufacturing is the mainstream of millions of people globally, with the most of them found in the world's poorest countries. The crisis facing the current coffee industry has been characterized by massive over production because of low markets and customer bases, collapsing prices, deteriorating coffee quality because of change of climatic conditions, disease and pest best of resistance of coffees plants to pesticides and above all the growing inequality in the coffee value-chain United Nations Conference on Trade and Development (UNCTAD, 1999). Ten years ago, emerging countries accounted for approximately 30% of the coffee market's value, compared to about 10% now. Coffee supplied over 60% of Kenya's foreign exchange

profits, making it one of the highest revenue sources until 2002, when it decreased to 25%. This collapse caused social and economic imbalances in over 3 million smallholder Kenyan coffee producers, disrupting their daily incomes and ways of life (Karanja and Nyoro, 2002). These coffee farmers meant not only money in their pockets, but it also translated into ability to afford education, health care, food security and improved household standards of living.

Kericho County in Kenya has exported 134.4 metric tons of coffee valued at Ksh110 million to South Korea making it the first consignment of coffee to make its way to a direct market to the East Asian country (Kirui *et al.*, 2021). County Governor Prof. Paul Chepkwony flagged off the produce and said a total of 9,582 small-scale farmers spread across Kericho, Bomet, and Nandi Counties are set to enjoy great benefits from the proceeds of the sale of the exported coffee (Chelangat, 2019).

### **2.3.1 Coffee production in Kericho**

Kericho County Executive Committee Member urged coffee farmers to continue adopting good agricultural practices to reap bountifully as the prices of the cash crop continued to gradually increase noting that grade AA coffee has easily risen above 400 US dollars per 50 Kilograms in previous auctions which he says was a sign of good tidings (Chelangat, 2019).

Coffee is Kericho County's second most important cash crop, behind tea, which is primarily grown in Kipkelion West Sub-County, but the other Sub-Counties contribute significantly to the cash crop. Kenya's coffee sub-sector generates roughly USD 230 million per year and is a source of income for over 800,000 smallholder coffee producers. It is also critical to the important agricultural role in

contributing to and achieving Kenya Vision 2030 and the government's big four strategy.

Coffee production, which covers approximately 2,000 Ha in the County, is increasing gradually as more farmers in the coffee zones of Kipkelion West, Belgut, and Bureti adopt the crop for increased farm incomes (Chelangat, 2019).

Coffee produced within Kericho County are taken to a coffee factory at Fort Tenan where milling starts. The outer shell of the coffee is the main byproduct of this process. Coffee husks are normally disposed of at the factory since (Chelangat, 2019)



Figure 0-2 : Images of Coffee husk varieties in Kericho County.

Figure 0-2 shows different samples of coffee husks used in the formation of blended briquettes from coffee mills in Kipkelion Coffee Factory.

#### **2.4 Eucalyptus Sawdust Generation**

The total County tree cover stands at 23.23% while the forest cover stands at 20.61%. County forests cover 63,179 ha. Of this, 49,746.6ha comprises indigenous forest while 13,432.4 ha falls under industrial plantations. The major tree species

growing in the plantations are *Cupressus lusitanica* (60% of total plantation area), *Pinus patula* (30% of total plantation area), and *Eucalyptus saligna* (5% of total plantation area). Kericho Forest Station has the largest forested area followed by Londiani Forest Station. Tendeno Forest Station has the smallest forested area of 2,341.65 hectares.

Sawmilling is the process of operating a Sawmill by converting logs into lumber. Although the general workflow of the modern Sawmills resembles the workflow of the ancient Sawmills, where logs are converted to dimensional lumber, there has been tremendous improvement in the efficiency of work in terms of mechanization and efficiency indices (Sandberg and Teischinger, 2023).

Table 0-2 shows forest cover in Kericho County, where most of the forests are situated in Makutano and the Sorget area. The eucalyptus sawdust from this thesis was collected from a sawmill situated at the Londiani region.

Table 0-2 : Gazzetted forest covers in Kericho, 2019

<b>Forest Station</b>	<b>Plantation Area (Ha)</b>	<b>Indigenous Forest (Ha)</b>	<b>Cupressus Lusitanica (Ha)</b>	<b>Pinus Patula (Ha)</b>
Kericho	990	24,111.90	594	297
Kuresio	2,346.10	5,020.70	1,408	704
Malagat	804.5	6,217.90	483	241
Londiani	1983.10	7,032.45	1,190	595
Makutano	3561.84	1,912.25	2,137	1,069
Tendeno	391	1950.10	235	117
Sorget	3355.30	3501.30	2,013	1,007
Total	13,432.40	49,746.60	8,059	4030



Figure 0-3: Image of Blue gam by-product from Londiani sawmill.

Figure 0-3 shows eucalyptus sawdust by-products at the factory. They were picked and sun-dried for ten days before grinding for the thesis runs and experiments.

## 2.5 Molasses

Molasses, a byproduct of sugar cane processing, has been frequently employed as a binder for briquettes due to its better binding ability (Zhai *et al.*, 2018). Molasses also assist to improving the mechanical properties and fuel characteristics (Drobíková *et al.*, 2016). The soluble sugars in molasses recrystallize during the drying operations to form solid bridges to trap additional particles, resulting in high mechanical strength of the pellets, which is advantageous during transportation and storage (Mišljenović *et al.*, 2016).

Binders were added to the prepared sample as it was mixed. Binder addition to biomass feedstock is a co-processing procedure that aids in densification or boosts the mechanical and thermal properties of the product (Bajwa *et al.*, 2018). The binder also helps to reduce wear and tear on manufacturing equipment by forming a bridge to increase strong inter-particle bonding with biomass components (Pradhan *et al.*, 2018). The amount of binder to be added relies on the binding capabilities of the raw material and the binding agent, and this should not go over 15% to avoid

affecting the overall properties of the blended briquettes (Asamoah *et al.*, 2016). Briquettes are made from a variety of binders, including inorganic, organic, and compound binders.

Molasses is the primary byproduct of sugar production in Kenya (Valli *et al.*, 2012) and for this experiment, it was set at 10% to improve the viscosity; a sample of briquettes was dissolved in an equivalent amount of water, ensuring homogeneity throughout mixing.

## **2.6 Briquetting Technologies.**

Briquetting is a lightweight technique provides a product with enhanced bulk density, lower moisture content, and homogeneous form, shape, and material qualities. A manually operated briquette Mold is used to shape the blended mixture into briquettes (Amrullah *et al.*, 2020).

The briquetting technologies have been divided into three types Namely (Emerhi, 2011):

- i. High-pressure compaction
- ii. Use a heating device for medium-pressure compaction.
- iii. Binder-based low-pressure compaction.

### **2.6.1 High-pressure technologies.**

In contrast to other types of presses, piston presses make entirely solid briquettes. The piston press uses a flywheel or the hydraulic system for producing densified biomass fuel (briquettes/pellets). A biomass sample is fed from the feedstock unit to the shaped piston drive, which can be operated mechanically or hydraulically. Heating the biomass leftover material is crucial for hardening the briquettes and preventing them from reabsorbing water. During compression, the temperature

ranges from 200<sup>0</sup>c to 250<sup>0</sup>c. The piston compresses the incoming biomass residual material into the conical-shaped die, and the briquettes are extruded through the die's opening face. A biomass piston press/pump apparatus is shown (Vaish *et al.*, 2022).

The High-Pressure Briquetting Machine is ideal for lignin-rich leftovers. At this high pressure, the temperature rises to between 200<sup>0</sup>C to 250<sup>0</sup>C, which is enough to fuse the residue's lignin content, which acts as a binder and eliminates the need for additional binding material. High temperatures guarantee that moisture content is reached, assisting in the combustion process.

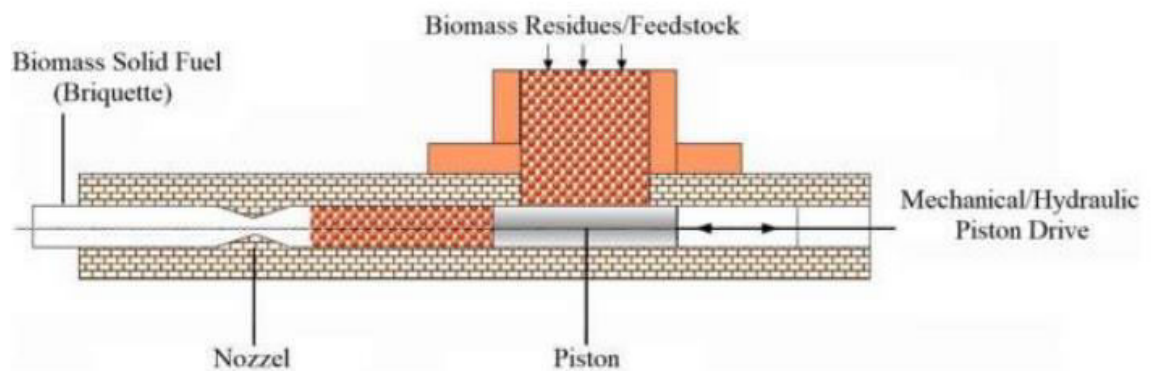


Figure 0-4: Piston Press Machine (Vaish *et al.*, 2022).

Figure 0-4 shows a piston press machine for used in briquetting. It has a mechanical piston drive and feedstock hopper and nozzle to assist in pressure generation in production of briquettes.

The advantages of the piston screw are that there is less relative motion between the ram and the biomass, therefore the wear and tear of the ram is significantly decreased, and its employment is a cost-effective technology of briquetting (Grover and Mishra, 1996). The disadvantage of piston screws is that they are only suited for raw materials with a moisture level of less than 12%. Higher MCs reduce efficiency; additionally, the quality of the briquettes decreases with increased output for the

same power; and finally, the briquettes produced are brittle, affecting their movement from one location to another.

### **2.6.2 Screw press techniques.**

Screw extruders have a revolving screw that compresses biomass residues from feedstock. A separate mechanical drive can be used to rotate a screw within the machine. Because biomass leftovers are highly compressed and congested, minimizing particle friction requires a significant amount of energy. At high starting temperatures, biomass particles lose stiffness and become softer. The high temperature and strong compression make the biomass material more suitable (Vaish *et al.*, 2022).

This system has a higher production rate; this makes it an appropriate substitute for coal in applications and boilers. Briquettes produced have a density of 1150 kg/m<sup>3</sup> and are formed from loose biomass with bulk densities ranging from 100 to 300 kg/m<sup>3</sup>. This higher density provides the briquette with a higher heat value (kJ/kg) (Kaliyan and Morey, 2009). This causes the briquettes to burn more slowly than the raw materials from which they are formed, resulting in an enhanced heat retention duration (Oladeji, 2015).

The exterior surface is slightly carbonized to protect against ambient temperature, which increases ignition and burning of the tested briquettes. Screw press machines require more power than piston press machines. They make briquettes with a center hole for improved combustion due to the increased specific surface area. Screw presses are ideal for small-scale applications (Oladeji, 2015). This press produces briquettes which are homogenous and have a high impact test hence don't disintegrate easily.

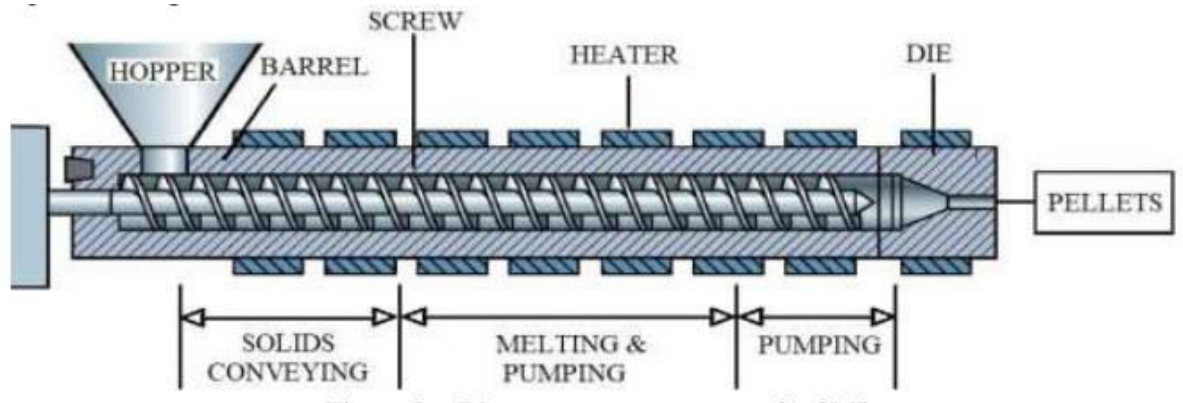


Figure 0-5: Image of screw press Machine (Vaish et al., 2022 )

Figure 0-5 shows the screw press machine which has introduction of heat to support in briquettes formulation.

Screw feed presses produce continuous and consistent production, so the briquettes created are homogeneous in size. The briquette's external surface is somewhat carbonized, allowing for easy ignition and burning while also protecting the briquettes from atmospheric moisture. A concentric hole in the briquette facilitates combustion by providing for proper air circulation. Screw feed press machines run very smoothly with no shock load, and they are lighter than piston presses due to the lack of reciprocating parts and a flywheel. Additionally, the machine's parts and oil are free of dust and raw material contamination. The screw feed press requires more power than the piston press, making it unsuitable for small-scale briquette manufacturing.

### **2.6.3 Medium pressure compaction with heating Mechanism.**

The biomass pre-heater is just a structure that incorporates a tube heat exchanger. A motor-driven screw feeder transports the materials through the tube, hot flue gases or heating medium from a biomass gasifier passes through the outside shell of the

press. The temperature of the flue gases is adjusted by mixing cold air with the hot gases to achieve the desired operational temperatures(Aqa, 1990).

The Medium Pressure Briquetting Machine operates between 5 and 100 MPa. This machine requires the use of an additional heat source for heat and melt the feedstock's internal lignin content, hence eliminating need for an additional binder.

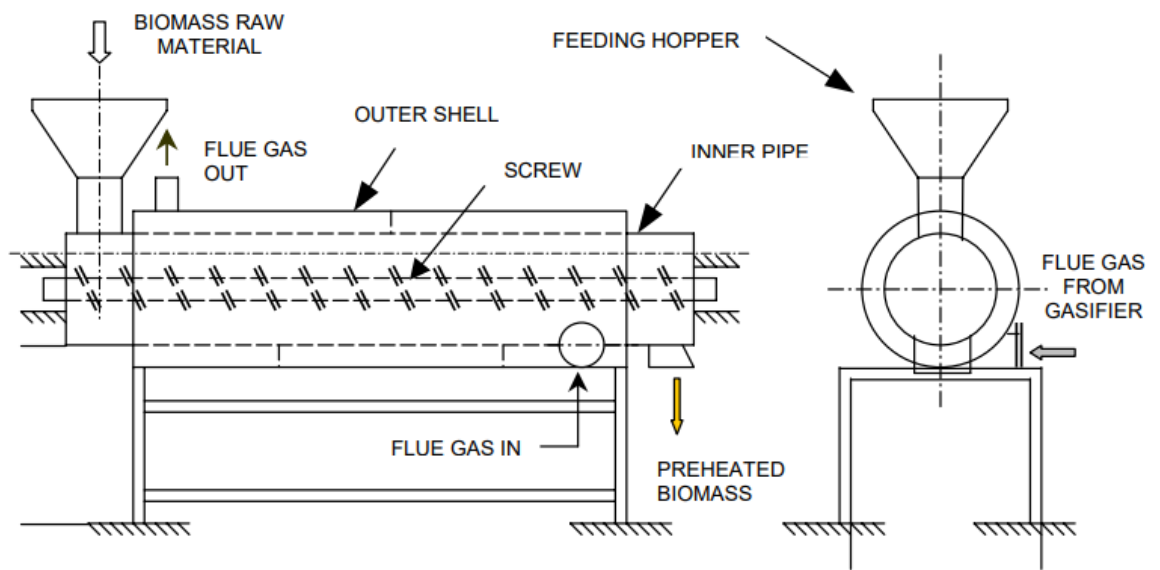


Figure 0-6: Image of Medium Pressure machine with a Heater (Aqa, 1990).

Figure 0-6 shows a framework with a tube heat exchanger fitted in it. A motor-driven screw feeder feeds materials into the tube, while hot flue gases or heating medium from a biomass gasifier travel through the presto's outer shell to form briquettes.

#### 2.6.4 Manual Press with compaction.

A low-pressure briquetting machine operates between 0 up to 5.5 MPa. This type requires an additional binding ingredient to be present at room temperature. The binding materials commonly used are molasses. This is regarded as the best type of

machine for both carbonized and non-carbonized agricultural waste. They are utilized for briquetting since the carbonization process removes the lignin substance and this sort of machine requires little energy.

Binders are added to the feedstock during the mixing stage before densification. Some biomass materials will not agglomerate without the addition of a binder, especially when a low-pressure compaction technique is utilized. Binder addition to biomass feedstock is a co-processing procedure that aids in density and increases the mechanical or thermal qualities of the product (Bajwa *et al.*, 2018). Binder addition decreases wear on production equipment. It creates a bridge to improve strong inter-particle interaction with biomass components (Pradhan *et al.*, 2018). The amount of binder to be applied depends on the binding qualities of the raw material and the binding agent. It is normally between 10% and 15% (Asamoah *et al.*, 2016).

Most low-pressure machines are piston and screw presses that are operated with bare hands and use very little pressure, necessitating the addition of binder.

There are several advantages of low Pressure Press first the cost of fabrication is low and its operating cost and capital cost is low as compared with other systems (Kpalo *et al.*, 2020). The system also requires little skill to run as compared to other technology, and finally, the machine function with minimum pressures, making it suited for low scale, although this type has a low output capacity of about 5 kg/h or 50 kilogram in a 10-hour day (Wilaipon, 2008).

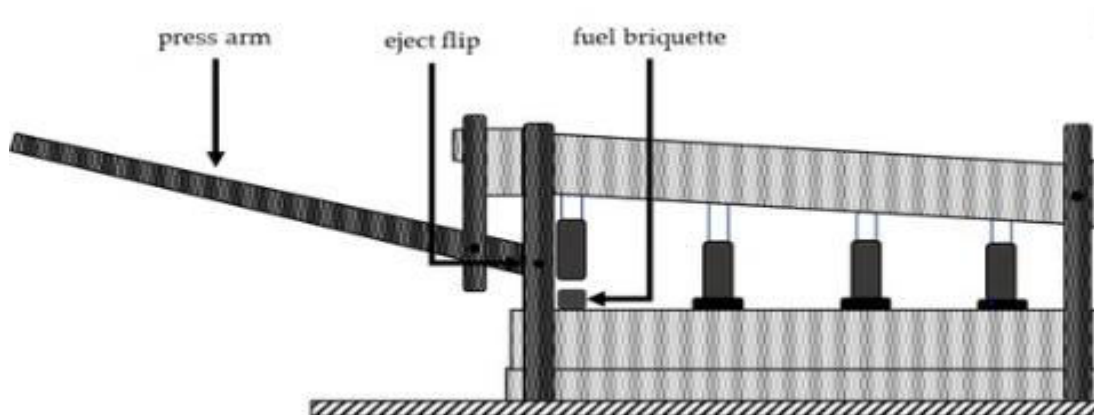


Figure 0-7: Image of a Low-pressure Machine ((Bajwa et al., 2018).

Figure 0-7 shows a low-pressure fabricated machine which produces under low pressure (Bajwa *et al.*, 2018)

## 2.7 Factors Affecting Briquettes Making.

Several elements affect briquette manufacture, including granular size, pressure applied, raw material moisture content, compaction speed, and pressing time.

Granular size was the most thoroughly investigated process variable. This is the size of the biomass particles used to produce the briquettes, which offers them uniformity (Marreiro *et al.*, 2021).

The pressure employed in briquette production is also one of the most significant criteria for briquetting equipment. Pressure, for example, enables biomass densification, which affects the briquette's density and strength (Granado *et al.*, 2021).

The binder is a crucial component in biomass particle adhesion and can be added to the material or its structure (Navalta *et al.*, 2020). During briquette manufacturing, extrinsic variables like heat and pressure can also activate the binder (Adegoke *et al.*,

2010; Kaliyan and Morey, 2009; Navalta *et al.*, 2020). There is a relationship between operational variables and the material's original characteristics.

The moisture content of the raw material must be such that smooth densification is achievable without affecting the physical and energy properties of the briquettes.(Grover and Mishra, 1996).It is worth noting that moisture in the formation of briquettes is essential to activate some binders, such as starch, which aids in the densification process (Adegoke *et al.*, 2010).

Pressing time during which the briquette is compacted.

Several studies (Araújo *et al.*, 2016; Martinez *et al.*, 2019; Sette Junior *et al.*, 2017) found out that cooling time is required for heating procedures in briquette production. Briquettes are made by densifying loose particles of solid material into a high-density fuel (Lei *et al.*, 2013; Panwar *et al.*, 2011). Thus, operating parameters such as pressure, temperature, and compaction time must be specified. As stated in the definition, biomass must initially be in the form of loose particles, preferably sorted by size and distribution, which is one of the most important material conditions for the densification process (Francik *et al.*, 2020; Martinez *et al.*, 2019). According to(Chaloupková *et al.*, 2018; Križan *et al.*, 2015) the variable can affect both the energy expended and the strength of the briquettes.

All of these characteristics are necessary for the biomass densification process in the form of briquettes, therefore those already listed as the most prevalent among the operations will be examined in detail in specific themes.

## **2.8 Large-scale production of briquettes.**

There are numerous types of briquetting machines used for biomass densification and compaction. Their working principles differ from one other. Screw Presses the screw extrusion briquetting process was designed and perfected in Japan in 1945

(Grover and Mishra, 1996). These briquetting machines are popular densification tools for small-scale applications in developing countries. Screw presses are another type of mechanical press equipment. Screw presses continuously feed material into a screw, which forces it into a cylindrical die. This die is routinely heated to achieve the necessary temperature for lignin flow. If the die is not heated, the temperature may not rise enough to allow lignin flow, and binding materials may be necessary (Bhattacharya *et al.*, 2002; Grover and Mishra, 1996; Ojo and Mohammed, 2015; Tabil *et al.*, 1997).

The briquette machine is a single-extrusion die screw press. It consists essentially of a drive motor, screw, die, belts, and a housing with a hopper. The belt transmits power from the motor to the screw via the pulley. When the motor starts, raw materials are fed into the machine through the hopper, crushed in the barrel, and extruded through the die.

### **2.8.1 Raw Material Preparation**

Sorting is often referred to as sieving. Typically, any undesired elements or large raw materials are eliminated to ensure that all feedstock is the appropriate size. A wire mesh can be used to screen away any undesirable bigger bits from the feedstock.

Shredding biomass materials into little pieces. This method entails cutting biomass materials into little pieces to improve their workability and compactness. This procedure is not generic and is determined on the type of maize stalks, and cobs needs to be cut into small pieces, biomass feed stocks such as coffee husks and eucalyptus sawdust would not require shredding (Oladeji, 2015).

Mixing: This is usually required when a variety of raw materials are to be employed, largely to improve the combustion properties of the blended fuel. To create a homogenous mixture, thoroughly blend the components. A common example is the combination of biomass sources with high and low ash levels.

Blending: Determine the required briquette composition and ratio depending on the study's unique objectives. This was accomplished in accordance with the design of experiments, which included both the quantity of individual components and the number of runs for the optimization process

The binder's application is determined by the briquetting technique used. In addition to biomass mixing, an appropriate binder is added and appropriately mixed with the biomass, particularly when employing a low-pressure method. This improves the compactness of the biomass components and prevents them from breaking apart. For this experiment, Molasses was used for all the runs and this was maintained constant for it to achieve the correct output required.

Finally, the feedstock is ready to be compacted mechanically or by hand. After some dwell time, the material will be ejected from the mold. For this experiment hand operated press was used.

Briquette Formation:

- i. Select an appropriate briquetting machine or press to form the briquettes.
- ii. Adjust the machine parameters, such as pressure and temperature, according to the specific requirements.
- iii. Feed the blended biomass mixture into the machine and apply pressure to form compact briquettes.
- iv. Allow the briquettes to cool and solidify before further testing.

### 2.8.2 Procedure of making briquettes

The briquetting production plant includes a briquetting machine, a hammer mill for grinding the coffee stalks, a binder storage tank, a mixing drum to prepare the slurry, and a drying area (Abakr and Abasaheed, 2006). This briquetting procedure involves extruding the material using a screw extruder that serves as a continuous feeding. The material's volume reduces as it goes from the hopper to the die output. This is performed by progressively expanding the threaded shaft's root diameter, starting with a tiny diameter at the feeding point and progressing to a maximum value at the die position. Because of the plant's limited production facilities, screw manufacturing was the most difficult aspect of the operation. The feedstock is the slurry mixture of the un-carbonized powdered cotton stalks and the binder (Abakr and Abasaheed, 2006).

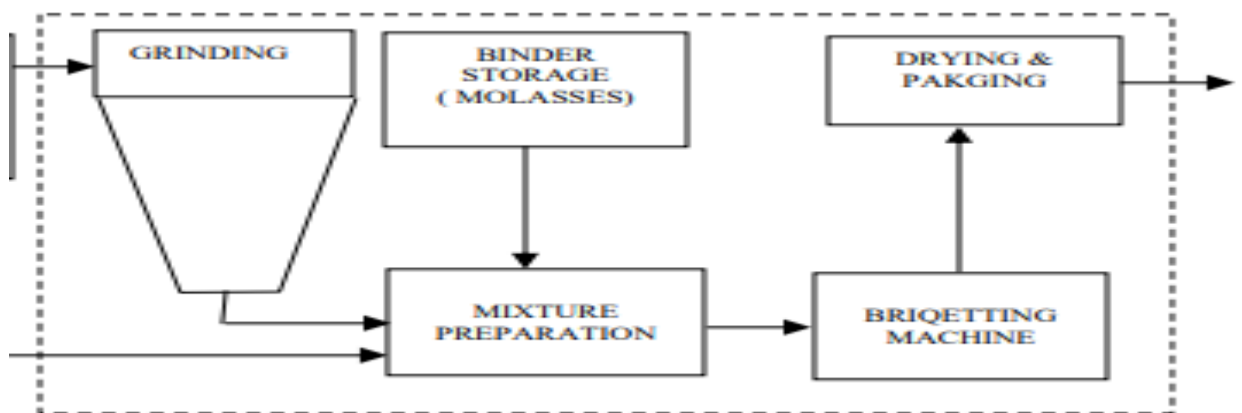


Figure 0-8: Schematic illustration of the briquette production scheme (Abakr and Abasaheed, 2006)

Figure 0-8 depicts a schematic view of briquette production, from the ground up to the final drying process.

The briquetting process typically begins with the collection of leftovers, followed by size reduction, drying, and compaction using an extruder or press. Briquetting can be

performed with or without the use of binders. The one without a binder is more convenient; however, it requires complex and expensive presses and drying equipment (Oladeji, 2015).

## **2.9 Response Surface Methodology**

Response surface methodology (RSM) is a better method for assessing the effect of individual process variables, effectively finding optimum process variable combinations for a multivariable system, and maximizing experimental points since it requires less experimental data (Nwabueze, 2010). The RSM is a combination of statistical and mathematical tools that helps model and evaluate situations where an intriguing response is affected by numerous factors, with the goal of maximizing this reaction (Montgomery, 2017).

A quantitative representation of the system that needs to be optimized is possible. Very vast and complicated processes may now be simulated and optimized because to the development of high-speed computers and the ease with which process optimization researchers can use them. The process of creating the best product in its category is known as optimization (Hu, 2017; Larmond, 1977). It evaluates many processes variable scenarios at once, differentiating it from the typical one-process variable at a time experimental technique. It reduces costs by employing novel experimental methodologies and objective testing to examine various effects on product reactions.

The availability of data gained through an adequate experimental design impacts the usefulness of altering the RSM for process optimization. Response surface approaches are useful for designing, improving, and optimizing response variables. When designing, generating, producing, and evaluating new scientific research and products, the Response Surface Methodology is critical. It also helps to improve

existing products and research. Response surface methodology is most commonly used in the following industries: industrial, food science, clinical and biological sciences, social science, physical science, and engineering. Methods that include selecting process combinations for optimization without taking into account relevant experimental designs are untrustworthy from a scientific standpoint and cannot be reproduced.

Response surface methodology and other mathematical models generate an accurate map that allows for successful optimization.

Box and Wilson proposed approximating the response variable with a first-degree polynomial equation and created the RSM method in 1951. They agreed that this model is not precise; it is only an approximation; yet, it can be simply approximated and implemented, especially when the technique is not well known (Wikipedia 2006). Furthermore, Mead and Pike believed that the use of Response Curves in the 1930s was the beginning of RSM (Myers, 1999; Myers *et al.*, 1989; Trocine and Malone, 2000).

The orthogonal design for the first-order model was inspired by Box and Wilson (1951). Many subject-matter scientists and engineers are familiar with Box and Behnken's three-level designs (1960) and central composite designs (CCDs) for second-order systems (Myers *et al.*, 1989). The same study indicates that Hartley (Bradley, 2007), who strove to build a more compact or affordable composite design, made a substantial contribution. The literature has various publications on response surface models. In comparison, there are few works on three-level fractional design. As a result, 3-level fractional design continues to be a research topic. The study's Fractional Factorial Experiment (Khuri and Cornell, 2018; Khuri and Mukhopadhyay, 2010).

Comparing data in these cases is challenging because it ignores how process variables interact, how sensitive specific variable combinations are, and how process factors affect the product quality criteria under consideration. Furthermore, many alternative combinations of process variables must be examined in order to establish the correlations between process parameters and product responses. To assure the dependability of bioprocess optimization utilizing a single-dimensional search, just one variable must be modified while the others are kept constant at a given level. When there are many variables, this technique might be complex and time-consuming (Ratnam *et al.*, 2005).

The response surface methodology (RSM), which uses fewer experimental data, is a more effective way for assessing the impact of individual process factors, discovering the optimal combinations of process variables for a multivariable system, and conserving experimental points (Mullen and Ennis, 1979).

**Order in RSM model.**

The order of an RSM model refers to the degree of terms included in the mathematical equation used to approximate the response variable (Y) as a function of independent variables (X). RSM typically uses first-order, second-order, or higher-order models depending on the complexity of the system.

**First-Order (Linear) Model**

Used when the response is expected to change linearly with the input variables.

Appropriate for flat response surfaces.

The model equation is

$$y = \beta_0 + \sum \beta_1 x_1 + \epsilon \dots \dots \dots \text{Equation 0-1}$$

The response surfaces are formalized using equations called models, which are similar to the well-known regression equation. First- or second-order regression models could be used to investigate the relationship between  $y$  and the independent variables. If the variables can linearly model  $y$ , a first-order model is appropriate.

### Second-Order (Quadratic) Model

For briquette formulation, second-order (quadratic) models are frequently selected because they effectively represent the impact of process factors on briquette characteristics while keeping the number of experiments manageable.

Most popular in RSM, particularly Central Composite Design (CCD) and Box-Behnken Design (BBD).

The model equation is:

$$y = \beta_0 + \beta_1x_1 + \beta_2x_2 + \beta_{11}x_{11}^2 + \beta_{22}x_{22}^2 + \beta_{12}x_1x_2 + \epsilon \dots \dots \dots \text{Equation}$$

0-2

### Choosing the Right Model Order.

Table 0-3: Choosing model order.

Model Order	Use Case	Pros	Cons
First order (Linear)	Initial screening	Simple, requires fewer experiments	Cannot model Curvature
Second –order (Quadratic)	Optimization	Captures curvature and widely used	Requires more experimental runs
Third-order (Cubic)	Strong non- Linearity	Captures complex interactions	High experimental cost and it is rarely used

If the response can be expressed as a linear function of independent variables, the resulting function called a first-order model. A first-order model with two independent variables can be expressed according to equation 2.3.

$$y = \beta_0 + \beta_1x_1 + \beta_2x_2 + \beta_{11}x_{11}^2 + \beta_{22}x_{22}^2 + \beta_{12}x_1x_2 + \epsilon \dots \dots \text{Equation 0-3}$$

If the link between the dependent (response) and independent (process) variables is complex, first-order models may fail to effectively forecast the outcome. The order produces linear or straight response surface plots; however, if the system includes curvature, a higher degree polynomial, such as the second-order model, may be used. The second-order model is usually chosen over the first-order model since the first-order model lacks any nonlinear terms(Myers *et al.*, 2016).

$$y = \beta_0 + \beta_1x_1 + \beta_2x_2 + \beta_{11}x_{11}^2 + \beta_{22}x_{22}^2 + \beta_{12}x_1x_2 + \epsilon \dots \dots \text{Equation 0-4}$$

The model's quadratic and cross-product ordering enables the projected response surface to curve and bend, which improves prediction of complicated interactions(Meilgaard *et al.*, 1999). RSM plots frequently require the insertion of data points to determine whether the regression equation is compatible with the experimental points

Response surface methodology is commonly used as a mathematical model for optimizing bioprocesses. The purpose for using these models is that they indicate the ideal operating circumstances for the system, as well as the region of the factor space in which the operational parameters are satisfied(Annor *et al.*, 2010).This approach was developed in the early 1950s and was initially extremely effective in the chemical industry(Wang DjaShin *et al.*, 2006).

Since then, it has been employed successfully in a variety of disciplines, including food, tobacco, military research, medications, petroleum, electronics, and many

more(Myers *et al.*, 1989).Furthermore, it has been widely employed in numerous industrial contexts for many years, much beyond its roots in chemical processes, such as semiconductor and electronics manufacture, machine, metal cutting, and biological operations(Shumate and Montgomery, 1996). Response surface methodology allows process factors to be handled concurrently in order to get the optimum product qualities and desired features.

Mathematical modeling for bioprocess optimization is gaining popularity, with the RSM being used to handle issues involving multiple independent variables (or factors) that influence the value of a dependent answer,  $f(x)$ . Many researchers have utilized it to optimize process variables in the system to acquire any or all product responses. Several recent researchers in the literature (Goyal and Kumar, 2011; Iqbal *et al.*, 2009; Nwabueze, 2010; Ratnam *et al.*, 2005). We used the RSM in central composite design as a mathematical model to properly determine the best circumstances for enhancing response quality.

For briquette formulation, a second-order quadratic model is frequently employed because it efficiently captures the impact of process variables on briquette qualities while keeping the number of tests reasonable.

### **The fundamental concepts of response surface methodology**

Unlike factorial treatment structures, Response surface methods experiment seeks to determine whether and how the factors influence the response by altering the values of experimental factors known as dependent variables. Thus, the primary goal of employing the RSM as a mathematical model for bioprocess optimization is to determine the optimal process variable combinations for increasing or decreasing product response. This information describes the direction and amplitude of process variable effects on product parameters and controlled process variables.

Response surface methodology's fundamental premise is the portrayal of interactions or cross-products between process variable conditions and product responses(Nwabueze, 2010).Thus, the model may be used to compute all combinations of variables and their effects within the test range(Shi *et al.*, 2013).

### **Steps in RSM adaptation as a mathematical model**

The RSM, as a mathematical model for process optimization, follows well-established practical strategies that raise the likelihood of delivering the desired product. Essentially, process optimization entails a few basic steps namely identifying the key process or independent variables, conducting statistically designed experiments or building the model, estimating the coefficients in a mathematical model, predicting the response, and checking the model's adequacy(Ratnam *et al.*, 2005; Wang DjaShin *et al.*, 2006). The solution search includes the following processes: statistical analysis (multivariate regression analysis) and interpretation of the resulting polynomial equations, response surface, and contour plots.

### **Choice of critical process or independent variable conditions**

Experiments are typically undertaken to identify critical or outstanding process factors  $x_i$  (for  $i = 1, 2, 3, \dots, k$ ) and the response  $y$ . The goal of this stage is to identify the primary process variables in the experiment that influence the product characteristic under consideration. After carefully evaluating the response, some essential process variables emerge, with the three most relevant being picked based on the experimental design for optimizations.

### **2.10 Experiment design**

The next step in converting RSM into a mathematical model for bioprocess optimization is experimental design or model construction. RSM is a sequential

technique whose major purpose is to swiftly and efficiently guide the experimenter to the broad region of the optimum (Nwabueze, 2010; Ratnam *et al.*, 2005).

The central composite design is one of the most widely used response surface designs in process optimization. This is owing to its efficiency in terms of the number of runs require(Montgomery, 2019; Wang DjaShin *et al.*, 2006).

### **2.10.1 Design of Experiments**

Design of experiments is a statistical tool for designing, developing, and optimizing products, systems, and processes. It is versatile and beneficial for a variety of applications, including design. Variable screening, transfer function identification, optimization, and comparisons. The design of experiments is a mathematical strategy used to plan, carry out, evaluate, and interpret experiments.

Despite their age, DOE tools have been widely used during the last 20 years in fields such as services, product/process quality improvement (Duraković and Bašić, 2012) and product optimization ((Durakovic and Torlak, 2017). At the time, DOE increased its research efforts in great part due to training and the availability of the latest, easily navigable commercial and non-commercial statistical software tools.

### **2.10.2 General practical steps and directions for designing DOE.**

First describe your objectives, which are a list of problems to be investigated. Define the response variable. The measurable result of an experiment based on its objectives has been ascertained. Identify the sources and levels. Determine which independent variables (factors) impact case change. Response variable. A fishbone diagram could be used to identify elements that potentially affect the response variable. Plan an experimental design, such as screening for relevant components also the factor-response function and number of tests will both be planned. Sample determination

and conducting the experiment using a design matrix. The data is examined statistically using ANOVA. And lastly draw significant conclusions and recommendations, including a graphical representation and confirmation of the results.

The system being optimized can be represented quantitatively. The availability of high-speed computers and their simplicity of use through process improvement and experts have made it possible to simulate and optimize very large and complicated processes. Optimization is a technique used to create the best possible product in its category(Hu, 2017; Larmond, 1977).

It differs from the typical one-process variable at a time experimental approach in that it simultaneously examines numerous process variable scenarios, uses creative experimental designs to reduce expenses, and measures several influences on product responses using objective testing(Dziedzak, 1990).

The critical stages for incorporating RSM into Box Behnken design (BBD) and multivariate analysis as mathematical models for bioprocess optimization. The BBD was chosen for its efficiency in terms of the number of runs required to fit a second-order response surface model (Montgomery, 2019; WANG *et al.*, 2006). Curvature can be calculated using the BBD, an embedded factorial or fractional factorial design with center points and a collection of corner and star points (Annor *et al.*, 2010).

The One factor at a time (OFAT) scientific technique was commonly used. This method only tests one variable/factor at a time, with all other variables bound save one being researched. Testing multiple variables simultaneously is helpful, especially when results must be thoroughly analyzed (Durakovic *et al.*, 2014).

Experiment design is a diverse approach to determining key input variables and their effects on output variables. According to reports, Experiment design is generally done with "hard tools". Furthermore, DOE is basically a regression study that may be employed in a variety of settings.

The following are some common design types.

- a. Comparisons: To determine the best alternative among several comparisons, use the t-test, z-test, or F-test.
- b. To find important factors, variables are screened using two-level factorial designs. Variable are just a handful of the many elements that affect the performance of a system and process.
- c. To discover transfer functions, you must first identify essential input variables and understand their relationships.

DOE is increasingly used for decision-making in various industries, including new product creation, manufacturing, and process improvement (Adegoke *et al.*, 2010).

Its applications extend beyond engineering to include administration, marketing, hospitals, pharmaceuticals, and the food business. Energy, architecture, and chromatography (Schlueter and Geyer, 2018). DOE applies to physical processes.

Until the early 19th century, the One Factor at a Time (OFAT) scientific technique was widely used. This method only tests one variable/factor at a time, with all other variables bound save the one under investigation. Testing numerous variables at the same time is useful, especially when data needs to be thoroughly examined. In the 1920s and 1930s, Ronald A. Fisher conducted agricultural research in the United Kingdom to increase crop yields. Obtaining data was tough.

### **2.10.3 The principal applications of the design of experiments.**

Experiment design is a diverse approach to determining key input variables and their effects on output variables. According (Durakovic *et al.*, 2014), DOE uses hard tools largely. Additionally, DOE is a regression study that can be applied in a variety of scenarios. Commonly used design types are the following (Guo and Mettas, 2010).

- i. Comparison - This is one of several criteria used to choose the best alternative using a t-test. F- or Z-test.
- ii. Using two-level factorial designs, essential factors (variables) influencing system, process, or product performance are identified.
- iii. Identifying transfer functions: Once the relevant input variables have been identified, The link between them and the output variables can be used to evaluate system, process, or product performance.
- iv. System Optimization Use the transfer function to optimize the experiment's variables. This enhances the performance of the system, process, or product.
- v. Overall, elements that cause. Robust design reduces variation in a system, process, or product without addressing the root reasons. Dr. Genichi Taguchi pioneered robust design, making systems noise resistant (including environmental and uncontrollable elements). Overall, components that cause.

### **2.11 Analysis of variance.**

When there are several test samples, ANOVA is used to identify statistically significant variations between their means treatments. For trials with only two samples, the t-test is adequate to identify statistically significant differences in

treatment means. To test the hypothesis, we require at least one mean treatment value ( $\mu$ ).

Different from the others. Thus, the null and alternative hypotheses can be stated as

$$H_0 = \mu_1 = \mu_2 = \dots = \mu_k = 0 \quad \dots\dots\dots\text{Equation 0-5}$$

The test approach includes both an ANOVA and an F-test. To determine the observed value, divide the treatment mean squares ( $MST_r$ ) by the error mean squares ( $MSE$ ), or error variance.

$$F_0 = \frac{MST_r}{MSE}$$

$$= \frac{\frac{SST_r}{a-1}}{\frac{SSE}{a(n-1)}} \quad \dots\dots\dots\text{Equation 0-6}$$

In this equation,  $SST_r$  represents the sum of squares of treatment,  $SSE$  represents the sum of squares of error,  $(a - 1)$  represents the degrees of freedom of the treatments,  $(n - 1)$  represents the degrees of freedom of the errors,  $a$  represents the number of treatments (number of samples), and  $n$  is the number of observations for a specific treatment. The total sum of squares ( $SST$ ) is calculated by adding the squares of treatment and the squares of error.

$$SST = SST_r + SSE \quad \dots\dots\dots\text{Equation 0-7}$$

Where  $y_{ij}$  is the  $j$ -th observation collected in treatment  $i$ , and  $\bar{y}$  is the overall average (grand mean) of all observations for each material group.  $\bar{y}_i$  represents the average value of observation in treatment.  $i$ , where  $a$  indicates the number of treatments (groups), and  $n$  is the number of observations for each treatment.

Material group	Observations				Averages
1	$y_{11}$	$y_{12}$	...	$y_{1n}$	$\bar{y}_1$
2	$y_{21}$	$y_{22}$	...	$y_{2n}$	$\bar{y}_2$
⋮	⋮	⋮	...	⋮	⋮
<b>a</b>	$y_{a1}$	$y_{a2}$	...	$y_{an}$	$\bar{y}_a$
					$\bar{y} = \frac{\sum_{i=1}^a \bar{y}_i}{a}$

After calculating  $F_0$ ,  $H_0$  can be accepted or denied in the following scenarios:

$$H_0 \text{ is } \begin{cases} \text{Rejected if } F_0 > F_{\alpha, (a-1), a(n-1)} \\ \text{Accepted if } F_0 < F_{\alpha, (a-1), a(n-1)} \end{cases} \dots\dots\dots \text{Equation 0-8}$$

If the observed value of  $F_0$  is greater than the critical values of  $F_{\alpha, (a-1), a(n-1)}$ , then  $H_0$  is rejected. The important value is determined from the statistical table for significance level  $\alpha$  and degrees of freedom, where the numerator (a - 1) has one degree of freedom and the denominator (a - 1) has two degrees of freedom. If the observed value ( $F_0 < F_{\alpha, (a-1), a(n-1)}$ ) is less than the essential value, then  $H_0$  is accepted. Using the p-value technique in statistics, If  $p < \alpha$ ,  $H_0$  will be rejected; if  $p > \alpha$ , it will be accepted.

**2.11.1 Choice of Design Factors.**

One, two, three, or more components can be included in a factorial experiment. Typically, simple comparative tests consist of just one element. The t-test or ANOVA was used to analyze the data. Two-level factorial designs are commonly used for identification in factorial experiments with two components (A and B). The impact of each potential factor combination on the response variable is investigated. The term factor effect describes the shift in the response variable brought about by altering a factor's amount.

### 2.11.2 Box-Behnken Designs

Box-Behnken designs are second-order designs that use three-level incomplete factorials and are rotatable or almost rotatable. Three components can be represented graphically in two ways:

The number of experiments (N) needed for the formation of BBD is defined as

$$N = 2k(k - 1) + C_0 \quad \dots\dots\dots\text{Equation 0-9}$$

Where  $k$  is number of factors and  $C_0$  is the number of central points)

Compared to other response surface designs (central composite, Doehlert matrix, and three-level full factorial), the BBD and Doehlert matrix are slightly more efficient than the central composite design, but significantly more efficient than the three-level full factorial designs. A single experimental design's efficacy is determined by dividing the estimated model's number of coefficients by the number of trials.

Comparison of BBD efficiency and response surface designs for the quadratic model. It also demonstrates that three-level full factorial designs are expensive when the factor count surpasses two.

The BBD also has the advantage of rejecting combinations in which all components are at maximum or lowest values at the same time. These designs are particularly effective at avoiding experiments undertaken under harsh conditions, which may produce unexpected findings. They are not suitable for scenarios in which we need to know the answers at the extremes; that is, the cube's vertices.

BBDs for four and five factors can be divided into orthogonal blocks.

The BBD is beneficial to the response surface technique since it allows for the following: calculating quadratic model parameters, developing sequential designs, detecting model lack of fit, and employing blocks.

A comparison of the BBD with different response surface designs (central composite, Doehlert matrix, and three-level complete factorial design) revealed that the Box-Behnken design and Doehlert matrix are slightly more efficient.

Techniques that include picking process combinations for optimization without taking into account adequate experimental designs are scientifically unreliable and irreproducible. Mathematical modeling, specifically response surface methodology, generates an accurate map that leads to effective optimization. The major process variables created the model and searched for solutions using Multivariate regression analysis, interpretation of the resulting polynomial equations, and response surface/contour plots are the first steps in modifying the core composite design to achieve process optimization. It also provided information on appropriate RSM software packages, RSM model order, and data economy in factorial trials, which resulted in a significantly reduced number of parameter combinations while keeping all information, including quadratic and interaction effects.

### **2.11.3 Benefits of using Box Behnken Designs.**

These designs enable efficient estimate of the first and second order coefficients. Because BBDs typically have fewer design points, they can be less expensive to apply than central composite designs with the same number of components. However, as they lack a factorial design, they are not appropriate for successive trials.

BBDs can be successful if you understand your process's safe operating zone. Axial points in central composite designs are often located outside the "cube". These points may be outside of the subject of interest or impossible to carry out owing to exceeding safe operating parameters. Box-Behnken designs do not contain axial points, thus you can be certain that all design points are within your safe operating

zone. BBDs additionally ensure that not all parameters reach their maximum values simultaneously.

## CHAPTER THREE

### MATERIALS AND METHODS

Physical and combustion properties were determined for blended briquettes of eucalyptus sawdust, maize stalks, and coffee husk waste, which required the following materials.

#### 3.1 Preparation of Materials

The basic components for the mixed briquettes included eucalyptus sawdust, coffee husks, and maize stalks. They were picked, sun-dried to minimize moisture content, and weighed based on the experiment runs.

Figure 0-1, to Figure 0-3 show samples of eucalyptus sawdust, coffee husks and maize stalks respectively before drying and grinding. Figure 0-4 shows the process of sample preparation and the mixing machine apparatus for use.



Figure 0-1: Image of eucalyptus Sawdust sample.



Figure 0-2: Image of Coffee husk sample



Figure 0-3: Image of Maize stalks sample

The mixing apparatus is a prefabricated square container fitted with a bearing and rotating handle. To ensure uniformity of mixing all samples were rotated with the same speed and fifteen turns before the molasses was added



Figure 0-4: Image of Mixing Equipment.

### **3.1.1 Preparation of eucalyptus sawdust.**

The following procedure was followed in preparation of eucalyptus sawdust.

- i. Eucalyptus Sawdust was sun-dry at an average temperature of 28 °C and relative humidity between 54%- 73% for ten days.
- ii. To produce eucalyptus sawdust particles smaller than 2 mm, it was ground using a crusher machine in Figure 0-5.
- iii. Finally, the ground eucalyptus sawdust was sieved and passed through a stainless steel mesh with a 2 mm opening.
- iv. The samples were measured using the digital scale as per the design of the experiment into six different samples and labeled.



Figure 0-5: Image of Crusher Machine.

Figure 0-5 shows a crusher machine for grinding sampled materials of coffee husk, eucalyptus sawdust, and maize stalks (Source: KIRDI Kisumu Lab)

### **3.1.2 Coffee Husk Preparation**

The following procedure was followed in preparation for the coffee husk

- i. Coffee husks were allowed to sun-dry at an average temperature of 28<sup>0</sup> C and relative humidity between 54%- 73% for ten days.
- ii. Coffee husks were ground using a crusher to give particles sizes of less than 2mm as per Figure 0-5.
- iii. The ground coffee husks were measured using the digital scale as per the design of the experiment.
- iv. Sixteen samples were labeled before mixing them.

### **3.1.3 Maize stalks Preparation**

The following procedure was followed in the preparation of maize stalks.

- i. Maize stalks were sun-dried for ten days with an average temperature of 28<sup>0</sup> C and relative humidity between 54%- 73% for ten days.
- ii. Then, the maize stalks were ground using a crusher to give a maximum of 2mm particle size as per Figure 0-5.

- iii. Finally, the ground maize stalks were measured using a digital scale, as per the experiment's design. Grinding the sample assisted in increasing its surface area, which supported the densification of the sampled briquettes.
- iv. The same was repeated for the remaining sample as per the design of the experiments.

#### **3.1.4 Molasses preparation.**

This investigation used commercial molasses. Five liters were purchased from the agrovet store and stored in the open lab and dry area of the workshop. It was black in color with a viscosity of 0.074 poise and density of 1.28 grams per cubic centimeter. In the current study, it was utilized as a binder during briquette manufacture, with a mass percentage of 10% in all briquettes made. To improve the viscosity of the molasses, a corresponding volume was added to it.

#### **3.1.5 Preparation of briquettes Sample**

- i. First, each sample were mixed using the fabricated mixing chamber.
- ii. The molasses was then added into the sample as the process of mixing by hand until we attained a uniform Mixture.
- iii. The mixture was fed into the pre-fabricated mold.
- iv. The fabricated mechanical mold with a plunger was used to form square briquettes with a compaction pressure of 3.5 bars.
- v. The same was done for all the remaining samples and labeled
- vi. The briquettes were dried in direct sunlight for 14 days.
- vii. Briquettes were stored in air-tight containers to avoid reabsorption of wet humidity.



Figure 0-6: Image of drying process of prepared briquettes.

Figure 0-6 shows the process of sun drying the prepared materials in order to reduce moisture content of prepared briquettes.

### 3.2 Determination of physical properties of Briquettes

#### 3.2.1 Density

Density is defined as the ratio of the mass and the volume of a sample. The volume of sampled briquetted was measure and recorded in Millimeters for length, width and height using Vernier Calibers

$$D = \left(\frac{M}{V}\right)$$

.....Equation0-1

where: D = Density; M = Mass; V = Volume

The masses of prepared briquettes were measured using the digital scale.

#### 3.2.2 Moisture Content

##### a) Moisture Content

The moisture content of the briquettes was assessed by drying a representative sample in an oven at a particular temperature and weighing it before and after drying. To determine the percentage moisture content (PMC). 2.5g of briquettes

were weighed, placed in a known mass crucible, and baked at  $105^{\circ}\text{C} \pm 5^{\circ}\text{C}$  for an hour.

To determine the moisture content of raw biomass, weight loss was estimated using the hot air oven drying method at  $105^{\circ}\text{C}$  to  $110^{\circ}\text{C}$  for one hour, resulting in a consistent weight loss. The contents were removed from the oven, let to cool to room temperature, and then reweighed. This procedure was continued until the weight after cooling remained consistent, which was recorded as the final weight. The sample's moisture content was determined using the equation 3-2 (Inegbedion and Ikpoza, 2022).

$$\text{MoistureContent}(\%) = \left( \frac{w_2 - w_3}{w_2 - w_1} \right) 100 \quad \dots\dots\dots\text{Equation 0-2}$$

where,

$w_1$  = weight of crucible, g

$w_2$  = weight of crucible + sample, g

$w_3$  = weight of crucible + sample, after heating, g



Figure 0-7: Image of Hot Air furnace.

Figure 0-7 shows a hot air furnace for measuring moisture content situated at Kirdi Labs Kisumu.

### 3.2.3 Calorific Value of Briquettes

The calorific value of the briquettes was evaluated with a bomb calorimeter. 1.5g of briquette sample was totally burned. The calorimeter and water absorbed the liberated heat. The heat lost by burning briquette was the heat absorbed by water and a calorimeter. The calorific value (CV) of the fuel was calculated from the measured data (Obi et al. 2013) using the equation 3-3

$$\text{Calorific Value (kCal/g)} = \left( \frac{\text{BFxt} - 2.3\text{lenthgwire}}{w} \right) \dots\dots\dots \text{Equation 0-3}$$

where: BF = Burn Factor

$\Delta t$  = Change of temperature ( $t_2 - t_1$ )

$t_2$  = final temperature.

$t_1$  = initial temperature.

W = mass of the sample used and BF = constant = 13,257.32

### 3.2.4 Operations of Bomb Calorimeter

Water was filled onto the outer bucket and a crusher was used to obtain a sample from each previously formed briquette and 1.5g was weighed using a digital scale of crushed sample and then placed into the crucible. The Ignition wire was installed and the bomb lid on the bomb head holder and connected just touched the sample, two ends of ignition wire should be hung on two conductive poles with slots (one of them is the crucible bracket. oxygen pipe was connected to the oxygen bomb and Gas valve was opened to fill the oxygen into the bomb slowly for around 30s. After Water was filled onto the inner bucket and an oxygen bomb was put on the bomb

seat in the inner bucket Close the cover of the outer bucket well. And lastly the temperature sensor was inserted and switched on the red power supply at the back of the instrument, and then the data was recorded for all the sixteen samples.



Figure 0-1: Images of Bomb Calorimeter

Figure 0-1 shows sampled photos of the operation of the bomb calorimeter during laboratory analysis of calorific value at KIRDI labs in Kisumu.

### **3.2.5 Ash Content:**

This was determined using a Muffle furnace by incinerating a representative sample and weighing the residual ash. 1.5g of the briquette's samples are kept in a closed furnace at 920 degrees and burnt completely. The weight of the residue was taken with an electronic digital balance scale (Davies and Abolude, 2013). The percentage weight of residue gives the ash contained in the sample (Washburn, 1933).The tests were done for all sixteen samples and recorded.

### **3.2.6 Volatile Matter Analysis.**

The dried samples in the crucible were covered with a lid and placed in a muffle furnace at  $920 \pm 30^{\circ}\text{C}$  for between 6-9 min. The crucible was cooled in the air, then placed into a desiccator and weighed again. Weight loss was reported as a volatile matter, expressed as a percentage.

$$\text{Volatile Matter (\%)} = \left( \frac{w_5 - w_6}{w_5 - w_4} \right) 100 \quad \dots\dots\dots \text{Equation 0-1}$$

where,

$w_4$  = weight of the empty crucible, g

$w_5$  = weight of empty crucible + sample, g

$w_6$  = weight of the crucible + sample after heating, g

### 3.2.7 Determination of Fixed Carbon

The percentage of fixed carbon (PFC) is given by equation 3.5;

$$\text{PFC (\%)} = 100\% - (\text{PMC} + \text{PVM} + \text{PAC}) \quad \dots\dots\dots \text{Equation 0-2}$$

where:

PFC - Percentage of Fixed Carbon

PMC - Percentage of Moisture Content

PVM - Percentage of Volatile Matter

PAC - Percentage of Ash Content

### 3.3 Briquetting Mold

For this Experiment, a square mold measuring 40 mm by 40 mm was fabricated from a square Hollow tube with a thickness of 3mm. The mold has a plunger at the top and a stopper at the lower end. The study used a simple household briquette molder that can be operated by a single person. The prepared sample was compressed using a pre-formed hand operated press. A premeasured mixed sample of briquettes was freely put onto a square Mold measuring 40mm by 40mm, and the mixture was pressed with a load of 3.5 bar for five minutes while maintaining the same force. Once a homogenous mixture of blended briquettes had been achieved.

The ingredients were compressed by shutting the molder's moveable upper half and pressing it down. The operator grips the handle in one hand. After that, the adjustable top is opened to retrieve the briquettes created and placed on trays for sun drying until ready for fuel consumption. Figure 0-2 depicts how materials were briquetted.



Figure 0-2: Briquetting Mold

### **3.4 Design of Experiments**

Experiment design and analysis were conducted using Design-Expert Software Version 10, Stat-Ease. The response surface methodology was utilized to investigate how burning affects the physical properties of mixed briquettes manufactured from coffee husks, maize stalks, and eucalyptus sawdust. The interaction of the parameters was also explored. There are two options for the in Design-Expert. The first option is a full design, while the second is a "small" design. The term "small" is only used when more than two components are present. In the current study, the tiny, which is the minimal-point designs required for term estimation in a second order model, was applied.

Response surface methodology is a set of statistical and mathematical approaches used to analyze the impacts of independent variables and determine the best conditions for a process (Mukherjee and Halder, 2016). The most frequent response surface methodology design matrices are CCD, Box-Behnken design, tiny CCD, and

orthogonal design, which includes fractional and 2k factorial design points (Box and Behnken, 1960; Dutta *et al.*, 2014), it may be efficiently utilized to fit experimental data to the second-order model (Dhawane *et al.*, 2018). Furthermore, RSM can accurately forecast the optimal condition with a small number of experimental runs (Dhawane *et al.*, 2015).

Table 0-1 shows design of experiment run with a total of sixteen run with different ratios of eucalyptus sawdust, maize stalks and coffee husks. The individual blended ratios are composed of different ratios and analysis of moisture content, gross calorific value, fixed carbon and volatile matter was investigated and recorded.

Table 0-1: Design of experiments for blended briquettes

	<b>Factor 1</b>	<b>Factor 2</b>	<b>Factor 3</b>	<b>Response 1</b>	<b>Response 2</b>	<b>Response 3</b>	<b>Response 4</b>
Run	A: Eucalyptus Sawdust (g)	B: Coffee Husks (g)	C: Maize Stalks (g)	Moisture Content (%)	Gross Calorific Value (kCal/g)	Fixed carbon (%)	Volatile Matter (%)
1	350	150	250				
2	150	350	250				
3	250	150	150				
4	150	250	150				
5	250	250	250				
6	150	150	250				
7	350	350	250				
8	250	150	350				
9	150	250	350				
10	250	250	250				
11	250	350	350				
12	350	250	350				
13	250	350	150				
14	250	250	250				
15	250	250	250				
16	350	250	150				

## CHAPTER FOUR

### RESULTS AND DISCUSSION

#### 4.1.1 Combustion and physical properties of eucalyptus sawdust, coffee husk, and Maize stalks Molasses

From the analysis of individual briquettes, moisture content ranges from 10.01 % and 12. 59%. Coffee husks gave the lowest MC which is an advantage in terms of being energy efficient (Emerhi, 2011). The Moisture content achieved is within the recommended ranges.

The volatile matter is between 71.25% and 78.30%. The fixed carbon range between 8.58% and 13.08%.The Calorific Value is between 3.8652 kCal/g and 4.2149 kCal/g.All the individual briquettes produced energy levels as per the past research done hence a clear indication that the process of preparation and analysis was good.

Table 0-1 shows the combustion properties of individual briquettes namely moisture content, gross calorific value, fixed carbon and volatile matter. These combustion properties fall within the recommended limits as others produced previously.

Table 0-1: Individual briquettes sample analysis

<b>Sample</b>	<b>Moisture Content (%)</b>	<b>Calorific Value (kCal/g)</b>	<b>Fixed Carbon (%)</b>	<b>Volatile Matter (%)</b>
Saw dust	10.45	4.1589	9.36	77.05
Coffee husks	10.01	4.2149	8.58	78.30
Maize stalks	12.59	3.8652	13.08	71.25

#### 4.1.2 Combustion and physical properties of Blended briquettes as per the design of experiments.

Table 0-2 shows the combustion properties of sixteen samples of pre formed briquettes. The moisture content of the sixteen samples ranged between 9.65% and 12.6%. Gross calorific value ranges between 4.0712 kCal/g and 4.4678 kCal/g, fixed carbon ranged between 2.22% and 12.36% and Volatile matter between 72.42% and 83.95% respectively. Blended briquette's showed superior qualities of combustions properties as compared with indivial briquettes.

Table 0-2: Combustion properties of blended briquette.

	<b>Factor 1</b>	<b>Factor 2</b>	<b>Factor 3</b>	<b>Response 1</b>	<b>Response 2</b>	<b>Response 3</b>	<b>Response 4</b>
Run	A: Eucalyptus Sawdust (g)	B: Coffee Husk (g)	C: Maize stalks (g)	Moisture Content (%)	Gross Calorific Value (kCal/g)	Fixed Carbon (%)	Volatile Matter (%)
1	350	150	250	9.65	4.4180	4.75	83.59
2	150	350	250	10.21	4.2151	7.32	79.65
3	250	150	150	10.17	4.2361	12.36	72.42
4	150	250	150	10.82	4.2390	6.40	79.88
5	250	250	250	12.60	4.1623	11.54	73.50
6	150	150	250	11.26	4.0712	12.11	74.01
7	350	350	250	10.16	4.2096	5.06	82.43
8	250	150	350	12.28	4.1307	2.22	82.51
9	150	250	350	11.38	4.1814	8.89	77.07
10	250	250	250	12.60	4.1625	11.32	74.05
11	250	350	350	11.63	4.4584	5.08	80.63
12	350	250	350	10.84	4.0765	6.03	80.62
13	250	350	150	11.57	4.4678	3.59	82.14
14	250	250	250	12.60	4.1620	12.09	73.98
15	250	250	250	12.60	4.1629	11.51	73.06
16	350	250	150	11.39	4.3781	8.04	76.70

## 4.2 Effects of mix ratios on the Gross Calorific Value of blended briquettes using the 2FI Model.

### 4.2.1 ANOVA for 2FI Model Gross Calorific Value.

Table 0-3: Gross Calorific value of blended briquettes

Source	Sum of squares	Df	Mean squares	F Value	P value	
Model	0.1069	6	0.0178	8.13	0,0111	Significant
A Sawdust	0.0022	1	0.0022	0.9989	0.3592	
B Coffee Husk	0.0059	1	0.0059	2.68	0.1530	
C Maize Stalks	0.5819	1	0.0581	26.50	0.0021	
AB	0.0064	1	0.0064	2.93	0.1376	
AC	0.0108	1	0.0108	4.92	0.0685	
BC	0.0161	1	0.0161	7.35	0.0351	

The model's F-value of 8.13 indicates that it is significant. Due to noise, there was only a 1.11% possibility of an F-value this large occurring. P-values < 0.0500 imply that model terms are significant for the analysis of gross calorific value. In this experiment, C and BC are key model terms. Values larger than 0.1000 show that the model terms are not significant.

Fit Statistics:  $R^2 = 0.8904$ ; C.V % = 1.12; Adequate Precision = 11.4238

The  $R^2$  value of 0.8904 lies in the acceptable range of 0.75 – 1.0 (Mukhopadhyay *et al.*, 2013), and indicates that 89.04% of variation of the results can be explained by this model.

Coefficient of variance (C.V.) is an indicator of the reliability of the experiment (Rasouli *et al.*, 2015). A C.V. value whose percentage is less than 10% is reproducible (Šumić *et al.*, 2016). The C.V. % for this experiment was 1.12%, and hence it is reproducible.

Adequate Precision measures signal-to-noise ratio, in the analysis of gross calorific value it was 11.424 for the analysis of Gross Calorific Value. A ratio greater than 4 indicates that external interference is negligible. The ratio of 11.424 attained shows a sufficient signal. This model can help explore the design space.

#### **4.2.2 Final Equation in Terms of Actual Factors**

$$\text{GrossCalorific Value} = +3.07535 + 0.003270A + 0.003703B + 0.002574C - 5.28535E - 06 AB - 6.84235E - 06 AC - 8.06288E - 06 BC \dots\dots \text{Equation 0-1}$$

where: A, B and C are eucalyptus Sawdust, Coffee Husks and Maize stalks respectively.

Equation 4-1 can be used to forecast the response for given element values, with levels provided in the factor's original units. This equation should not be used to calculate each element's relative influence because the coefficients have been scaled to match the units of each factor, and the intercept is not located in the center of the design space.

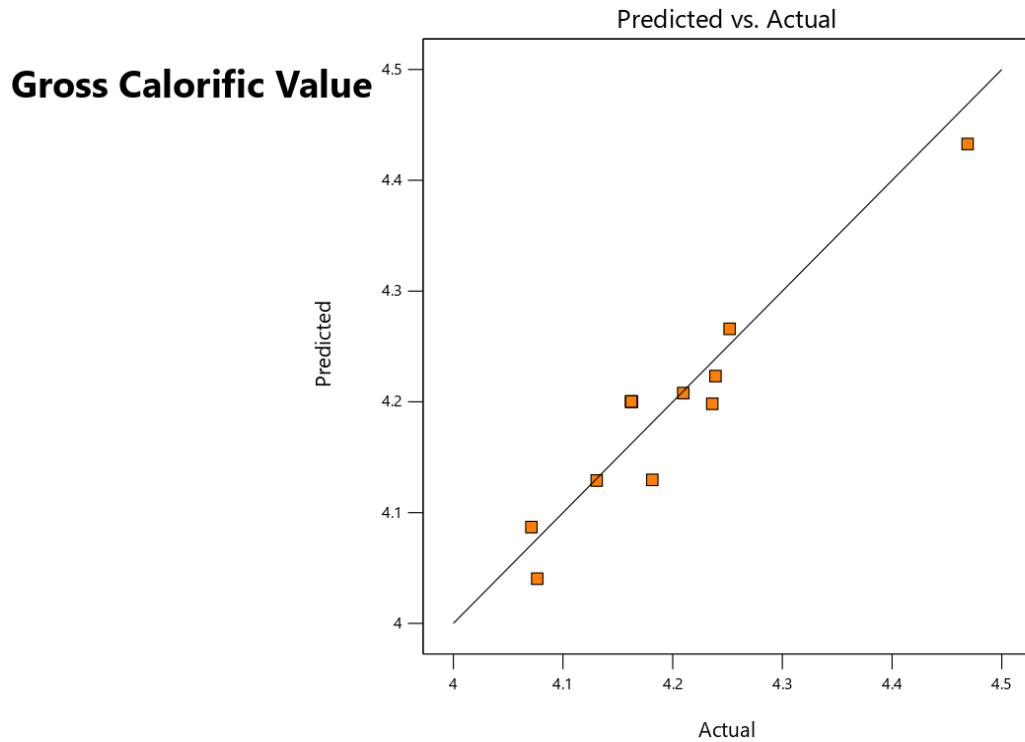


Figure 0-1: A graph of projected calorific value versus experimental results.

Figure 0-1 shows the projected gross calorific value plotted against the experimental results. As shown, the actual and predicted fixed carbon have a good degree of agreement ( $R^2 = 0.8904$ ), showing that the model is significant and adequate to replicate the experimental data in the range under consideration. Also, the graph shows that most points are split evenly by the 45-degree line, therefore the projected values are near to the actual ones. The data also does not contain values that deviate significantly from the diagonal line.

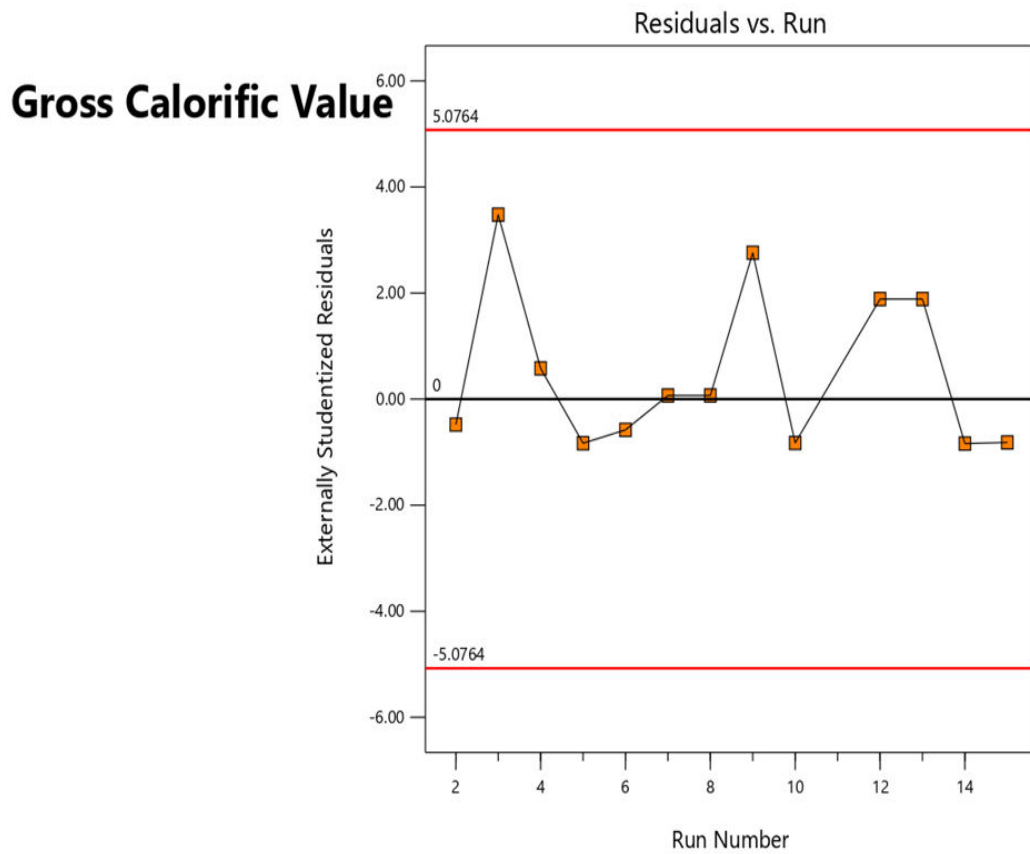


Figure 0-2: A graph of externally studentized residuals versus the run number.

The externally studentized residuals are plotted versus the run number in Figure 0-2. another sign of the 2FI Model's sufficiency is the residuals' random distribution around the line.

Factor Coding: Actual

Gross Calorific Value (Kcal/g)

● Design Points

- - -95% CI Bands

X1 = A

X2 = B

Actual Factor

C = 250

■ B- 150

▲ B+ 350

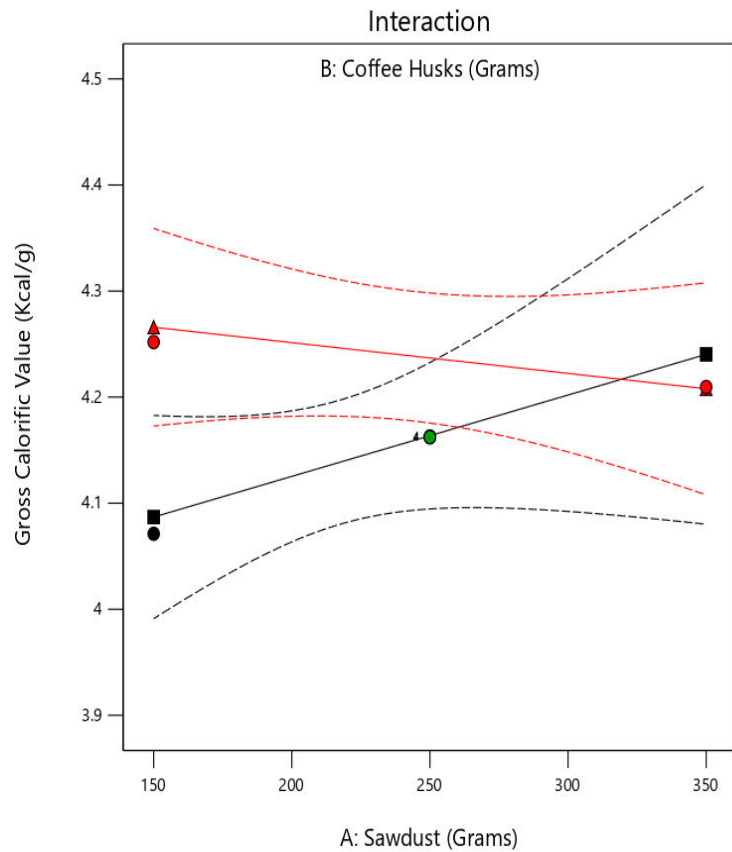


Figure 0-3: A graph of two factor interaction plots between coffee husks and eucalyptus sawdust.

The link between coffee husks and eucalyptus sawdust in the analysis of gross calorific value is shown Figure 0-3. The graph shows that the lines linking the data points indicating different amounts of coffee husks are not parallel across the levels of eucalyptus sawdust. The lines also intersect, indicating a strong interacting effect, which means that the relationship between eucalyptus sawdust and coffee husks and the response variable varies depending on the level of the other factor.

Factor Coding: Actual

Gross Calorific Value (Kcal/g)

● Design Points  
- - -95% CI Bands

X1 = A  
X2 = C

Actual Factor

B = 250

■ C- 150  
▲ C+ 350

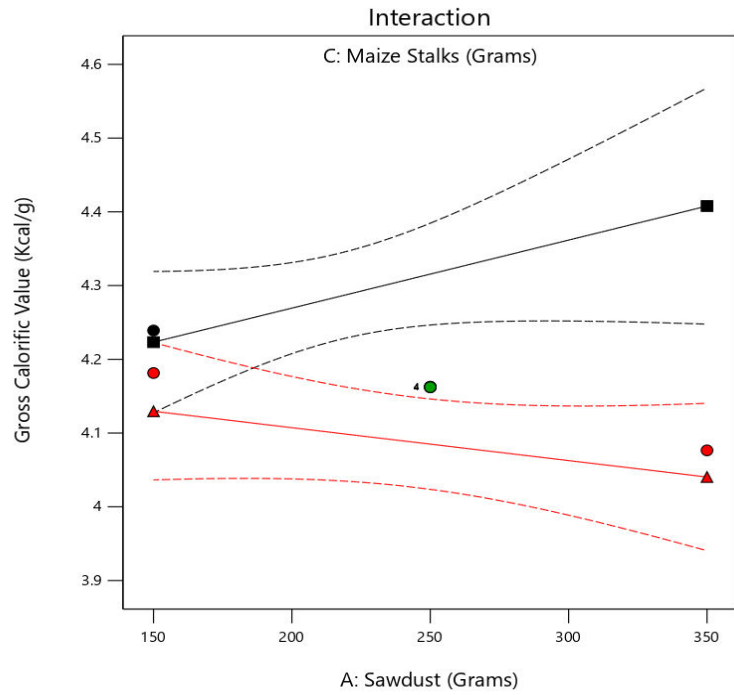


Figure 0-4: A graph of a two-factor interaction between maize stalks and eucalyptus sawdust.

Factor Coding: Actual

Gross Calorific Value (Kcal/g)

● Design Points  
- - -95% CI Bands

X1 = B  
X2 = C

Actual Factor

A = 250

■ C- 150  
▲ C+ 350

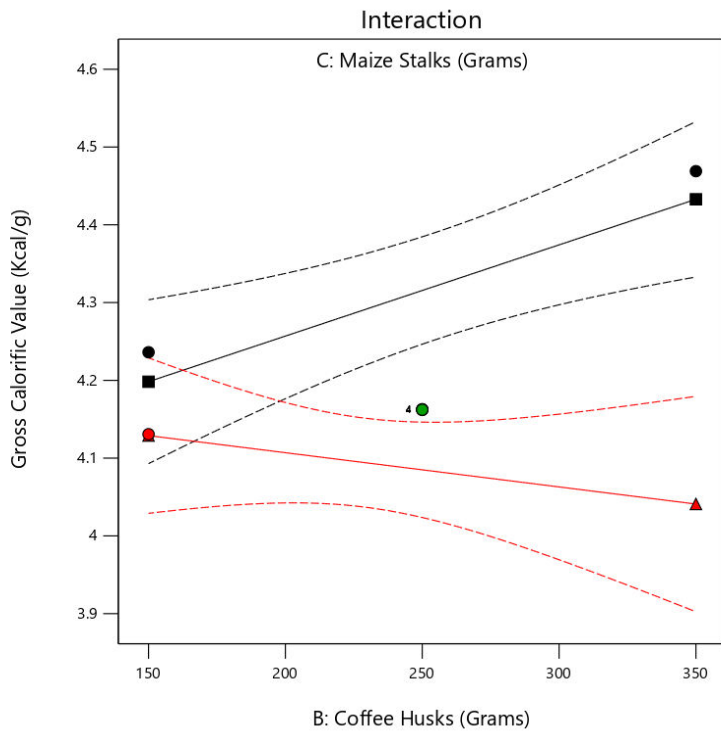


Figure 0-5: A graph of two-factor interaction plots for Maize stalks and coffee husks.

Figure 0-5 shows that there is an interaction between maize stalk and coffee husks on the analysis of gross calorific value. The bars in the interaction graphs are used to determine if a difference between two means exists. There is a high likelihood of significant differences in predictions if there is no overlapping. If the lines are parallel (do not cross each other) in the interaction plots, then there is an indication that the effect of one factor is dependent upon the level of the other (Abdul-Wahab and Abdo, 2007). The amount of heat produced by the mass (weight) in the calorimeter during complete combustion with oxygen is known as the calorific value.

### 4.3 Effects of mix ratios on the Fixed Carbons on blended briquette using Reduced Cubic Model.

#### 4.3.1 ANOVA for Reduced Cubic model

##### Fixed Carbon

Table 0-4: ANOVA for Reduced cubic model for Fixed carbon

Source	Sun of squares	Df	Mean square	F value	P Value	
Model	176.40	12	14.70	133.96	0.0009	Significant
A Sawdust	0.37	1	0.37	3.39	0.1628	
B Coffee Husks	8.73	1	8.73	79.55	0.0030	
C Maize Stalks	18.71	1	18.71	170.41	0.0010	
AB	6.50	1	6.50	59.24	0.0046	
AC	5.06	1	5.06	46.12	0.0065	
BC	33.81	1	33.81	308.06	0.0004	
A <sup>2</sup>	7.71	1	7.17	70.28	0.0036	
B <sup>2</sup>	34.02	1	34.02	309.91	0.0004	
C <sup>2</sup>	33.32	1	33.32	303.57	0.0004	
A <sup>2</sup> B	0.25	1	0.25	2.33	0.2244	
A <sup>2</sup> C	10.42	1	10.42	94.93	0.0023	
AB <sup>2</sup>	8.82	1	8.82	80.35	0.0029	

The model's F-value of 133.96 indicates that it is significant. There is only a 0.09% probability that this high F-value will occur due to noise.

P-values < 0.0500 imply that model terms are significant. Key model terms include B, C, AB, AC, BC, A<sup>2</sup>, B<sup>2</sup>, C<sup>2</sup>, A<sup>2</sup>C, and AB<sup>2</sup>. Values larger than 0.1000 show that the model terms are not significant.

### 4.3.2 Fit Statistics

The R<sup>2</sup> = 0.9981, CV 4.13% and Adequate precision = 33.954 are all in the acceptable range, and hence the model is acceptable.

### 4.3.3 Final Equation in Terms of Actual Factors

$$\begin{aligned}
 \text{Fixed Carbon} = & 12.79594 + 0.261387A - 0.2133681B + 0.220781C + \\
 & 0.000999AB - 0.001254AC + 0.000291 BC - 0.000799 A^2 + 0.000233B^2 - \\
 & 0.000289C^2 + 3.57500E - 07A^2B + 2.28250E - 06A^2 C - 2.1000E - \\
 & 06AB^2 \dots\dots\dots \text{Equation 0-2}
 \end{aligned}$$

where:

A: eucalyptus sawdust

B: Coffee husks

C: Maize stalks

The equation in terms of actual factors can be used to predict the response at different levels of each element. The levels for each constituent should be displayed in their original units. This equation should not be used to calculate each element's relative influence because the coefficients have been scaled to match the units of each factor, and the intercept is not located in the center of the design space.

## Fixed Carbon

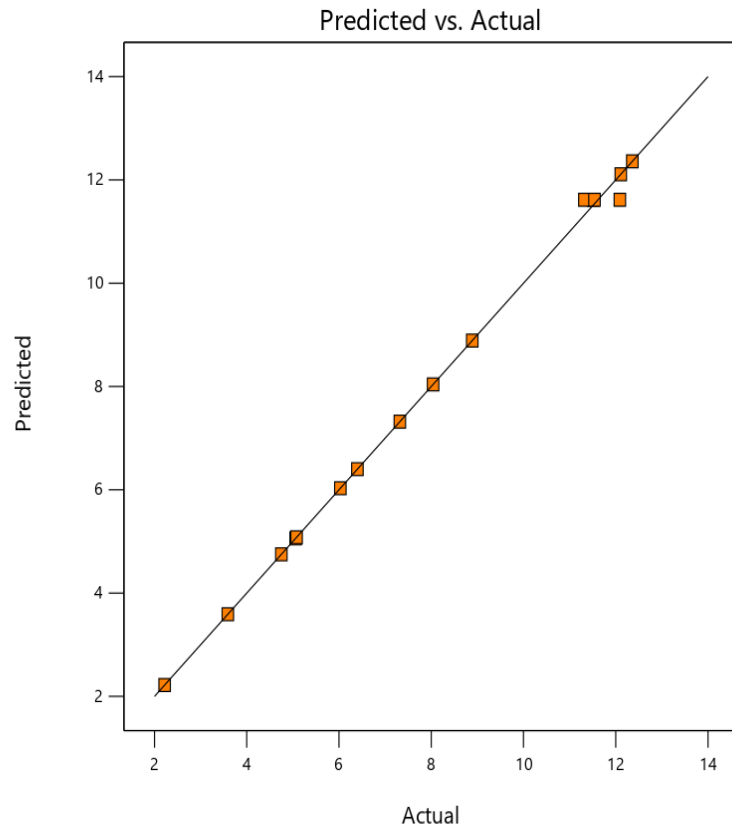


Figure 0-6: A graph of Predicted Fixed versus Actual fixed Carbon of blended briquettes

Figure 0-6 depicts the expected fixed carbon values plotted against the experimental results. The observed good agreement ( $R^2 = 0.9981$ ) between actual and expected fixed carbon suggests that the model is substantial and sufficient to represent the experimental results in the area under consideration. Also, the graph shows that most points are split evenly divided by the 45-degree line, therefore projected values are near to actual ones. The data does not have values that deviate significantly from the diagonal line.

Factor Coding: Actual

**Fixed Carbon**

- Design Points
- - - .95% CI Bands

X1 = A

X2 = B

**Actual Factor**

C = 250

- B- 150
- ▲ B+ 350

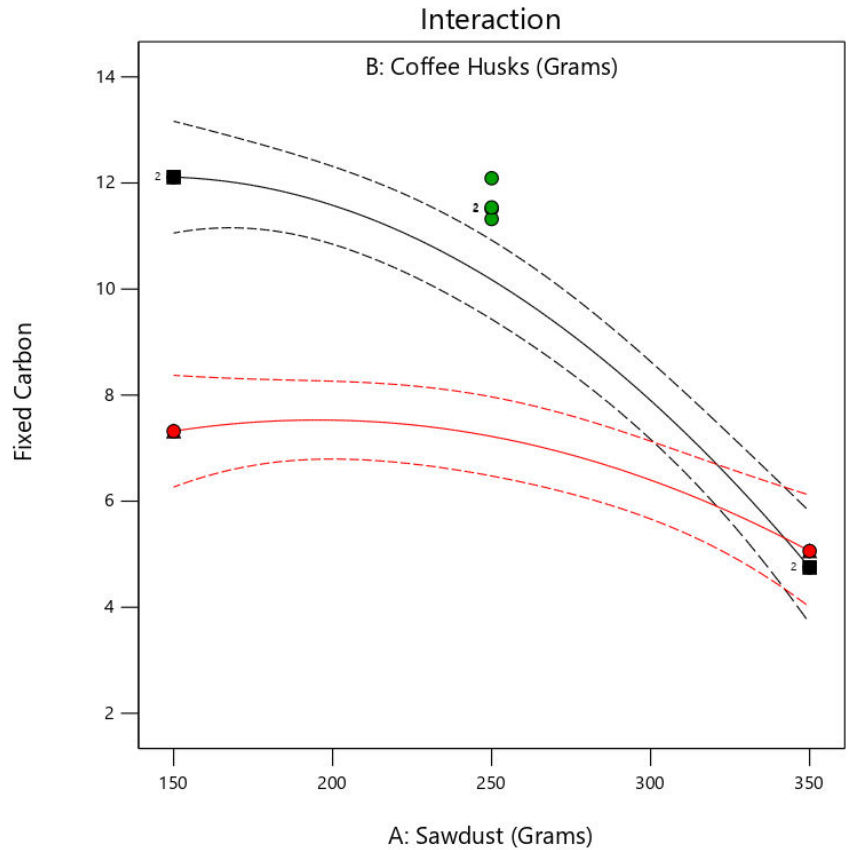


Figure 0-7: A graph of two factor interaction plots between coffee husk and eucalyptus sawdust

Figure 0-7 depicts the interaction of coffee husks and eucalyptus sawdust in the measurement of fixed carbon. The graph shows that the lines linking the data points indicating different amounts of coffee husks are not parallel across the levels of eucalyptus sawdust. The lines also intersect, which strongly shows an interaction effect, implying that the relationship between eucalyptus sawdust and coffee husks and the response variable varies depending on the degree of the other element.

Factor Coding: Actual

**Fixed Carbon**

● Design Points

- - -95% CI Bands

X1 = A

X2 = C

**Actual Factor**

B = 250

■ C- 150

▲ C+ 350

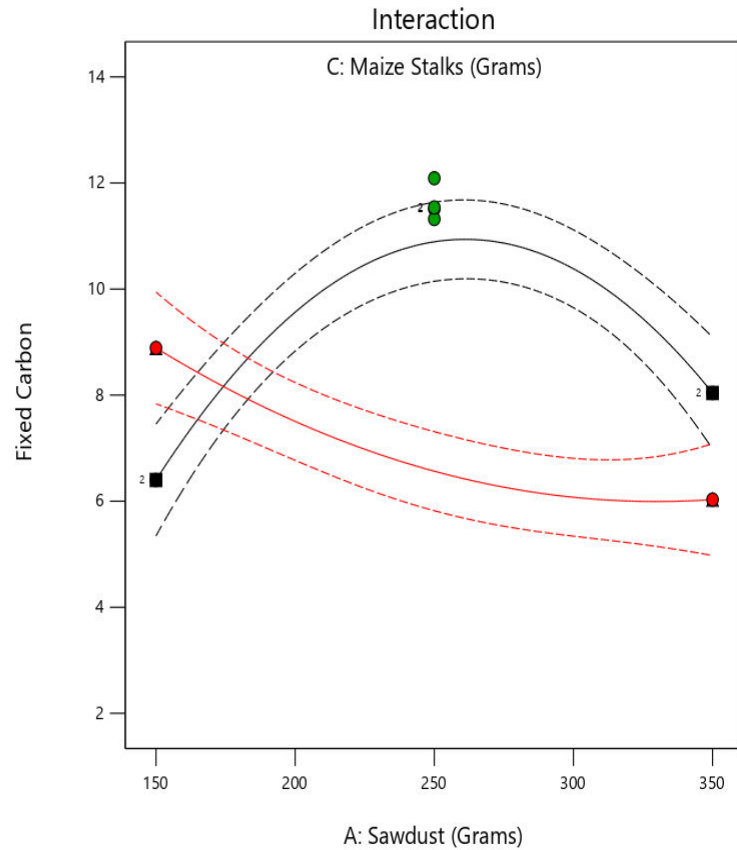


Figure 0-8: A graph of two factor interaction between maize stalks and eucalyptus sawdust

Figure 0-8 depicts the interaction of maize stalks and eucalyptus sawdust in the study of fixed carbon. The graph shows that the lines linking the data points indicating different amounts of coffee husks are not parallel across the levels of eucalyptus sawdust. The lines also intersect, indicating a strong interaction effect. This implies that there is a link between eucalyptus sawdust and coffee husks and the response variable varies depending on the level of the other factor.

Factor Coding: Actual

**Fixed Carbon**

● Design Points

- - -95% CI Bands

X1 = B

X2 = C

**Actual Factor**

A = 250

■ C- 150

▲ C+ 350

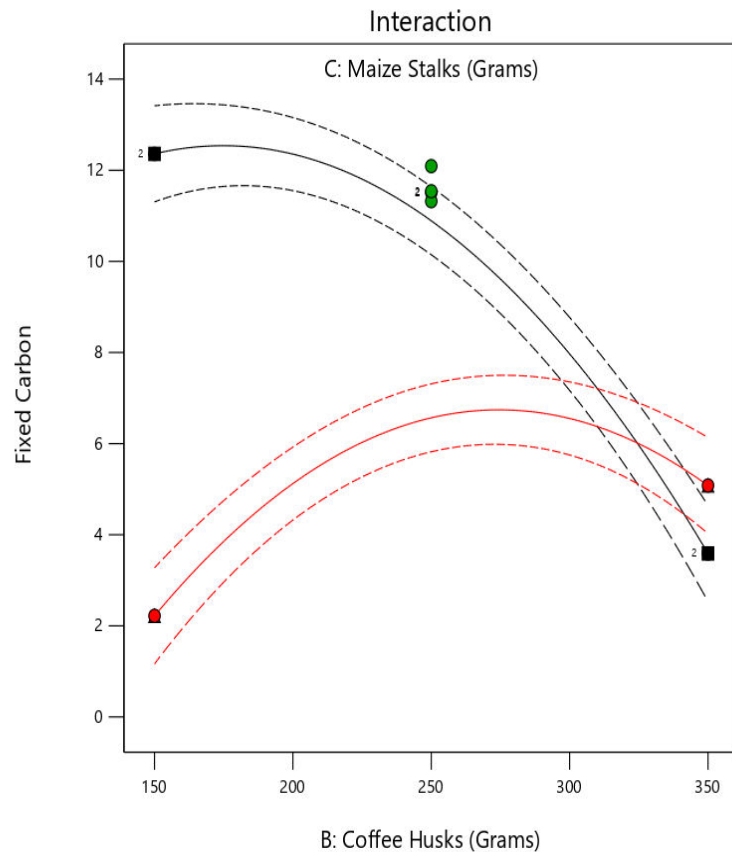


Figure 0-9: A graph of two factor interaction between maize stalks and coffee husks

To investigate fixed carbons, the two-factor interaction plots maize stalks and coffee husks was plotted to see if there is a difference between two means, the interaction graphs. Figure 0-9 depicts the interaction of maize stalks and coffee husk in the study of fixed carbon. The graph shows that the lines linking the data points indicating different amounts of coffee husks are not parallel across the levels of eucalyptus sawdust. The lines also intersect, indicating a strong interaction effect. This means that the relationship between eucalyptus sawdust and coffee husks and the response variable varies depending on the level of the other factor.

Fixed carbon represents a fuel's thermal value and serves as the primary heat source during combustion. It also displays the proportion of char left after the volatile ingredient is eliminated. It provides a general approximation of a fuel's heating value and works as the primary heat generator during combustion (Akowuah *et al.*, 2012).The

fixed carbon observed in this study (7.42% to 7.51%) is relatively within the recommended as reported by (Adegoke *et al.*, 2010; Emerhi, 2011). A good quality and efficient fuel briquette depends on lower volatile matter and ash content and a higher fixed carbon content (Asamoah *et al.*, 2016), in collaboration with the results of this investigation. The percentage of fixed carbon content in briquettes is an important factor in determining the calorific value of fuel (Thabuot *et al.*, 2015). The amount of fixed carbon increases in proportion to the carbon composition in the mixed ratio. This is compatible with the assertion of who said that high fixed carbon implies high calorific value and thus an indication of easy ignition and proportionate increase in flame length (Onukak *et al.*, 2017).

The percentage of fixed carbon content in briquettes is an important factor in determining the calorific value of fuel (Thabuot *et al.*, 2015). The amount of fixed carbon increases in proportion to the composition in the mixed ratio. This is compatible with the assertion of (Onukak *et al.*, 2017) who said that "high fixed carbon implies high calorific value and thus an indication of easy ignition and proportionate increase in flame length. The quality of bio-briquettes improves as the fixed carbon value rises. Fixed carbon serves as a primary source of heat during combustion. Low fixed carbon reduces the caloric energy of the briquettes. The more the fixed carbon, the better the charcoal produced, as the related calorific energy is high (Veeresh and Narayana, 2012)

#### 4.4 Effects of mixing ratios on the moisture content of blended briquettes using Reduced Quadratic Equation.

##### 4.4.1 ANOVA for Reduced Quadratic model

Table 0-5: ANOVA for reduced Quadratic equation for moisture content.

Source	Sum of squares	Df	Mean Square	F value	P Value	
Model	12.570	6	2.0900	8.470	0.0027	Significant
A sawdust	0.331	1	0.3321	1.340	0.2762	
B Coffee Husks	0.005	1	0.0055	0.022	0.8846	
C Maize Stalks	0.594	1	0.5490	2.400	0.1555	
BC	1.050	1	1.0500	4.250	0.0693	
A <sup>2</sup>	6.680	1	6.6800	27.030	0.0006	
B <sup>2</sup>	3.900	1	3.9000	15.780	0.0032	
Residual	2.220	9	0.2472			
Lack of fit	2.220	6	0.3708			
Pure Error	0.000	3	0.0000			

The model's F-value of 8.47 indicates that it is significant. There is only a 0.27% probability that an F-value of this magnitude will occur due to noise. The F-value for each component ranges between 0.0223 and 2.40. The overall F-value is 4, which is the acceptable limit, indicating significance and the feasibility of running the analysis.

The model terms are significant, as indicated by the P-value of 0.0027, which is less than 0.0500. Important model terms are A<sup>2</sup> and B<sup>2</sup>. Values greater than 0.1 indicate that the model terms are not significant.

#### 4.4.2 Fit Statistics

Standard Deviation = 0.4972 ;  $R^2 = 0.8496$ ; Adequate Precision = 7.6326

Adequate Precision assesses the ratio of the signal to noise. It is better if the ratio is more than 4. The 7.633 ratio indicates a strong signal. With this model, the design space can be explored.

#### 4.4.3 Final Equation in Terms of Actual Factors

$$\text{Moisture Content} = 5.19063 + 0.062588A + 0.62450 B + 0.015537C - 0.000051BC - 0.000129 A^2 - 0.000099B^2 \dots \dots \dots \text{Equation 0-3}$$

where A, B and C are Eucalyptus Sawdust, Coffee Husks and Maize stalks respectively.

The response at various values of each element can be predicted using the equation expressed in terms of actual factors. Each constituent's levels ought to be shown in their original units. Since the intercept is not in the center of the design space and the coefficients are scaled to fit the units of each factor, this equation should not be utilized to determine the relative influence of each element.

## Moisture Content

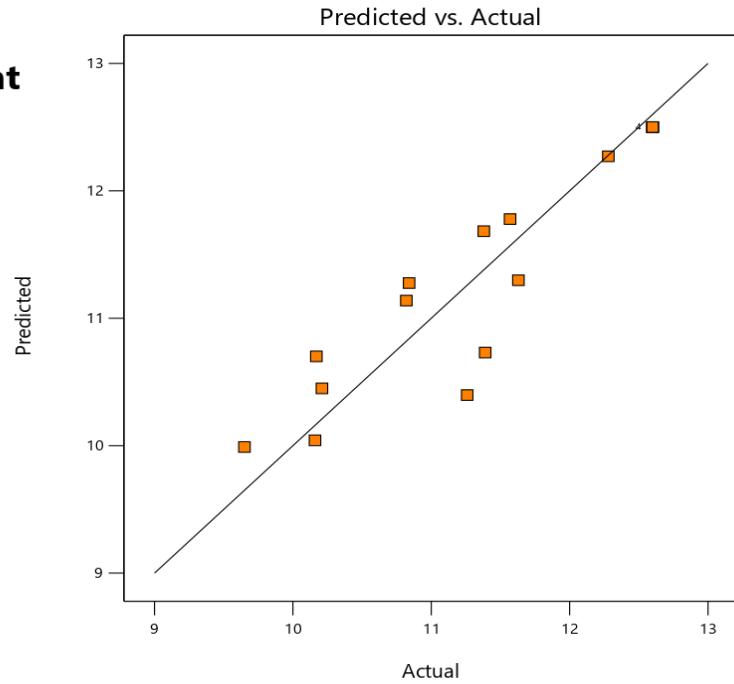


Figure 0-10: A plot of Expected moisture content versus Experimental results of blended briquettes.

Figure 0-10 shows a plot of expected moisture content versus experimental results. It is evident that a great agreement exists ( $R^2 = 0.8496$ ) between the actual and anticipated moisture content values, suggesting that the model is relevant and adequate therefore perfectly equipped to replicate the experimental results within the region under analysis. Additionally, the graph demonstrates that the 45-degree line splits most points uniformly, meaning that the predicted values are close to the real ones. There are no values in the data that substantially depart from the diagonal line.

## Moisture Content

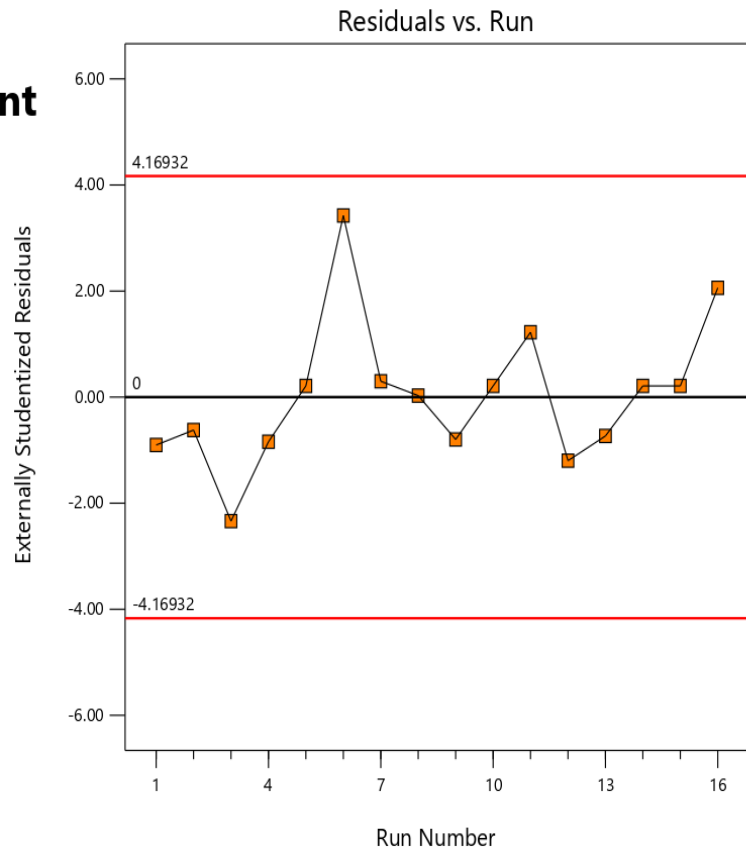


Figure 0-11: A plot of externally studentized residual versus run number in blended briquettes.

The externally studentized residuals are plotted versus the run number in Figure 0-11. The residuals are dispersed randomly around the line, which further suggests that the simplified quadratic model is adequate.

Factor Coding: Actual

Moisture Content (%)

● Design Points

- - -95% CI Bands

X1 = B

X2 = C

Actual Factor

A = 250

■ C- 150

▲ C+ 350

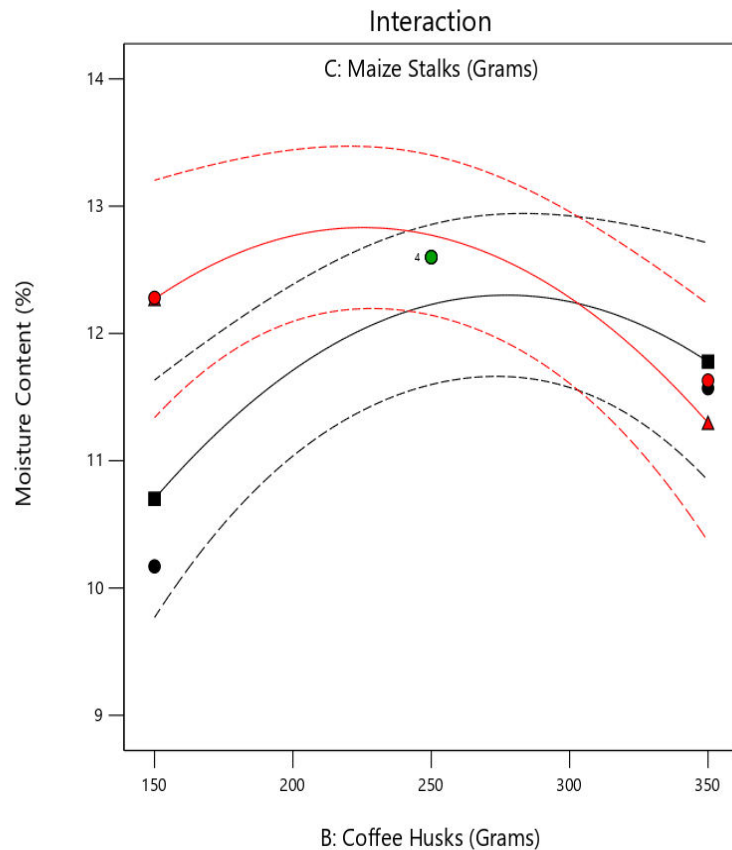


Figure 0-12: A graph of two factor interaction for Maize stalks and coffee husks

Figure 0-12 presents the interaction graph of maize stalks and coffee husks in the analysis of moisture content. From the graph the lines connecting the data points representing different levels of coffee husks are not parallel across the levels of eucalyptus sawdust. The lines also intersect hence its strongly indicates an interacting effect meaning the relationship between eucalyptus sawdust and coffee husks and the response variable varies depending on the other factor's level.

If the material moisture content is extremely low or extremely high (meaning outside the 8%-18% range), the elements are inconsistent and the briquette falls apart. The briquette breaks into pieces when the moisture content of the material is extremely high due to the evaporation of surplus water. Higher pressures must be used to obtain briquette quality when the material moisture content is very low (less than 8%), which is very costly and unfeasible. Therefore, the drying procedure should be used

to reduce the material's moisture content before briquetting. Lower moisture content improves the quality of briquettes (Chaney, 2010). The observed moisture content indicates that the produced briquettes are easily ignited and higher calorific values and superior quality are expected.

Briquette samples have moisture content that is consistent with those reported between 5% and 15% (Chaney, 2010) with the exception of composite uncarbonized briquette samples, for high-quality briquettes. Briquettes with high moisture content bloat and disintegrate, interfering with thermochemical conversion processes. A portion of the energy used during burning is used to evaporate the water, which lowers the briquettes' overall energy efficiency and produces low heating values. Additionally, incomplete combustion from biomass fuels' high moisture content results in increased greenhouse gas emissions.

Moisture content should be as low as feasible, often within the range of 10-15% (Grover and Mishra, 1996). High moisture content will cause problems in grinding (Kaliyan and Morey, 2009) and additional energy is necessary for drying (Ollet *et al.*, 1993).

## 4.5 Effects of mix ratios on the Volatile Matter of blended briquettes Using Reduced Cubic Model.

### 4.5.1 ANOVA for Reduced Cubic model

Table 0-6: ANOVA for reduced Cubic model for Volatile Matter

Source	Sum of squares	df	Mean Square	F square	P value	
Model	233.59	12	19.47	91.32	0.0017	Significant
A	0.03	1	0.03	0.16	0.7155	
Sawdust						
B Coffee	15.37	1	15.37	72.09	0.0034	
Husk						
C Maize	18.40	1	18.40	86.34	0.0026	
Stalks						
AB	11.56	1	11.56	54.23	0.0052	
AC	11.32	1	11.32	53.12	0.0053	
BC	33.64	1	33.64	157.82	0.0011	
A <sup>2</sup>	29.32	1	29.32	137.56	0.0013	
B <sup>2</sup>	50.84	1	50.84	238.49	0.0006	
C <sup>2</sup>	19.58	1	19.58	91.86	0.0024	
A <sup>2</sup> B	1.41	1	1.41	6.62	0.0823	
A <sup>2</sup> C	6.98	1	6.98	32.72	0.0106	
AB <sup>2</sup>	17.97	1	17.97	84.30	0.0027	

The model's F-value of 91.32 shows that it is significant. There is just a 0.17% probability that a F number this huge will increase due to noise.

P-values < 0.0500 indicate significant model terms. Key model terms include B, C, AB, AC, BC, A<sup>2</sup>, B<sup>2</sup>, C<sup>2</sup>, A<sup>2</sup>C, and AB<sup>2</sup>. Values above 0.1000 indicate that the model terms are unimportant. If the model has a large number of insignificant terms (excluding those required for hierarchy), model reduction may improve it.

#### 4.5.2 Fit Statistics

CV % = 0.5927; R<sup>2</sup> = 0.9973; Adequate Precision = 26.8405

Adequate precision is a measure of signal-to-noise ratio. A ratio greater than four is preferred. A ratio of 26.840 suggests a good signal. This model allows the exploration of the design space

#### 4.5.3 Final Equation in Terms of Actual Factors

*Volatile Matter* = 93.41937 – 0.285106A + 0.278538B – 0.175456C –  
0.001249AB + 0.001102AC – 0.000290BC + 0.000948A<sup>2</sup> – 0.000221C<sup>2</sup> –  
8.40000E – 07A<sup>2</sup>B – 1.8675 E – 06A<sup>2</sup>C + 2.9975E – 06AB<sup>2</sup> .....Equation 0-4

where:

A; sawdust

B: coffee husks

C; Maize stalks.

The reaction at particular values of each ingredient can be predicted using the equation expressed in terms of actual factors. Each element's levels ought to be shown in their original units. Since the intercept is not at the center of the design space and the coefficients have been scaled to match the units of each factor, this equation should not be used to calculate the relative influence of each element.

## Volatile Matter

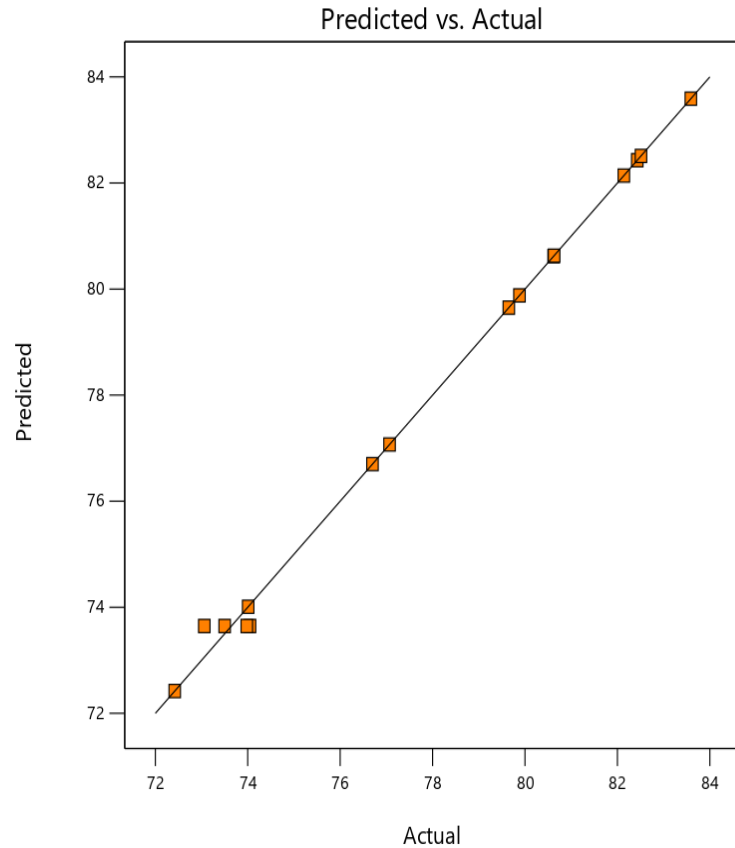


Figure 0-13: A plot of Predicted verse Actual Volatile Matter for Blended Briquettes

Figure 0-13 shows a plot of projected volatile matter against experimental data. The model's remarkable agreement ( $R^2 = 0.9973$ ) between predicted and actual moisture content values validates its effectiveness in reproducing experimental data within the explored range. Also, the graph shows that most points are split and the projected values are consequently close to the actual ones since they are distributed equally by the 45-degree line. The data does not have values that deviate significantly from the diagonal line. The amount of volatile material influences the burning behavior of fuels. Fuel with little volatile substance must be burned in powdered form; else, combustion will take a long time (Veeresh and Narayana, 2012).

Factor Coding: Actual

**Volatile Matter**

● Design Points

- - - 95% CI Bands

X1 = A

X2 = B

**Actual Factor**

C = 250

■ B- 150

▲ B+ 350

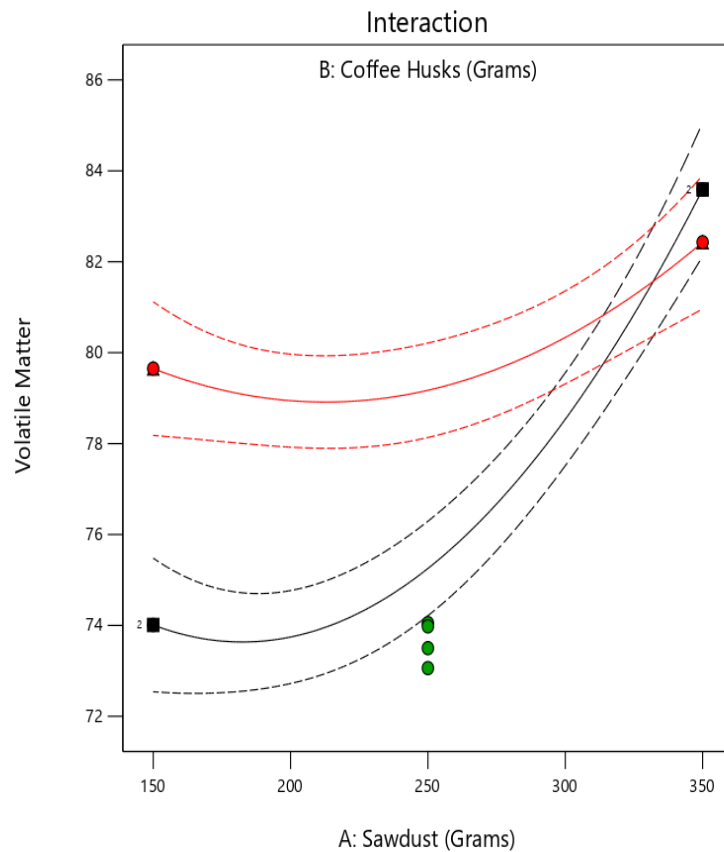


Figure 0-14: A plot of two-factor interaction on volatile matter between coffee husks and eucalyptus sawdust

Figure 0-14 demonstrates the interplay of coffee husks and eucalyptus sawdust in the study of Volatile Matter. The graph shows that the lines linking the data points indicating different amounts of coffee husks are not parallel across the levels of eucalyptus sawdust. The lines also intersect, indicating a strong interaction effect. This means that the relationship between eucalyptus sawdust and coffee husks and the level of the other element determines how the response variable changes.

Factor Coding: Actual

**Volatile Matter**

● Design Points

--- -95% CI Bands

X1 = A

X2 = C

**Actual Factor**

B = 250

■ C- 150

▲ C+ 350

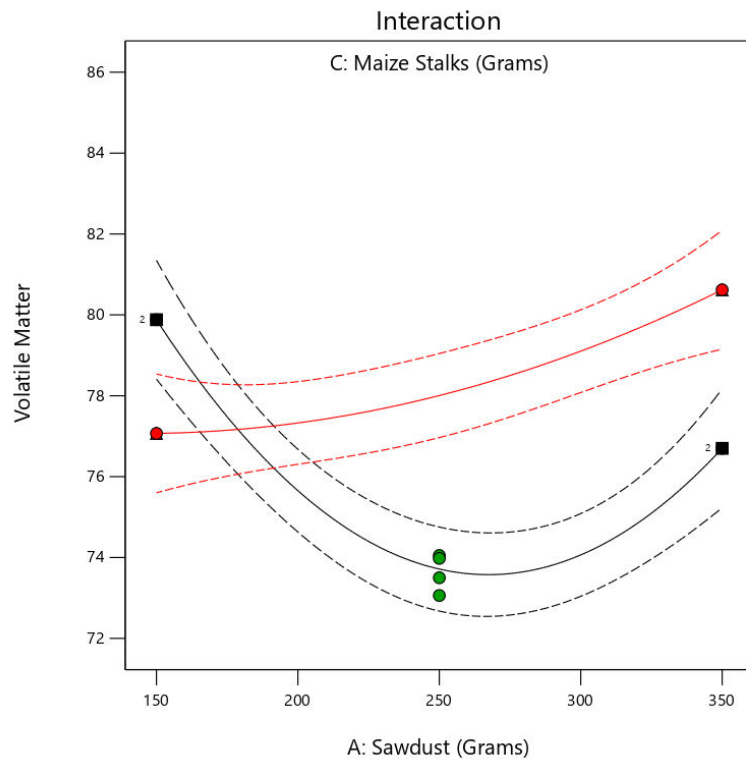


Figure 0-15: A plot of two factor interaction of Volatile Matter between Maize stalks and Eucalyptus Sawdust

Figure 0-15 demonstrates the interplay of maize stalks and eucalyptus sawdust in the study of Volatile Matter. The graph shows that the lines linking the data points indicating different amounts of coffee husks are not parallel across the levels of eucalyptus sawdust. The lines also intersect, indicating a strong interaction effect. This means that the relationship between eucalyptus sawdust and coffee husks and the level of the other element determines how the response variable changes.

Factor Coding: Actual

**Volatile Matter**

● Design Points

- - -95% CI Bands

X1 = B

X2 = C

**Actual Factor**

A = 250

■ C- 150

▲ C+ 350

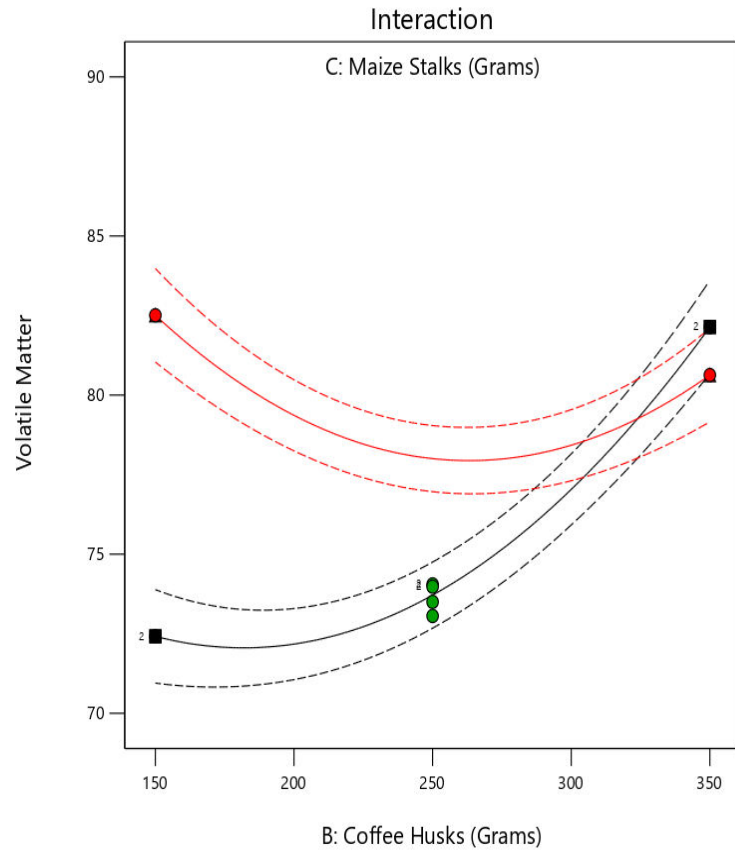


Figure 0-16: A plot of two factor interaction of Volatile Matter between Maize stalks and Coffee Husks

Figure 0-16 depicts the interaction of maize stalks and coffee husks in the study of Volatile Matter. The graph shows that the lines linking the data points indicating different amounts of coffee husks are not parallel across the levels of eucalyptus sawdust. The lines also intersect, indicating a strong interaction effect. This indicates that the degree of the other component influences the association between eucalyptus sawdust and coffee husks and the response variable.

The volatile matter in this study indicates easy ignition, fast burning, and a proportionate increase in flame length. High volatile matter of a briquette indicates ease of ignition, rapid burning, and proportionate increase in flame length, but low heating values (Inegbedion, 2022).

#### **4.6 Optimization of combustion properties of blended briquettes**

The ideal combustion parameters of blended briquettes were determined via numerical optimisation. Design-Expert® Software's optimization method is based on a technique created by Derringer and Suich (1980), as described in (Myers et al., 2009).

The parameters aims were designed to fall within the maximum range for fixed carbon and Gross calorific value. The parameter for Moisture content was also set to Minimum, within range for Volatile Matter of the design space, while the goal of the response was set to 'maximise', with lower and upper limits of 9.65 and 12.6 for Moisture Content, 4.0712 Kcal/g and 4.44689 kCal/g for Calorific Value, 2.22 and 12.36 for Fixed Carbon, and 72.42 and 83.59 for Volatile Matter, respectively. The ramping results, shown in Figure 4-17, were produced using the aforementioned optimization criteria and a response desirability of 0.894.

Figure 4-17 shows the desirability bar graph of the input variables and the response (Fixed carbon, Gross calorific value, fixed carbon and Volatile matter) while the optimization criteria is presented in Table 0-7. The starting points for optimization and solutions from optimization are presented in Table A-2 and Table A-3 respectively.

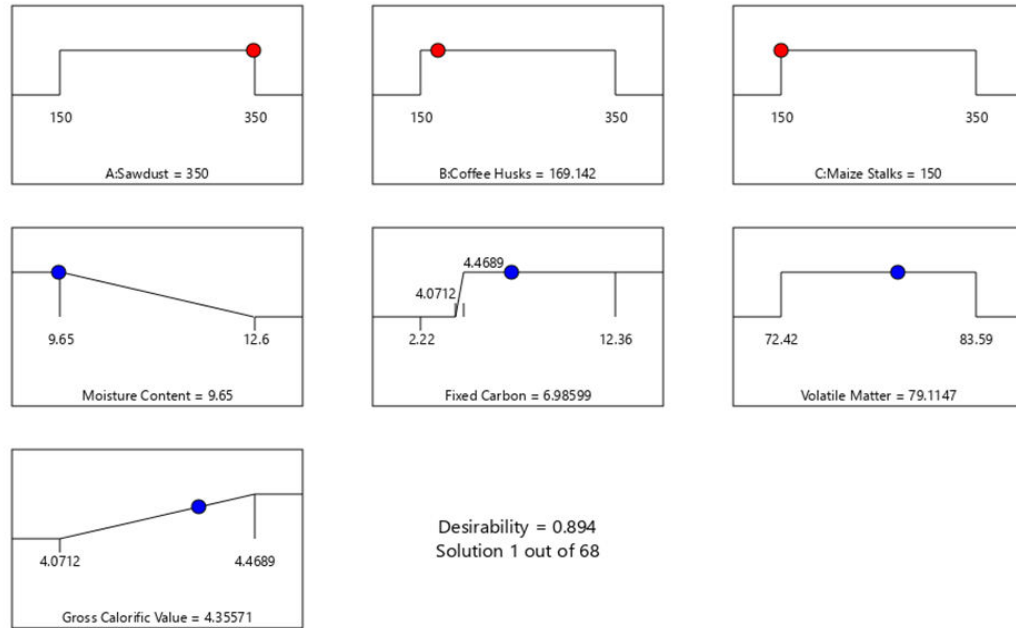


Figure 0-17: Schematic representation of Numerical optimization for Combustion properties

Table 0-7: Optimization matrix

Name	Goal	Lower Limit	Upper Limit
Moisture Content	Minimum	9.65	12.6
Gross Caloric value	Maximum	4.0712	4.4689
Fixed Carbons	Maximum	2.22	12.36
Volatile Matter	Within Range	72.42	83.59

The optimum blended ration was a combination of eucalyptus sawdust, coffee husk and maize stalks at a ratio of 350g, 169.142g, and 150g with a result of 9.65% moisture content, 6.98599% fixed carbon, 79.1147% volatile matter, and 4.35571 kCal/g Gross calorific value and a desirability of 0.894.

In the optimization of moisture content, this was capped at minimum point hence achieving 9.65%: Properly dried eucalyptus sawdust, maize stacks, and sugar cane

waste are commonly utilized to assure low moisture content in briquettes. Low moisture content promotes effective burning. Briquettes with moisture content less than 8% or greater than 18% are unsuitable for further combustion procedures.

The optimization of fixed carbon was capped at maximum because it approximates a fuel's thermal value and acts as the major heat source during combustion. It also shows the percentage of char that remains after the volatile substance is removed (Adegoke *et al.*, 2010; Akowuah *et al.*, 2012; Emerhi, 2011). It provides a general estimate of a fuel's heating value and functions as the major heat generator during combustion. A good quality and efficient fuel briquette depends on lower volatile matter and ash content and a higher fixed carbon content (Asamoah *et al.*, 2016) in collaboration with the results of this investigation. The optimization of volatile matter this was cap at within range.

## CHAPTER FIVE

### CONCLUSION AND RECOMMENDATIONS

#### 5.1 Conclusion

Blended briquettes were developed from coffee husks, maize stalks, and eucalyptus sawdust, measuring 45mm by 45mm by 35mm.

From the analysis of individual briquettes, Individual briquettes moisture content ranges from 10.01 % and 12. 59%. Coffee husks gave 10.01%, Maize stalks briquettes 12.59% and coffee husks 10.01. The Moisture content achieved is within the recommended ranges. The volatile matter is between 71.25% and 78.30% where eucalyptus sawdust gave 77.05%, coffee husks 78.30% and maize stalks 71.25%. The amount of volatile material influences the burning behavior of fuels. The fixed carbon ranges between 8.58% and 13.08%. Eucalyptus Sawdust gave 9.36%, coffee husks 8.58% and maize stalks at 13.08%. The quality of bio-briquettes improves as the fixed carbon value rises. Fixed carbon serves as a primary source of heat during combustion. The Calorific Value is between 3.8652 kCal/g and 4.2149 kCal/g. Eucalyptus sawdust generated 4.1589 kCal/g, Coffee Husks 4.2129 kCal/g, and maize stalks 3.8652 kCal/g.

The optimal mix ratio of eucalyptus sawdust: coffee husks: maize stalks is 350 :169.142:150. This ratio gives a moisture content of 9.65%, a gross calorific value of 4.356 kcal/g, a fixed Carbon of 6.986%, and a volatile matter of 79.115%. This has verified that blended briquette fuel has better combustion properties than individual briquettes.

## **5.2 Recommendations**

Further research should be done to investigate the influence of change in particle size and change pressure in the creation of blended briquettes based on the design of experiments to examine both their physical and combustion properties.

In the current investigation, the uncarbonized briquette binders were held constant at 10%. This should be adjusted to find out if it impacts both the physical and combustion properties under investigation. The current finding can be used as the basis for further investigation and optimization of briquette blending in the future, because the effect of modifying individual components has been known.

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## APPENDICES

Table A-0-1: Design of Experiments Weight Calculation

	Factor 1	Factor 2	Factor 3	Response 1	Response 2	Response 4	Response 4
Run`	A: Sawdust (g)	B: Coffee Husk (g)	C: Maize stalks (g)	Moisture Content (%)	Gross Calorific Value (kCal/g)	Fixed Carbon (%)	Volatile Matter (%)
1	350	150	250	9.65	4.4180	4.75	83.59
2	150	350	250	10.21	4.2151	7.32	79.65
3	250	150	150	10.17	4.2361	12.36	72.42
4	150	250	150	10.82	4.2390	6.40	79.88
5	250	250	250	12.60	4.1623	11.54	73.50
6	150	150	250	11.26	4.0712	12.11	74.01
7	350	350	250	10.16	4.2096	5.06	82.43
8	250	150	350	12.28	4.1307	2.22	82.51
9	150	250	350	11.38	4.1814	8.89	77.07
10	250	250	250	12.60	4.1625	11.32	74.05
11	250	350	350	11.63	4.4584	5.08	80.63
12	350	250	350	10.84	4.0765	6.03	80.62
13	250	350	150	11.57	4.4678	3.59	82.14
14	250	250	250	12.60	4.1620	12.09	73.98
15	250	250	250	12.60	4.1629	11.51	73.06
16	350	250	150	11.39	4.3781	8.04	76.70

Table A-0-2: Table optimization starting points.

Sawdust	Coffee Husks	Maize Stalks
350.000	250.000	350.000
250.000	250.000	250.000
150.000	250.000	350.000
250.000	350.000	150.000
250.000	150.000	150.000
150.000	150.000	250.000
150.000	350.000	250.000
150.000	250.000	150.000
250.000	350.000	350.000
350.000	250.000	150.000
350.000	150.000	250.000
350.000	350.000	250.000
250.000	150.000	350.000
333.669	163.375	222.676
289.438	271.777	213.020
282.378	180.005	202.639
328.314	175.409	166.055
163.131	296.348	294.634
260.817	269.458	333.590
172.253	242.558	202.305
285.651	272.199	198.035
179.943	179.152	328.919
196.630	256.544	270.770
298.871	155.343	157.475
299.680	348.135	327.782
233.407	179.096	175.012
156.741	324.434	348.374
245.946	194.051	204.247
181.440	262.106	155.274
167.289	307.197	155.638
284.454	217.760	209.325

225.378	2548. 81	226.475
191.743	184.878	241.661
167.127	312.835	317.604
344.869	165.973	324.246
229.920	159.155	286.586
289.278	272.050	168.625
255.159	178.086	169.941
202.228	331.195	314.796
344.720	224.598	229.752
234.133	325.984	344.435
255.880	207.111	241.925
219.866	273.631	200.970
190.038	347.237	236.993
262.211	187.688	299.830
171.955	259.954	164.039
339.097	295.187	215.335
190.043	193.664	195.562
242.814	302.512	159.641
269.693	167.453	197.836
260.999	177.163	290.778
208.876	268.809	169.109
179.687	312.495	242.340
348.828	208.575	208.814
259.226	204.170	294.432
267.403	176.537	298.917
179.673	166.191	287.208
284.833	191.505	246.638
235.451	254.859	161.396
240.985	195.140	259.170
236.828	247.841	225.920
195.089	236.776	218.968
193.993	261.073	327.571
312.671	165.279	194.190
196.750	174.944	312.953

219.679	191.204	237.740
174.293	227.806	268.953
292.977	150.484	242.881
299.409	189.840	219.630
176.097	280.690	307.363
218.725	279.823	228.984
263.647	217.611	315.679
326.701	195.049	192.709
322.721	232.438	235.035
169.179	214.587	257.795
302.174	254.310	200.722
189.522	278.389	284.752
304.738	239.478	170.827
318.879	230.148	225.920
302.540	234.299	328.587
321.090	248.822	276.633
168.920	280.916	198.878
332.369	193.397	264.337
188.409	153.968	218.915
293.117	262.129	296.209
252.286	157.412	291.645
168.100	342.318	162.503
203.170	262.426	247.375
242.159	231.199	236.248
253.664	306.141	198.894
290.836	319.399	164.208
225.071	222.287	330.578
225.728	234.645	322.899
276.624	270.270	266.812
230.468	230.487	212.346
318.904	165.682	313.302
188.140	215.983	329.005
312.200	168.674	221.725
325.543	190.494	227.895

160.202	189.462	176.961
299.527	170.09	318.145
186.193	175.425	187.790
258.767	269.941	250.059
308.076	183.180	286.939
240.183	330.781	265.883
273.094	169.910	188.993
203.485	341.923	295.721
333.108	234.704	342.039
336.928	328.974	263.227
217.153	162.098	216.550
162.195	317.035	223.776
205.454	245.610	244.907
311.211	320.184	218.825

Table A-0-3: Optimizations solutions.

Number	Sawdust	Coffee Husks	Maize Stalks	Moisture Content	Fixed Carbon	Volatile Matter	Gross Caloric Value	Desirability	
1	350	169.142	150	9.65	6.986	79.115	4.356	0.894	Selected
2	349.999	168.124	150	9.628	6.931	79.2	4.355	0.894	
3	349.999	168.771	151.148	9.65	6.993	79.144	4.354	0.893	
4	349.271	168.17	150	9.649	7.003	79.106	4.354	0.893	
5	349.998	165.267	150	9.566	6.771	79.446	4.353	0.892	
6	350	168.219	152.861	9.65	7.002	79.191	4.352	0.89	
7	349.35	164.117	150.001	9.558	6.767	79.466	4.352	0.89	
8	349.999	162.555	150.001	9.505	6.611	79.689	4.351	0.89	
9	347.72	166.234	150.001	9.65	7.044	79.079	4.351	0.889	
10	350	155.352	150	9.337	6.151	80.383	4.347	0.885	
11	345.162	163.133	150	9.65	7.112	79.032	4.345	0.883	
12	350	152.744	150	9.273	5.972	80.651	4.345	0.883	
13	350	151.133	150.001	9.233	5.858	80.821	4.344	0.882	
14	349.985	165.695	160.552	9.65	7.009	79.429	4.341	0.879	
15	345.808	151.719	150	9.363	6.333	80.191	4.338	0.876	
16	350	192.404	150	10.093	7.961	77.541	4.371	0.862	
17	349.999	150	167.583	9.343	6.014	81.087	4.325	0.861	

18	350	198.5 45	150	10.19 3	8.128	77.24 4	4.375	0.854	
19	342.5 12	150.0 01	165.5 61	9.529	6.73	80.07 3	4.317	0.852	
20	350	311.2 87	150	10.69 1	4.469	80.58 7	4.447	0.849	
21	350	316.3 59	157.1 54	10.64 9	4.469	80.82 7	4.434	0.845	
22	349.9 99	304.7 51	150.0 01	10.73	5.029	79.93 7	4.443	0.84	
23	347.4 27	313.0 09	150	10.75	4.469	80.6	4.447	0.84	
24	350	223.2 45	150.0 03	10.51 6	8.417	76.54 9	4.391	0.828	
25	350	329.9 47	179.4	10.49	4.469	81.53 4	4.386	0.827	
26	350	229.2 68	150	10.57 7	8.395	76.50 1	4.394	0.823	
27	350	238.6 64	150	10.65 7	8.288	76.52 1	4.4	0.817	
28	350	239.8 16	150	10.66 6	8.268	76.53 2	4.401	0.816	
29	350	270.9 9	150	10.80 1	7.241	77.47 6	4.421	0.813	
30	350	261.6 21	150.0 01	10.78 1	7.652	77.05 8	4.415	0.811	
31	350	150	209.1 81	9.67	5.866	81.97 5	4.282	0.808	
32	150	349.9 92	199.2 39	10.57 2	4.469	82.40 5	4.331	0.765	
33	150	350	200.1 36	10.57	4.532	82.34 7	4.329	0.765	
34	150	348.8 84	198.3 79	10.59 3	4.469	82.40 1	4.33	0.762	
35	151.4 71	349.9 35	198.4 01	10.61	4.469	82.38 2	4.332	0.762	
36	150	350	203.9 04	10.56 1	4.793	82.10 5	4.325	0.761	
37	152.2 98	349.6 42	197.7 2	10.63 6	4.469	82.36 8	4.332	0.759	

38	150	347.5 01	197.3 08	10.61 8	4.469	82.39 6	4.33	0.759	
39	154.3 11	349.9 99	196.9 19	10.67 8	4.469	82.33 9	4.334	0.755	
40	150	349.9 97	217.0 5	10.52 9	5.639	81.30 9	4.308	0.748	
41	350	150	238.5 18	9.9	5.161	83.06 1	4.252	0.747	
42	158.1 23	350	194.8 7	10.76 7	4.469	82.28 2	4.337	0.746	
43	150	350	222.2 7	10.51 7	5.947	81.01 4	4.301	0.742	
44	164.9 4	349.9 97	191.2 32	10.91 8	4.469	82.18 4	4.342	0.73	
45	150	350	233.2 94	10.49	6.546	80.43 1	4.287	0.73	
46	166.5 19	350	190.4 01	10.95 1	4.469	82.16 2	4.344	0.726	
47	150	331.8 96	185.3 11	10.86 6	4.469	82.32 4	4.323	0.719	
48	348.2 2	150	248.5 04	10.02 7	4.936	83.30 7	4.24	0.719	
49	170	349.9 99	188.5 8	11.02 2	4.469	82.11 5	4.347	0.718	
50	175.1 54	350	185.9 36	11.12 1	4.469	82.04 7	4.351	0.707	
51	290.2 95	150	150	10.40 9	10.67 6	74.55 1	4.257	0.702	
52	150	350	267.3 4	10.40 8	7.953	78.97	4.244	0.686	
53	150.0 4	313.7 76	171.5 8	11.07	4.469	82.20 1	4.311	0.678	
54	150	350	277.2 24	10.38 5	8.237	78.64 2	4.231	0.671	
55	350	157.8 61	270.3 95	10.29 3	4.648	83.59	4.217	0.659	
56	269.6 89	150	150	10.61 1	11.701	73.24 2	4.227	0.641	
57	150	291.1 25	154.8	11.19 6	4.469	81.99 6	4.289	0.639	

58	150.1 45	287.7 63	152.1 88	11.20 7	4.469	81.95 6	4.286	0.634	
59	150.0 02	286.4	151.3 31	11.20 5	4.469	81.94 6	4.284	0.633	
60	259.0 84	350	165.1 17	11.71 3	4.469	81.43 3	4.406	0.632	
61	222.7 67	350	167.2 98	11.69 7	4.469	81.56 4	4.391	0.627	
62	251.8 23	350	164.4 76	11.74	4.469	81.43 7	4.405	0.625	
63	228.8 02	350	166.0 55	11.72 5	4.469	81.52 4	4.395	0.623	
64	150.0 06	243.7 17	150	11.10 1	6.73	79.52 2	4.213	0.565	
65	157.6 56	254.3 84	150	11.33 5	6.771	79.33 7	4.238	0.564	
66	150	349.9 99	338.9 49	10.23 7	8.73	77.57 1	4.153	0.547	
67	159.1 06	219.5 69	150.0 01	11.08 9	8.617	77.28	4.181	0.522	
68	213.9 28	185.0 2	152.2 67	11.37 9	12.37 8	72.42	4.193	0.502	

Figure A-1: Additional Photos of different samples mixed before adding molasses  
(Sampled Photos).



**Figure A-2: Different samples mixed before adding molasses**



Figure A-3 : Mixing Apparatus.



Figure A-4 : Briquettes Preparations.



Figure A-5: Drying of Briquettes.