MEKELLE UNIVERSITY

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Production and Optimization of Briquettes from Sawdust Bagasse blends Using Thermoplastic Waste as a Binder

By

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Thesis Acceptance Approval Form

This is to certify that **Mr. Samuel Teklemariam Gaim** has incorporated all comments forwarded by the internal and external examiners and advisor during the thesis defense held on March 26, 2026, G.C.

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DECLARATION

I, the undersigned, declare that this thesis entitled **‘**production and optimization of briquettes from sawdust-bagasse blend using thermoplastic waste as a binder’ is my original work, has not been presented for an award in any other university and that all sources of materials used for the thesis have been appropriately cited.

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I certify that this thesis is carried out under my supervision, to the best of my knowledge the work reported here does not form part of any other thesis report or dissertation based on which a degree or award was conferred on this or any other candidates.

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ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of variance
AC	Ash Content
ASTM	American Society for Testing Materials
ASTM (D3172)	Standard method for Fixed carbon content
ASTM (D3173)	Standard method for moisture content determination
ASTM (D3174)	Standard method for ash content determination
ASTM (D3175)	Standard method for volatile matter content
ASTM(D1989)	Standard method for calorific value determination
CCD	Central Composite Design
CS	Compressive Strength
CV	Calorific Value
C.V%	Coefficient of Variation percentage
DF	Degrees of Freedom
DOE	Design of Experiments
FAO	Food and Agriculture Organization
FC	Fixed Carbon
FTIR	Fourier Transform Infrared Spectroscopy
GCV	Gross Calorific Value
GHGs	Greenhouse gases
H:C	Hydrogen to Carbon ratio
HDPE	High density polyethylene
HHV	Higher Heating Value
LDPE	low-density polyethylene
LCA	Life Cycle Assessment
(LPG)	Liquefied petroleum gas
MC	Moisture Content
NOx	Oxides of Nitrogen
O:C	Oxygen to Carbon ratio

OPEFB	0il palm empty fruit bunches
PET	Polyethylene Terephthalate
PP	Polypropylene
SCB	Sugarcane bagasse
SEM	Scanning Electron Microscopy
SOx	Oxides of Sulfur
Std. Dev.	Standard Deviation
SW	Sawdust
VM	Volatile Mater

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ABSTRACT

The rising need for sustainable, affordable sources of energy has encouraged interest in converting agricultural residues and waste plastics into solid biofuels. This study was conducted to produce and optimize sawdust bagasse blends briquettes. The briquettes were produced using thermoplastic waste, specifically HDPE, as a binder at proportions ranging from 5% to 25%. The bagasse and sawdust were dried, ground, and sieved to a particle size of less than 3 mm, then mixed with softened HDPE. The effects of compaction pressure (5–15 MPa), binder content (5–25%), and sawdust-to-bagasse ratio (25–75%) on briquette density, compressive strength, and key combustion properties, including calorific value, moisture content, ash content, volatile matter, and fixed carbon were evaluated. The optimum parameters obtained from the model were a compaction pressure of 15 MPa, an HDPE binder content of 16.34%, and a sawdust proportion of 51.49%, resulting in a density of 0.9145 g/cm^3 and a compressive strength of 2.968 MPa, which provide sufficient mechanical integrity for handling and use. Proximate analysis showed low moisture (5.21%) and ash (3.46%) contents, while ultimate analysis revealed high carbon (53.85%), moderate hydrogen (6.03%), and oxygen (39.97% by difference), with very low nitrogen (0.13%) and sulfur (0.017%) levels indicating low potential for NOx and SOx emissions during combustion. The optimized briquettes achieved a calorific value of 4107 kcal/kg, reflecting a balance favoring enhanced mechanical durability over the study's maximum observed value of 5061 kcal/kg under other conditions. In conclusion, the optimized briquettes produced from sawdust, bagasse, and HDPE binder show satisfactory mechanical integrity, good fuel characteristics, and low environmental impact, indicating their potential as a sustainable alternative for energy generation while supporting effective management of agricultural and plastic waste.

1 NTRODUCTION

1.1 Background of Study

The world utilization of energy is highly relied on fossil fuels which include coal, oil, and natural gas, approximately 80% of the global energy demand. Nevertheless, the contribution of the non-renewable energy to greenhouse gas emission combined with their limited nature have major concerns and need for renewable energy[1]. Biomass is one of the renewable sources of energy and is a promising option to solve this problem while, at the same time helping rural development, employment, and socio-economic growth[2]. Biomass based energy can be used indifferent domestic and industrial applications such as steam generation, as well as domestic heating and cooking, but effective and efficient utilization and implementation is crucial. Briquette production from agricultural residues, industrial by-products, and other plant-based wastes, is one of the best and most feasible options of integrating biomass based renewable energy which reduces waste generation and environmental pollution[3].

The rapid population growth, industrialization and urbanization suggests the constrains of over dependence on fossil fuel based energy which have environmental risk and economic instability [2]. Biomass includes a widely available renewable resource that strengthen the energy capacity of developing country like Ethiopia. Despite its abundant availability, untreated biomass like saw-dust, wood chips, and agricultural residues are underexploited due to their low density, high moisture content, and limited energy value make storage and transport difficult.[4]. In addition, the direct combustion of raw biomass for energy generation can result in deforestation, environmental degradation, indoor air pollution, and poor combustion efficiency[5]. The solution to these problems is densification and treatment of the raw biomass in to briquettes which have higher density, improved mechanical strength and ensuring homogenous combustion and becomes more suitable for house hold and industrial applications[6]. The countries such as, France, Sweden, Brazil, Austria, Germany and others proof that producing and implementing biomass briquettes is relevant. But while densifying biomass in to briquette there some key factors that has to be considered these are, the types of biomass, the binder used and the processing parameters that motivates researches to optimize these aspects[7].Sawdust and sugarcane bagasse are widely available biomass wastes, which are by-products of the sugar processing and wood processing industries[8][9]. They are produced in large amounts but are efficient if used as a row fuel due to high moisture, low density, low calorific value and not suitability to feed into stove which results low over all combustion efficiency and environmental pollution [5]. Globally, sugarcane bagasse production is estimated at approximately 500 million tons per year, while sawdust from timber processing contributes over 100 million tons of waste annually. Bagasse typically has a moisture content of 40–50% and a calorific value of 7–8 MJ/kg, whereas sawdust has lower moisture (10–12%) and a higher calorific value of 16–18 MJ/kg. Therefore, producing densified briquette from these biomass wastes not only increases energy density but also improves handling, storage, and transportation enhance combustion chrematistics and economically feasible by diverging reliance on more expensive fuels like coal and petroleum[8].

Binder is the most briquette quality determining parameter as it directly affects the thermal and mechanical properties of the biomass briquettes. The physiochemical properties of briquettes which are density, ignition temperature, compressive strength, durability and overall combustion efficiency are all influenced by the type and amount of binder used. We have traditional binders like starch and molasses which have been extensively studied. There are also binders like thermoplastic waste which have recently attracted attention that are supposed to give improved performance and sustainability[6]. HDPE constitutes 20% of global plastic waste[10], offering an abundant source for binder utilization. It has a high calorific value making it effective both as a binding agent and as a contributor to the energy content of biomass briquettes. Although utilizing single biomass for briquette production has been studied extensively, there are few studies on biomass blends briquettes that mix more than biomass residue bound by innovative binders like thermoplastic waste. Briquettes formulated from mix of biomass like mixture of sawdust and bagasse demonstrate better fuel characteristics than that produced from single biomass particularly when plastic-based binder is used. Optimization of the biomass feedstock composition and binder content and processing parameters using experimental designs results in cost-effective, high-quality briquette production suitable for scaling up in developing countries[8].

Relaying on these facts, the production and optimization of briquettes from a sawdust-bagasse mixture bound by thermoplastic waste presents a viable strategy for renewable energy production, waste minimization and addressing environmental problems. The objectives of the current study are to find the optimum combination of the sawdust to bagasse blend and the thermoplastic binder, to characterize the briquette produced using different physiochemical properties. By addressing the gap in knowledge in composite biomass briquetting utilizing locally available plastic waste as a binder to contribute to sustainable energy solution and promoting environmental issues[11].

Furthermore, while individual biomass sources have been studied extensively, there is a paucity of research on composite biomass briquettes that combine multiple residues with innovative binders[12]. Composite briquettes, for instance, mixtures of sawdust, bagasse, and paper with binders like starch or thermoplastics, demonstrate improved fuel properties, including higher calorific value, increased density, and lower ash content, while simultaneously reducing harmful emissions and deforestation. Optimizing material composition and binder content using experimental designs, such as factorial designs and analysis of variance (ANOVA), allows for cost-effective, high-quality briquette production suitable for scaling up in developing countries[8].

Given these considerations, the production of biomass briquettes from a sawdust-bagasse mixture using thermoplastic waste as a binder presents a promising approach to sustainable energy generation, waste management, and environmental protection. This study aims to investigate the optimal combination of biomass residues and binder proportions, characterize the physical and combustion properties of the resulting briquettes, and provide insights into the economic feasibility and scalability of producing high-quality, sustainable alternative fuels. By addressing the current knowledge gaps in composite biomass briquette production, particularly the use of locally available feedstock and thermoplastic waste as binders, this research contributes to advancing sustainable energy solutions while promoting environmental stewardship in developing countries[11].

1.2 Statements of the Problem

The growing global need for sustainable and environmentally friendly energy sources has intensified efforts to develop renewable solutions to reduce fossil fuels dependence. Biomass briquetting has emerged as a promising technology due to its potential to convert agricultural and industrial residues into efficient, eco-friendly, and cost-effective solid fuels. However, despite its advantages, the large-scale adoption of biomass briquettes is constrained by persistent challenges related to their mechanical durability, water resistance, and combustion efficiency. A major limitation in briquette production lies in the choice and performance of suitable binders. Conventional organic and inorganic binder often present trade-offs such as high cost, poor thermal stability, or high ash content, which negatively affect fuel quality. In contrast, thermoplastic wastes such as low-density polyethylene (LDPE) and polypropylene (PP) have shown potential as alternative binders due to their ability to enhance mechanical strength, water resistance, and calorific value. Nonetheless, their optimal application in biomass briquetting, particularly concerning binder ratio, emission safety, and compatibility with different biomass feedstock remains insufficiently studied. Furthermore, the combined utilization of bagasse and sawdust, two abundant yet underutilized agro-industrial residues, has not been thoroughly explored. Limited research exists on how variations in their blending ratios influence the physical, mechanical, and combustion properties of briquettes when thermoplastic waste is used as a binder. Most previous studies have focused on single-variable analyses, overlooking the interactive effects of compaction pressure, binder ratio, and feedstock proportion on overall briquette performance.

Despite extensive research on briquette production from single biomass sources, several critical gaps remain. First, studies on composite biomass briquettes, such as sawdust–bagasse blends, are limited, particularly regarding the optimal mixing ratios to balance mechanical strength and combustion efficiency. Second, while thermoplastic waste like HDPE have been proposed as binders, there **is** insufficient quantitative data on how varying binder content influences both the energy content and durability of blended biomass briquettes. Third, the combined effect of process parameters including compaction pressure, binder ratio, and biomass blending ratio on the mechanical, thermal, and combustion properties of briquettes have not been systematically investigated. Addressing these gaps, this study examines the interplay of sawdust bagasse blend ratio, HDPE binder content, and compaction pressure to develop an optimized, high performance, and sustainable briquetting process suitable for practical applications and resource efficient waste management.

1.3 Objectives

1.3.1 General Objective

To produce and optimize biomass briquettes from sawdust–bagasse mixtures utilizing thermoplastic waste as a binder, with the aim of evaluating the effects of key production parameters on their physical, mechanical, and fuel properties.

1.3.2 Specific Objectives

The specific objectives of this study are to:

1. To produce biomass briquettes from sawdust–bagasse blends using thermoplastic waste as a binder.
2. To evaluate the effect of compaction pressure, thermoplastic binder ratio, and sawdust-to-bagasse proportion on the density and compressive strength of biomass briquettes.
3. To determine the proximate composition and calorific value of representative biomass briquette samples and perform ultimate analysis of the optimized biomass briquette.
4. To optimize the briquette production parameters to obtain briquettes with improved mechanical performance and energy properties.

1.4 Research Questions

1. How do compaction pressure, thermoplastic binder ratio, and sawdust–bagasse proportion affect the density and compressive strength of biomass briquettes?
2. What are the proximate composition and calorific value of representative biomass briquette samples produced from sawdust–bagasse blends with a thermoplastic binder, and what is the elemental composition of the optimized biomass briquette?
3. What combination of compaction pressure, thermoplastic binder ratio, and sawdust–bagasse proportion produces biomass briquettes with optimal density, compressive strength, and energy properties?

1.5 Scope and Limitations of the Study

This research mainly focuses on production and optimization of biomass briquette formulated from mixture of sawdust and sugarcane bagasse utilizing thermoplastic waste as a binder, specifically HDPE. The study aims to explore how the quality and performance of a briquette is affected by plastic binder ratio, compaction pressure and the blending ratio of bagasse to sawdust. The scope of this research includes first the preparation of the raw materials (sawdust, bagasse and thermoplastic waste), densification and formulation of the briquettes. Then characterization of the briquettes using different physiochemical properties such as density, compressive strength, proximate and ultimate analysis and calorific value was done. Furthermore, the experiments of producing and characterization of the briquette samples were conducted at Mekelle University and Messebo Cement Factory, using available briquetting and testing equipment. The study on the production and performance evaluation was limited to laboratory. But it does not extend to large scale manufacturing. Full economic analysis and flue gas emission related to burning plastic bound briquettes were acknowledged but were not investigated in this study.

1.6 Significance of the Study

This study has a lot of importance environmentally, academically and practically. In academic perspective it fills a knowledge gap in utilizing mixed biomasses (sawdust and bagasse) and plastic based wastes for briquette production. While there are enormous previous studies done on utilizing organic and inorganic binders like starch, molasses, limestone and cement. But limited attention has been given to briquettes studies using plastic waste especially in relation to compaction pressure and feedstock blending ratios. In the Environmental perspective, this research promotes sustainable waste management by valorizing agricultural residues and plastic waste. This multidimensional benefit of producing environmentally friendly and sustainable energy along with reducing plastic pollution aligns with circular economic goals and supports global efforts toward climate change mitigation.

2 LITERATURE REVIEW

2.1 Overview of Biomass Briquetting

Biomass briquetting, which converts low density biomass waste, industrial residue and municipal waste into high energy and dense solid fuel, is widely recognized as an effective waste-to-energy technology. It is important in addressing two critical problems in developing countries; one is the increment in the generation of solid waste, and the second one is the heavy dependence on fossil fuels[13]. The briquette quality parameters such as moisture content, volatile matter, fixed carbon, ash content, particle size, and calorific value determine combustion efficiency and durability can be significantly affected by the choice of raw materials. Briquetting is also important in improving handling by increasing density, decreasing storage space and ease transportation. There are various types of briquetting technologies including, piston pressing, manual pressing, screw extrusion, roller press, and hydraulic compression. The quality of good briquette is determined using different physical, chemical, mechanical and fuel characteristics[1].

Upon densification of the raw biomass under controlled parameters, the energy density and suitability of the briquette for domestic and industrial applications is improved and enhanced. Factors like particle size, binder type and pressing pressure highly affect briquette quality. Raw biomass lacks natural ability to bind so, binders are added to enhance mechanical and fuel properties. Binder used in biomass briquetting technology are wastepaper, molasses, piston pressing, clay, or synthetic materials like plastic. Therefore, optimizing these parameters is crucial to formulate briquettes with desired physiochemical, mechanical and combustion behaviors[8].

Briquetting technology solves the problems related to burning raw biomass with poor heating value, high moisture content, poor combustion efficiency, and challenges in handling, storage, and transport. Process parameter optimization in briquette production is very important as it directly affects the combustion performance and structural integrity while offering a cost-effective and sustainable solid fuel alternative[11].

Binder is very impactful parameter in briquetting production as it determines the quality and cost of the product. There are different types of briquettes such organic (starch, molasses, cow dung and wastepaper), inorganic (limestone, cement), synthetic (plastic based such as HDPE and LDPE) combined binders. It affects durability, compressive strength, and calorific value. Processing variables, particularly compaction pressure, processing temperatures and binder concentration, are the most critical in investigating physical and energy characteristics. Studies show that optimal conditions yield briquettes with high fixed carbon content, low moisture, and improved bulk density, underscoring biomass briquetting's potential as an efficient renewable energy technology[6].

Biomasses from agricultural, manufacturing and demotic residues are the major renewable energy sources in developing countries. Utilization of these wastes unwisely causes environmental pollution including water contamination, air pollution deforestation and greenhouse gas emission. In Ethiopia, the most abundant biomass residues are sugarcane bagasse, sesame husk, coffee husks, and sawdust and chat waste but underutilized. Therefore, producing briquettes from these wastes not only enhances energy utilization but also dresses environmental waste management challenges. The produced briquettes exhibit desired fuel properties such as high carbon content, high calorific value and good combustion efficiency relative to the raw biomass[14].

Furthermore, the physiochemical, mechanical, and fuel characteristics of the briquette are affected by the type of biomass and binder choice. For instance, sawdust combined with paper pulp yields the highest fixed carbon and calorific values while minimizing ash and sulfur content. This result indicates that the potential of mixture of raw materials as sustainable energy sources which reduces the dependence on nonrenewable resources and environmental impact mitigation[10].

Another important consideration in briquette densification is the pretreatment methods which significantly affects briquette quality, performance, and combustion efficiency[13]. Studies on briquette production from *Gmelina arborea* sawdust passing through thermal pretreatment utilizing printing paper, newspaper, and montmorillonite clay as a binder enhanced energy content, grind ability combustion and handling performance. The pretreatment process influences parameters such as particle size, moisture content, and density which in turn determines the fuel performance[13].

2.2 Biomass Resources and Feedstock for Briquetting

Biomass generally refers to all biological materials derived from living organisms, including animals and plants. Within the context of biomass briquetting, an example of biomass would include a wide range of materials, such as wood shavings from forest operations, agricultural residues from Agro-processing activities, industrial wastes, animal, and domestic and municipal wastes[14].

According[15], biomass resources can be grouped in terms of properties ('woody' and 'non-woody' biomasses) or sourcing (agricultural residue and harvested natural materials). Biomass feedstock resources are classified into four specific groups, namely woody, herbaceous, fruit, and aquatic biomass. The supply of biomass from various sources around the globe is approximately 220 billion tons per year. These resources are used as fuel, directly or indirectly, avoiding needless burning, burying, or storage[16], but can also cause extensive environmental pollution when used inefficiently. In comparison to other renewable energy options, several studies noted that biomass is abundant in supply from various sources and its energy has the key advantages of being nearly carbon neutral .The carbon neutrality of biomass resources is dependent on the net CO2 equivalent greenhouse gases (GHGs) emitted across the entire life cycle processes considered, which also involves the emissions generated during the manufacturing and transport phases. The CO2 released through its burning, utilization, and exploitation processes does not cause an increase in atmospheric CO2 but instead leads to a faster transfer of CO2 into the atmosphere that is reused by plants to produce biomass again. This environmentally friendly attribute of biomass makes it an ideal renewable and sustainable source for briquette production[18].

The performance and suitability of biomass feed stock is highly affected by its physicochemical characteristics. These physicochemical properties (VM, AC, FC, Moisture content, and calorific value) are key factors in determining durability, burning efficiency and energy output of the resulting briquettes. Table 1 summarizes typical ranges of these properties for common biomass materials based on values reported in the literature.

Table 2.1: Calorific value, moisture content and ash content of different biomass materials [10], [13], [14].

Biomass material	Calorific value(MJ/kg)	Ash content (%)	Moisture content (%)
Rice husk	13.38	19.5	10.04
Sawdust	18.48	2.91	8.52
Corn stalk	13.79	10	16.8
Ground nut	18.81	1.3	12
Bagasse	17.85	6	49.8
Cotton stalk	17.85	9	12
Coconut	17.79	1	10.9
Coffee husk	17.56	NA	15
olive	13	5	7.5

2.3 Binders used in Biomass Briquetting

The type and proportion binder used play an important role in briquette production technology as it directly determines mechanical chemical and combustion performance of the briquettes. As reported by [13] briquettes produced by utilizing paper based binder generally have good combustion characteristics and flame formation, even though, ash content could be increased when high proportion of binder. Thermoplastics waste, like HDPE, LDPE and PP, have also been currently considered as alternative binders to enhance mechanical and combustion properties.[6]studied briquettes made from agricultural residues, including sawdust, okra stalks, and corn cobs, using PP at concentrations of 5–15%.

2.3.1 Thermoplastic Waste as a Binder in Biomass Briquetting

Currently the utilization of thermoplastic waste in biomass briquetting as a binder is attracting the interests of researchers because it has good potential in improving briquette quality. It is also a good opportunity to address environmental waste management related to plastic disposal. Thermoplastics waste originated from polyethylene (PE), polypropylene (PP), serves as a binder and an auxiliary fuel when combined with biomass feedstock, enabling the production of solid fuels with enhanced physical and calorific properties. As has been reported by several studies, thermoplastic waste is viable for this purpose. [20] Studied briquette produced from sawdust and date palm mixture bounded by plastics waste of electrical and electronic equipment (WEEE) and automotive shredder (ASR). The ratio was varied from (10–30%) with compaction pressure pressures of 22–67 MPa. The addition of plastic waste as a binder showed an improvement in density and durability of briquette[20]. This also has strong support from the environmental and policy perspective to recycle such solid waste for fuel production. The European directives for waste incineration and solid biofuels supports to use such thermoplastic waste as a viable option for producing sustainable energy while adhering to environmental standards[18].

Thermoplastic waste not only serves as a binding agent but also improves and enhances the fuel properties of biomass briquettes. For instance, [21] studied co-torrefaction of fungus bran with polypropylene waste and found that PP addition increased the calorific value and reduced ash content. The optimal blending ratio was 20%, demonstrating that plastics can serve as both a binder and a fuel enhancer. Likewise, study by [22] demonstrated that utilizing PET bottles combined with sawdust for briquette production shown the potential of thermoplastics to improve briquette quality. The highest calorific value was observed in the sample with highest sawdust proportion but incorporating of the PET ensured adequate binding and structural integrity. Lastly [23] investigated a briquette production from wood waste and PET mixture at a blending ratios of 100:0, 60:40, 50:50, and 40:60 wood waste to PET respectively. The incorporation of the plastic waste improved the calorific values significantly (17.85–20.77 MJ/kg) and decreased the ash content from (1.05–1.37%)[24].

Generally, all these studies confirmed that thermoplastic waste can be a good binder in biomass briquetting, enhancing mechanical strength, calorific value, and durability. Moreover, the integration of plastic waste into briquettes aligns with principles of circular economy and sustainable waste management, offering both environmental and economic benefits.

2.4 Briquette Production Process and Technology

2.4.1 The Briquetting Process

The method of densification of loose biomass material into favorable shapes as well as sizes through pressing to produce a solid product for different applications is known as briquetting. The pioneer proposal of briquetting was in Russian from wood waste, hard coal, and charcoal with importance low dust, sulfur, and ease of handling and high calorific values. Briquettes are shaped through a method of briquetting. This. Method includes the densification of free biomass buildups, for example, sugarcane bagasse into high-thickness strong squares that can be utilized as fuel. Direct burning of biomass like bagasse is very inefficient due to the transportation, storage, and handling problems associated. While briquettes provide a sustainable approach for improved and efficient utilization of agricultural and other biomass remainders. The common types of briquettes are charcoal briquettes and biomass briquettes[25]. Various technologies have been developed for biomass briquette production, broadly classified into piston press, screw extruder**,** and roll press technologies. These technologies vary in terms of the operating mechanism, temperature, pressure, binder requirement, energy input, and final product characteristics.

Piston Press Technology:

This is one of the most widely used technologies in biomass briquetting. It operates on a reciprocating mechanism, where a piston compresses the biomass against a die, forming cylindrical briquettes. Studies by [26]show that piston press briquettes are dense and have good mechanical strength. This method usually does not require binders, especially when lignin in the biomass acts as a natural binder under high pressure and temperature. However, the intermittent nature of piston movement can limit production throughput.

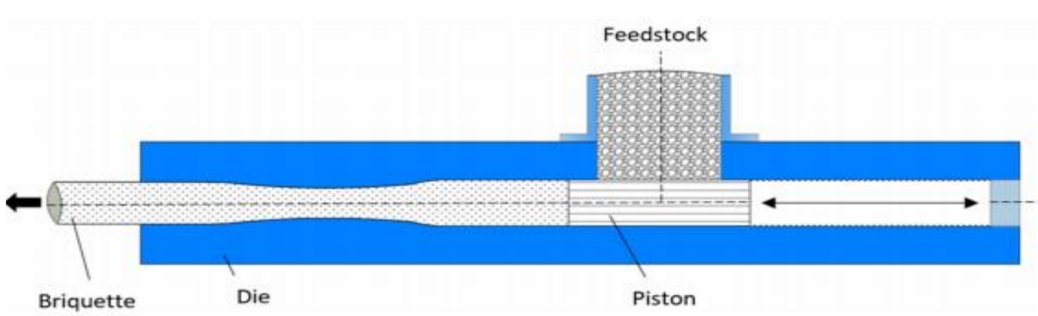

Figure 2.1: Schematic representation of Hydraulic or mechanical piston press

Screw Extrusion Technology

This method involves continuous compression of biomass using a rotating screw that forces the material through a die, forming briquettes with a central hole. This central cavity enhances combustion efficiency by facilitating better air circulation. According to research by[23], screw extruder briquettes have higher combustion efficiency but are more prone to wear and tear of machinery due to the friction involved. Unlike piston presses, screw extruders often operate at lower pressures and may require binders unless the feedstock has sufficient lignin content.

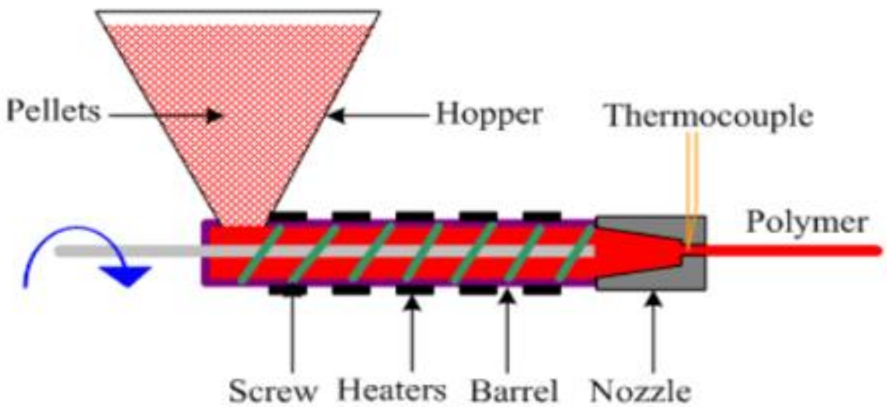

Figure 2.2: Schematic representation of Screw Extrusion press

Roller Press (Roller Press) Technology

This technique compresses biomass between two counter-rotating rollers with indentations that form pillow-shaped briquettes. This method is commonly used for low-moisture, fine powders and is especially prevalent in industrial applications. Roll press briquetting is more suitable for coal and charcoal fines and typically requires binders for cohesive strength. The equipment is simpler and has lower energy consumption compared to screw or piston technologies, but the briquettes tend to have lower mechanical strength[27].

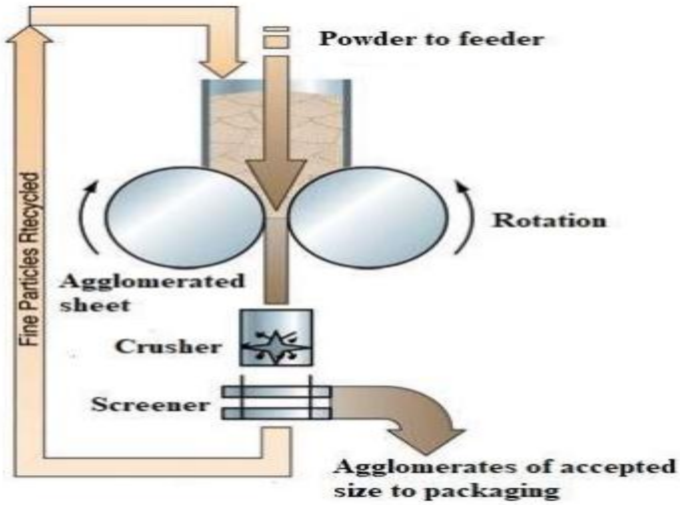

Figure 2.3: Schematic representation of Roller press type briquetting device [18]

Manual Briquetting Technology

Briquettes containing biomass can be prepared manually using hand operated lever presses or molds. This briquetting technology is widely applicable in rural and off grid areas owing to its advantages such as simplicity, inexpensive, applied without using advanced machine or electricity, and easily availability. To prepare Briquettes manually, the Biomass materials such as Agricultural residues and charcoal dusts are mixed with binders like clay or starch. Then, the materials are shaped in molds to the desired size. Finally, they are subjected to manual compression before drying using sunlight. Even through the technology is affordable, it has limited output capacity, and the briquettes produced are low in density and non-uniform. Previously reported literatures such as [19] support its potential for enhancement of energy access and diminishing reliance on firewood in resource-limited communities.

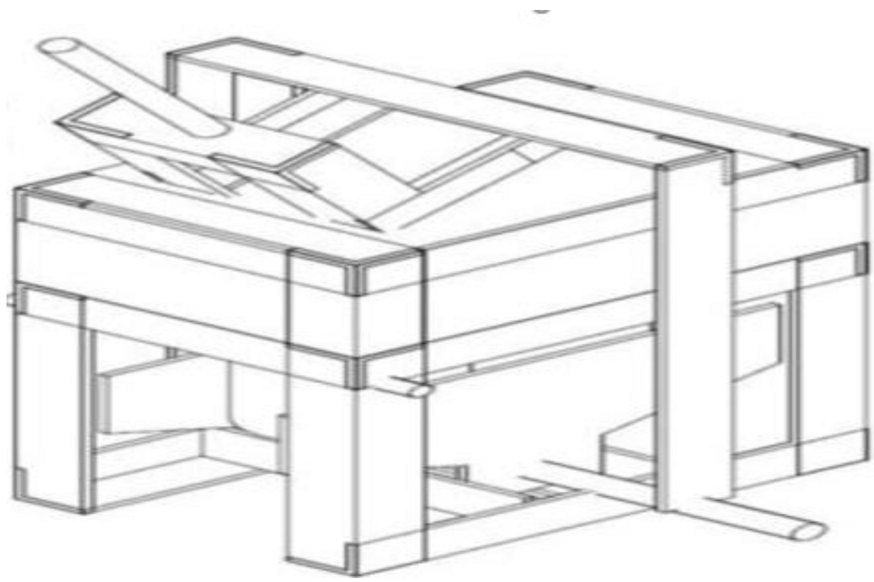

Figure 2.4: Manual briquette production machine[28].

2.5 Fuel Properties of Biomass Briquettes

Fuel properties such as calorific value, moisture content, density, fixed carbon, volatile matter, ash content significantly determines the performance and market of the biomass briquettes. Therefore, to produce briquettes which are economically and technically feasible, optimizing and understanding these properties is needed.

2.5.1 Physical Properties of Briquettes

Bulk density

Density is a critical fuel physical property that directly affects the energy content, transportation and handling of the briquettes. [16] Investigated a study of biomass briquettes produced by using various types of binder and found that higher pressure and particle sizes strongly affected density and calorific value. It was observed that the briquette formulated using cassava starch binder exhibited highest density and compressive strength. Bio solid and microalgae binders increase density but reduce compressive strength and combustion performance because of their fine particle size. [9] Concluded that although the density increased with these fine binders, mechanical durability was compromised, and emissions were not evaluated.

Moisture content

Moisture content is the water content of the biomass briquettes, and it is one of the most critical fuel properties determinants. Studies observed that increasing moisture content increases the durability and strength of biomass briquette until an optimum is reached. But during the combustion of a briquette with high moisture content, it requires additional energy loss to evaporate the water. Before briquetting or any fuel formulation, the analysis of biomass compositions is important to assess the quality of the solid fuel being produced. Sugarcane bagasse contains moisture amounting to 52.06 ± 1.39% w/w as received[8].

Mechanical Durability

Mechanical durability, which refers to the resistance to crumbling and abrasion during handling and transport is another very significant biomass briquette fuel property. It is often measured by the percentage of mass retained after tumbling or drop tests. Based on the standard of EN ISO 17831-2:2015, a durable briquette should retain more than 90% of their original mass after standard testing. Briquettes made with cassava starch and rice dust binders showed superior. The improved performance was attributed to the low fat and high cohesion properties of starch and the fine particle size of rice dust. In contrast, binders with higher lignin and fat content tended to act as lubricants, reducing inter-particle bonding and hence durability [26].

2.5.2 Proximate Analysis

Fixed carbon

Fixed carbon is the carbon percentage that is remaining when moisture percentage, volatile mater content, ash percentage compositions are subtracted from hundred. Most of the time the percentage of fixed carbon is 9 to 25%. The percentage of fixed carbon (PFC) is determined following the standard (ASTM D-3172) by subtracting the sum of PVM, PAC, and PMC content from 100, Where; Fc is the (wt %) fixed carbon obtained for each briquette sample, VM is the (wt %) volatile matter obtained for each briquette sample, Mc is the moisture obtained for each briquette sample and Ac is the (wt %) ash content obtained for each briquette sample[27].

Volatile matter

[30]determined volatile matter based on the American Society for Testing Materials Standards (ASTM- D3175) in the following procedure. a gram of moisture-free sample was weighed into a crucible, covered with the lid; and the crucible and its content placed in the furnace and heated to 925°C. After 7 min it was withdrawn from the furnace before attaining the ignition 17 temperature and was then cooled in a desiccator. The crucible with its content was weighed and expressed as the percentage weight loss volatile matter.

Ash content

The quantity of inorganic material that remains after burning a briquette is called ash. Since ash does not contribute to combustion, a high ash concentration reduces the fuel's calorific value[29]. Typically, slagging occurs when biomass fuels with an ash concentration of more than 4% and non-slagging fuels with an ash level of less than 4% are combined[32]. There is less ash in the better-quality briquette Ash values are predicted to fall between 0.6% and 9.8% for commercial fuels, 1.8% and 4.8% for cereals, 1% and 9.6% for energy crops, and 0.4% and 22.6% for industrial waste.

2.5.3 Ultimate Analysis

Ultimate analysis determines the elemental composition of a fuel, including carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O). This analysis is commonly performed using a CHNS/O elemental analyzer. Alternatively, when direct elemental analysis is unavailable, the elemental composition particularly C, H, and O of biomass briquettes can be estimated from proximate analysis data using established empirical correlations[33].

$$\%C = 0.637F_c + 0.455V_m \tag{2.1}$$

$$\%H = 0.0052F_c + 0.062V_m \tag{2.2}$$

$$\%O = 0.304F_c + 0.476V_m \tag{2.3}$$

Where, F_C, Fixed Carbon Content, V_M, Volatile Matter Content of the briquettes.

2.5.4 Calorific Value

The heating value of any substance can be defined as the amount of heat energy released by the complete combustion of a unit weight of fuel. If the latent heat of condensation of water is included in this, it is termed as gross calorific value; otherwise, it is called net calorific value. It also helps in predicting the amount of oxygen required for the complete combustion of any fuel. The better the biomass briquettes are created, the higher the briquettes' calorific value. Briquettes' calorific value is influenced by the kinds of raw material and quantity of binder used. [34] Found 12.3 MJ/kg, 12.87 MJ/kg, and 14.7 MJ/kg for briquettes made of rice husks, cassava peels, and sawdust briquettes without binder respectively. The calorific or heating value (HHV) of each sample of the briquette was estimated using the model developed which has good prediction accuracy within the error bar of ±10%. The correlation can be expressed as the equation below[35]:

$$HHV = 0.1846V_m + 0.0352F_c \tag{2.4}$$

2.5.5 Burning Rate and Ignition Time

Burning Time

Burning time refers to the duration for which a briquette continues to combust before it is completely reduced to ash. Studies show that burning time generally increases with higher binder content, because binders improve particle bonding and lead to higher density and lower porosity. The reduced air gaps between particles limit oxygen diffusion and heat transfer within the briquette, causing slower flame propagation and a longer burning period. However, this also means that briquettes with very high density may exhibit lower volatile release and incomplete combustion, especially if the feedstock contains more incombustible or ash-forming components. Previous investigations have reported that briquette density directly influences combustion rate, as reduced porosity restricts both the inflow of oxidizing air and the outflow of combustion gases[36].

Ignition Time

Ignition time is the average amount of time needed to bring a volatile flame to a steady glow. It rises as the number of binders does, and this is explained by the increased density brought on by improved bonding. Because of the reduced porosity caused by this improved bonding, there is less oxidant infiltration and combustion product outflow during combustion. Because of its low density and thermal conductivity, the ash created slows down the rate of combustion and flame spread. The low porosity of briquettes also hinders drying and chars burning processes due to less free space for mass diffusion. According to[31], ignition time is the time taken for a known mass of fuel to ignite and was determined using the following procedure, exactly 100 g of briquette was placed on a wire mesh grid (of known mass resting) in between two fire-retardant bricks to allow free flow of air around it. A Bunsen burner was placed directly underneath this platform and adjusted to a blue flame. The burner was lit until the briquette was ignited. The ignition time was computed using the formula below:

$$I_t = t_1 + t_0 \tag{2.5}$$

Where; It, the ignition time, t1, the time briquette ignited (min), and t0, time the flame lighted (min).

2.6 Briquettes from Mixed Biomass

To enhance fuel quality production and utilization of mixture of different biomass is very good strategy and at the same time valorizing the differ types of biomass waste from agriculture or agro industry and wood processing industries. This manufacturing of biomass briquette from different biomass blends helps for optimization of the desired fuel characteristics of the briquette such as ash content, moisture, calorific value, and mechanical durability, which determines the suitability of the resulting briquette for both domestic and industrial applications. There are studies on investigating the benefits of manufacturing from mixed biomass. [37] Studied a briquette produced from a mixture of oil palm empty fruit bunches (OPEFB) and palm oil shells. The goal of this study was to maximize calorific value and the result showed that highest calorific value (5,475 Cal/g), was obtained at the blending ratio of 25:75 oil palm empty fruit bunches to palm oil shells. This implying that the proportion of each biomass strongly influences energy content.

Similarly, [36] investigated biomass briquette from blends of coconut shell waste, bamboo charcoal, rice husk, and coffee skin. The calorific value ranged widely depending on the additive, with coconut shell and bamboo charcoal achieving the highest value (7110.73 Cal/g). The influence of the different biomass blends on the briquette's physiochemical properties like; moisture, ash, and volatile matter were also demonstrated by the study. The influence of blend ratio on mechanical properties was further explored by [37], who examined briquettes made from rice husk and pine sawdust. Using a factorial experimental design, they found that mechanical durability exceeded

97.5% under optimal conditions (110 °C, rice husk ≤60%). Compaction time and biomass proportion were statistically significant in achieving appropriate density and elasticity, indicating that mechanical performance can be tailored by adjusting blend ratios and processing parameters. Additionally, [40] formulated briquettes from blend of rice straw, sugarcane bagasse, banana peels, coconut shells, and cattle manure, targeting to obtain briquettes with high physical, mechanical, and calorific properties. Among theses the best briquette in terms of calorific value, compressive strength, durability, and density was shown at the briquettes produced with high sugarcane proportion achieved a calorific value of 18.71 MJ/kg, durability of 99.8%, compressive strength of 24.07 MPa, and bulk density of 1538.8 kg/m³. [41]focused on pine sawdust and rice husk mixtures, evaluating mechanical behavior using both compression and free-fall tests alongside finite element modeling (ANSYS). Increasing the rice husk content enhanced Young's modulus and compressive strength, indicating stronger briquettes capable of withstanding transportation and handling, while free-fall tests confirmed durability under impact. All these studies indicated that mixing different biomasses for briquette production plays a crucial role in optimization of calorific value, mechanical durability, density, and combustion properties. Despite these advantages, further research is needed to standardize optimal blend ratios for different feedstock, assess long-term storage stability, and evaluate emission characteristics under real combustion conditions.

2.7 Sustainability Considerations: Economic and Environmental Aspects

Biomass briquetting has both combined benefits of economic feasibility and environmental benefits with a promising pathway towards sustainable energy production. This two-way aspect is very significant for treating briquettes as an alternative to fossil fuels in domestic and industrial applications.

2.7.1 Economic Considerations

One of the most critical factors in briquette production technology as a sustainable fuel alternative is its economic feasibility. Briquetting adds value to agricultural and industrial residues that are otherwise underutilized or discarded, creating a low-cost feedstock for energy production**.** This strategy addresses waste management challenges along with providing opportunities for income generation, cost savings, and local energy security [18].

Several studies have demonstrated the economic feasibility of biomass briquette production. For instance, cashew nutshell briquettes produced in Southeast Sulawesi, Indonesia, at a production capacity of 2,000 tons per year, were analyzed for profitability. The study reported revenue of USD 1,052,878 per year, production costs of USD 842,304, and a net profit of USD 147,402 per year, with an investment rate of 23.55% and a payback period of 3.42 years. Additionally, replacing liquefied petroleum gas (LPG) with these briquettes reduced household fuel costs by 37%, highlighting the economic benefits to both producers and consumers[42]. These results indicate that large-scale biomass briquette production can be financially sustainable while providing an affordable alternative to conventional fuels.

The economic performance of briquettes is influenced by several factors, including feedstock availability, production technology, densification pressure, binder type, and energy input. Utilizing low-cost or waste feedstock, such as agricultural residues, sawdust, or bagasse, significantly reduces raw material costs, improving overall profitability. Moreover, the integration of briquette production into local energy markets can enhance economic resilience by providing a renewable, locally sourced fuel that reduces dependence on imported fossil fuels[18]. In addition, small-scale production models can support community-based enterprises, create employment and foster local economic development.

Despite the positive economic outcomes reported, several research gaps remain. Most studies focus on single-site or laboratory-scale analyses, limiting the understanding of scalability and long-term profitability. Furthermore, there is a lack of detailed regional cost-benefit analyses for different feedstock, binder types, and production technologies, particularly in developing countries. Addressing these gaps through comprehensive techno-economic studies will strengthen the case for widespread adoption of biomass briquettes and guide policy decisions aimed at promoting renewable energy utilization.

2.7.2 Environmental Considerations

The environmental performance of biomass briquetting is a critical aspect in promoting it as a sustainable alternative to fossil fuels. Biomass briquettes not only utilize agricultural and industrial residues, thereby reducing waste, but also offer a renewable energy source with lower net greenhouse gas emissions. Life Cycle Assessment (LCA) studies have shown that the environmental impacts of briquette production are influenced by feedstock type, blending ratio, densification technology, and the inclusion of additives such as plastics.

For example, an LCA model developed for mixed rice husks and corn cobs indicated that the briquetting unit itself contributed approximately 42% of the total life cycle operational energy**.** The study further demonstrated that increasing the proportion of rice husk in the blend increased environmental impacts including global warming potential, acidification, human toxicity, ozone depletion, and terrestrial Eco toxicity due to lower briquette density and higher handling energy requirements[43]. Similarly, a review of biomass briquette and pellet production in Latin America highlighted that dedicated biomass systems, especially using urban forest residues, tend to be more environmentally benign than multifunctional systems. Global warming potential, cumulative energy demand, acidification, and eutrophication were found to be significantly lower for pellets and briquettes produced in these optimized systems[44].

Feedstock choice and blending also play a major role in reducing environmental impacts. Studies on corncob, burnt corncob, burnt rice husk, and polypropylene briquettes showed that corncob briquettes without plastic exhibited superior chemical properties and lower environmental impacts, with an eco-cost of only 0.387 USD per unit. The inclusion of plastics as binders slightly increased environmental burdens, suggesting that pure biomass blends are generally preferable for minimizing emissions[43]**.** Furthermore, the mixing of feedstock, such as sawdust with cornhusk or cassava peels, has been found to enhance structural integrity, reduce voids in the briquette, and improve combustion efficiency, thereby lowering CO_2 and NO_2 emissions during use [32]from previous discussion). Mineral content in feedstock, such as calcium, phosphorus, and potassium, also positively affects briquette agglomeration and combustion quality.

Despite these advantages, several challenges remain. Most studies are limited to laboratory or small-scale evaluations**,** and comprehensive industrial-scale LCA data are scarce. Moreover, the long-term impacts of binder additives, particularly plastics, on air quality and the formation of potentially harmful compounds need further investigation. Comprehensive life cycle assessments, including production, transportation, and end-use stages, are required to fully understand the environmental footprint of biomass briquettes in various contexts.

In conclusion, biomass briquetting presents significant environmental benefits by reducing waste, lowering greenhouse gas emissions, and providing a renewable energy alternative. Optimization of feedstock blends, careful selection of binders, and efficient densification technologies are crucial to minimizing environmental impacts. Future studies focusing on industrial-scale production, co-firing with fossil fuels, and regional LCA assessments will further strengthen the adoption of briquettes as a sustainable and environmentally friendly energy source.

2.7.3 Integrated Implications

The integration of economic and environmental aspects underscores the sustainability potential of biomass briquetting. By utilizing locally available agricultural residues, communities can generate renewable energy while minimizing greenhouse gas emissions and reducing reliance on fossil fuels. Economic incentives, such as reduced household energy costs and profitable production models, combined with environmental benefits like lower emissions and waste valorization, make biomass briquettes a compelling solution for sustainable energy transitions. Nonetheless, challenges remain, particularly regarding industrial-scale production, feedstock collection logistics, and the environmental impact of binders such as plastics. Comprehensive life cycle assessment studies covering production, transportation, and end-use phases are necessary to fully understand the sustainability profile of briquettes in different contexts. Policies supporting renewable energy adoption, investment in densification technologies, and regional environmental monitoring are crucial for maximizing both economic and environmental gains.

2.8 Summary of Related Studies and Research Gap

Recent studies have highlighted the potential of agricultural residues and plastic wastes for producing high-quality biomass briquettes with improved mechanical and combustion properties. [8]investigated briquettes from sugarcane bagasse and reported densities of 0.91–1.03 g/cm³ and calorific values of 17.8–18.5 MJ/kg**,** demonstrating the influence of feedstock characteristics on fuel quality. [41]evaluated sawdust-rice husk briquettes and found compressive strengths ranging from 2.8 to 5.1 MPa**,** emphasizing that feedstock blending ratios critically affect structural integrity and durability. Similarly, [39]reported that rice husk–pine sawdust briquettes achieved compressive strengths of 3.2–4.8 MPa**,** confirming the importance of feedstock composition on mechanical performance. The use of thermoplastic waste as a binder has been shown to improve both durability and water resistance. [44]produced LDPE-coconut husk briquettes with binder contents of 5–15%**,** resulting in compressive strengths of 3.5–6.2 MPa and high tumbling durability, indicating that binder percentage significantly enhances mechanical performance. [19]studied PET-sawdust briquettes and reported a calorific value of 22.3 MJ/kg. [23]evaluated agricultural-plastic wastes and highlighted that particle size, chemical composition, and binder content influence both binding mechanism and fuel properties, demonstrating the importance of carefully selecting feedstock and plastic type.

Several studies have also addressed the combined evaluation of mechanical, physical, and combustion properties. [38]produced briquettes from mixtures of agricultural residues and binders, reporting high compressive strength, low water absorption, and calorific values between 18.5–21 MJ/kg**,** while [10]measured burning rate and CO emissions from rice husk pine sawdust briquettes, showing that both feedstock composition and binder type influence combustion efficiency and emission characteristics. [20]additionally evaluated solid waste-derived fuel briquettes from mixed wood and PET, demonstrating that plastic-bonded briquettes can achieve higher durability and energy content compared to conventional biomass fuels. Despite these advances, significant research gaps remain. Very few studies have examined sawdust-bagasse mixtures with thermoplastic waste as a binder, and none have systematically varied binder percentage, feedstock blending ratio, and compaction pressure simultaneously. Additionally, comprehensive evaluations that consider mechanical strength, water resistance, combustion efficiency, and emission characteristics together are still limited.

This study addresses these gaps by producing briquettes from sawdust-bagasse mixtures with three levels of thermoplastic binder, three compaction pressures, and three feedstock blending ratios, evaluating the combined effects of these parameters on mechanical, physical, and combustion performance. The uniqueness of this study lies in its focus on a feedstock combination not previously studied, its systematic investigation of multiple processing variables, and its holistic assessment of briquette quality. This approach provides a comprehensive understanding of how to produce high-performance, environmentally friendly biomass briquettes, contributing to sustainable waste utilization and renewable energy development.

3 MATERIALS AND METHODS

3.1 Description of Study Area and Location

The experiments of the study, except for the calorific value and proximate analysis determinations, which were conducted in Messebo Cement Factory, all the others were performed at Mekelle University, Mekelle city, located at a latitude of 13º 25'30" N and longitudes of 39º 27'0" E with an altitude of 2,044 meters above sea level. It is 780 km from Addis Ababa, capital city of Ethiopia. The raw sawdust was collected from furniture processing house in Mekelle city, and the raw sugar bagasse was collected from Metehara Sugar Factory, and the thermoplastic waste was collected from Aynalem a village near to Mekelle University. The following Figure 3.1 shows the map of the study drawn using a software called ArcGIS.

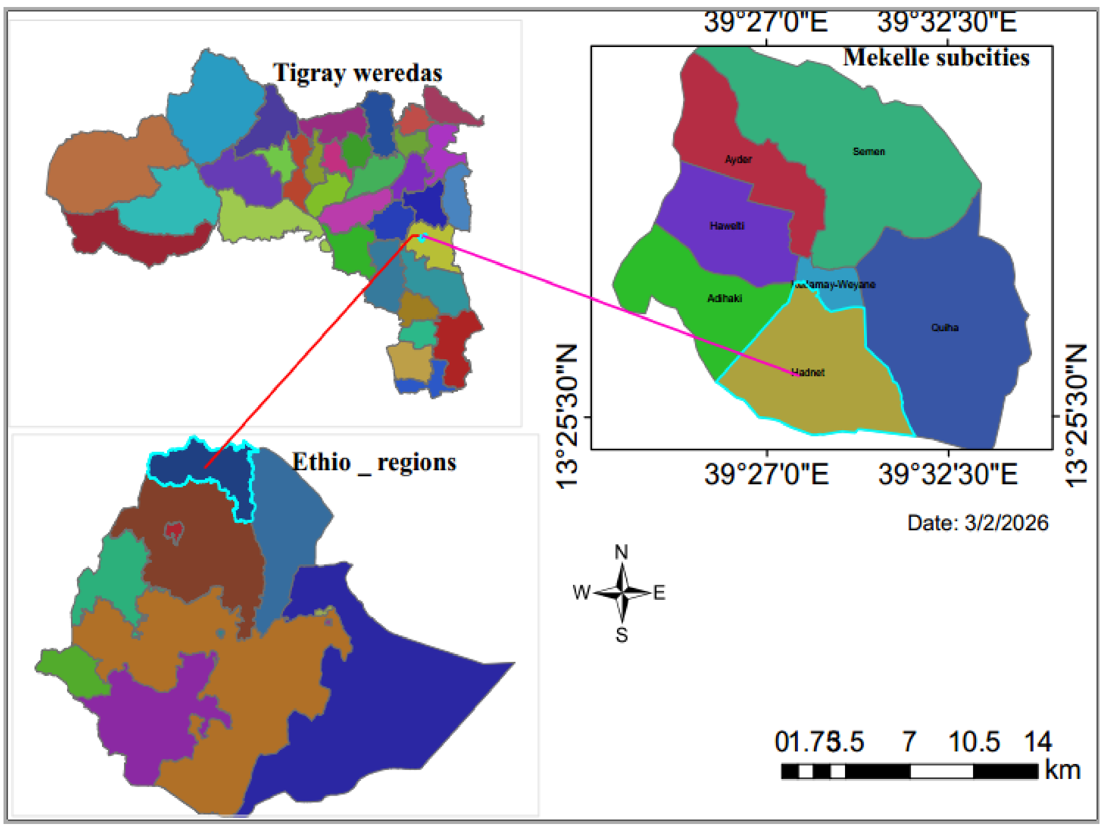

Figure 3.1: Description of study area and location using ArcGIS software

3.2 Materials, Instruments, Equipment and Chemicals

3.2.1 Materials and Chemicals

The feedstock used in this study is a mixture of sawdust and bagasse. Sawdust was collected from wood processing and furniture workshops in Mekelle City, which is readily available as a by-product. Bagasse, a fibrous residue from sugarcane processing. These materials are chosen due to their local availability, low cost, and good fuel characteristics, such as good calorific value and low ash content. The binder used was thermoplastic waste, collected from post-consumer plastic waste such as packaging films and bags. These plastics are selected due to their high calorific value, good binding properties when heated, and potential to reduce plastic pollution. The chemicals used during the investigation of organic carbon, nitrogen, and sulfur were potassium dichromate ($K_2Cr_2O_7$, 1 N), concentrated sulfuric acid (H_2SO_4), ferrous sulfate ($FeSO_4$), hydrochloric acid (HCl), nitric acid (HNO_3), nitrogen and sulfur standard solutions, bromine standard solution for calibration, a clarifying agent for turbidity removal, and distilled water.

3.2.2 Equipment and Instruments

The instruments and equipment used for the preparation, production, and characterization of the biomass briquettes were Oven and convection dryers (CE-130) were used to dry the bagasse and briquettes and to determine their moisture content. Grinders and mills (Study apparatus MG, CE-261, HERZOG D-49086) were used for size reduction. An electronic beam weighing balance (ISO 9001 certified) was used to measure the mass of samples. An analytical sieve shaker (CE-264) was used to classify particles by size. Cylindrical mold with external diameter of 6.4cm and internal diameter of 2.4 cm and a computer controlled hydraulic test machine (China, WAY-2000) were used to produce and to determine the compressive strength of the briquettes. Metal shears were used to manually cut the plastic waste into coarse flakes, and an electric hot plate was used to heat and soften the plastic waste. An IKA-Calorimeter (C4000 Adiabatic Oxygen Bomb Calorimeter) was employed to determine the calorific value. Desiccators and crucibles were used for cooling and handling of heated samples, and a ruler was used to measure briquette dimensions. a UV–Visible spectrophotometer, an automatic titrate, a magnetic stirrer, a mechanical shaker, a fume hood, a hot plate, quartz or glass cuvettes with a 1 cm path length, and standard laboratory glassware including beakers, volumetric flasks, pipettes, burettes, measuring cylinders, funnels, filter papers, watch glasses, sample containers, and spatulas. All investigations on the physical and combustion properties of the briquettes were conducted at the laboratories of the Department of Chemical Engineering, Geology, and Civil Engineering at Mekelle University, as well as at Messebo Cement Factory.

3.3 Methods

3.3.1 Framework of the Study

The organization of this study systematically includes all stages starting from the preparation of the raw materials (sawdust, bagasse and thermoplastic waste) up to process optimization. Firstly, the raw materials were collected and passed through different pretreatment processes such as cleaning, sorting, drying, grinding and sieving to make it pure, uniform and suitable for briquetting. Then the materials were mixed in varying ratios according to the experimental design plan. The experiment was design employing Design of Experiments (DOE) and Response Surface Methodology (RSM) to optimize process efficiency and briquette quality. The main responses considered were density and compressive strength while three independent variables namely, compaction pressure, sawdust to bagasse blend ratio, and binder ratio were selected. Calorific value, proximate and ultimate analysis were also determined for selected and optimized briquette samples. A Central Composite Design (CCD) structured the experimental runs, including factorial, axial, and center points, with randomization to minimize bias.

The Briquettes were produced under the specified variables and process conditions and characterized by their mechanical and fuel properties. Quadratic regression models for density and compressive strength were developed using experimental data. Furthermore, ANOVA, R^2 statistics, and lack-of-fit tests were used to validate the developed models. Finally, the validated models were employed for optimization using a desirability function in Design-Expert 13, predicting factor levels that maximize the responses. The predicted optimum conditions were confirmed experimentally. The flowchart in Figure 3.1 below shows the visual illustration of the organization of the framework of the study.

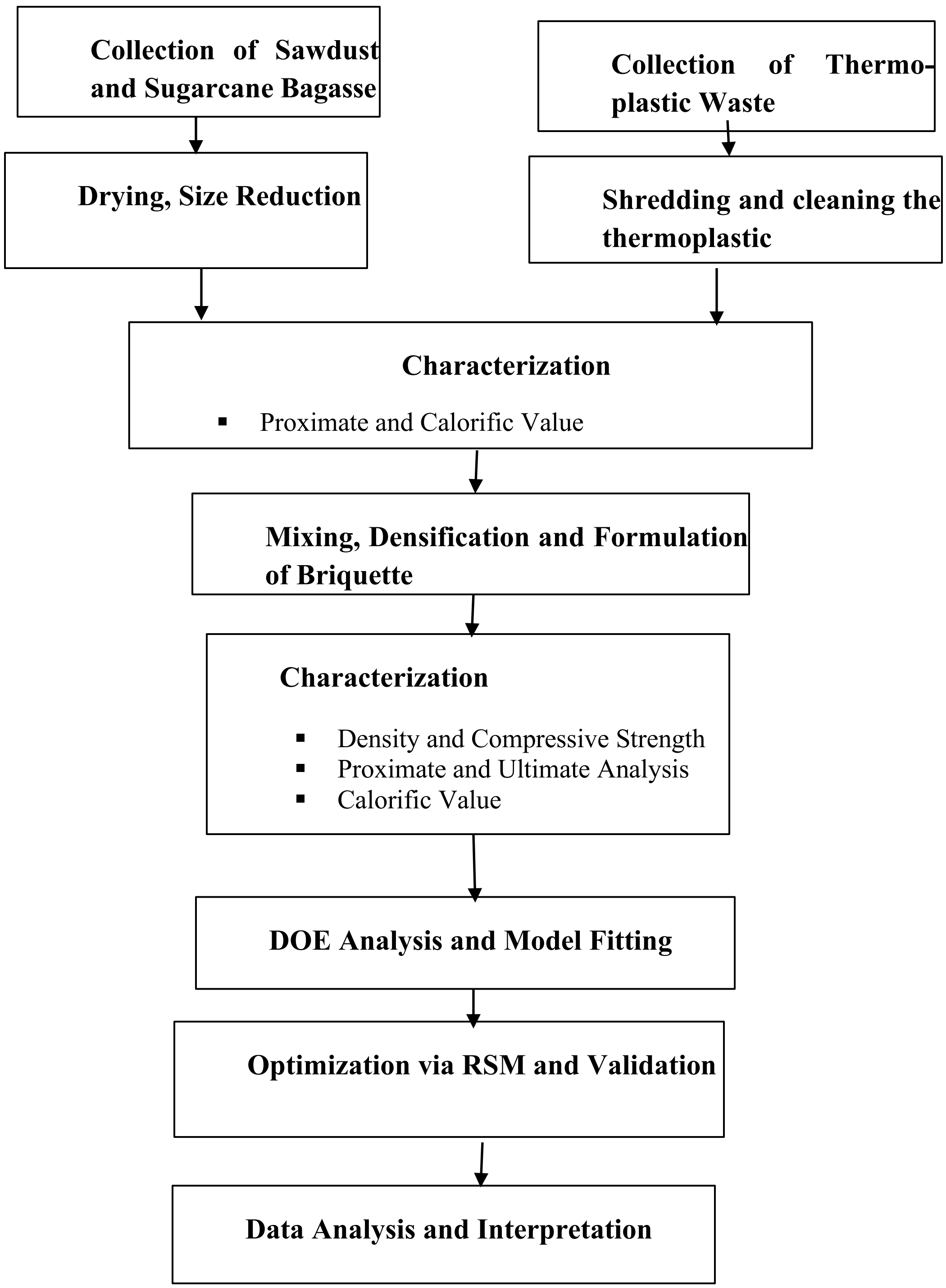

Figure 3.2: Framework of the study

3.3.2 Preparation of Raw Material (Sawdust and Bagasse)

To produce a high-quality briquette in terms of durability and combustion, raw material pretreatment is essential. Sawdust and bagasse collection, dying, size reduction, and sieve analysis are all included.

Raw Material Collection and Drying: The feedstock sugarcane bagasse from Metehara sugar factory and sawdust were gathered from furniture house in Mekelle city, then sun-dried to lower its moisture level. Fresh sugarcane bagasse has about 48% moisture after milling in the facility. The first step in solidifying the feedstock is to dry it to a moisture content of 1 to 15%. This was done in a convection dryer at 75 °C with air circulation. The source material (feedstock) is dried to increase its efficiency. However, because a tiny amount of moisture helps to bind the biomass particles, the biomass does not need to be completely dry [38]. The bagasse was dehydrated and then kept in a dry container.

Cleaning (Sorting): Sorting and cleaning the feedstock is usually the first step in the process of densifying biomass materials into briquettes. By removing any unwanted items, this procedure also referred to as sieving ensures that all the feed stock is the required size. To make the feedstock as clean as possible, contaminants like metal, plastic threads, silt, and dirt were eliminated.

Size Reduction: The size reduction was an important unit operation because it partially breaks down the lignin content of sawdust and bagasse. It increases the total surface area and bulk density leading to greater inter-particle bonding which enhances its flow during densification. The raw biomass was grounded using a mortar grinder before mixing with the binder as shown in Figure 3.2 below.

Figure 3.3: Size reduction operation using mortar grinder

Proximate and calorific value analyses were conducted on the individual raw materials sawdust, bagasse, and thermoplastic waste to characterize their baseline fuel properties before briquette production.

3.3.3 Preparation of Binder (Thermoplastic Waste)

The binder used in this study was thermoplastic waste, primarily consisting of polyethylene-based plastic materials such HDPE. These materials are selected based on their local abundance, high energy content, thermoplastic behavior, and potential to reduce plastic pollution through waste valorization. Prior to utilization, the thermoplastic waste was manually collected from household and institutional sources, followed by sorting to remove contaminants such as food residues, paper labels, and non-thermoplastic items. The cleaned plastic waste was then washed thoroughly with water and air-dried at ambient conditions to remove moisture that could interfere with bonding during briquetting. After drying, the plastic materials were shredded into small pieces with dimensions less than 5 mm to improve homogeneity and ensure effective melting and dispersion during mixing. The shredded thermoplastics were stored in sealed containers to prevent recontamination and moisture absorption. Depending on the experimental condition, the binder was incorporated into the biomass mixture at three different proportions: 5%, 15%, and 25% by weight relative to the dry biomass. Although 25% binder content may appear high due to potential environmental and health concerns, the experimental range was selected to comprehensively evaluate binder effects, and the results indicated that the optimum binder ratio was approximately 16%, achieving high mechanical strength and energy content while remaining within safe and sustainable limits. The prepared thermoplastic binder (HDPE) was blended with the biomass feedstock under mild heating conditions (100–120 °C) to partially soften the HDPE, enhancing its adhesive properties during compaction without fully melting the polymer or degrading the biomass. At this temperature, HDPE becomes sufficiently pliable to coat the biomass particles and improve binding performance.

3.3.4 Energy Densification and Briquette Production Process

To improve inter-particle bonding and increase the density of the biomass mixture, an energy densification phase was used in the briquette production process. As recommended by [38][39][40], the raw sawdust and bagasse materials were dried, crushed, and sieved to a consistent particle size of roughly 1-3 mm. Then, in accordance with the experimental design, the processed biomass materials were blended at various ratios, with bagasse serving as the supplementary fraction and sawdust ranging from 25% to 75%. According to the Central Composite Design, thermoplastic waste was utilized as a binder, with binder content ranging from 5% to 25% by weight. A cylindrical mold with outer diameter of 6.4 cm and an inner diameter of 2.4 cm made up of steel was designed in mechanical engineering workshop for briquette production. The total mass the biomass blend and the binder mixture of used to produce one briquette was 70g based on the volume of the mold used.

Figure 3.4: Production of the briquette using hallow cylindrical mold and computer controlled universal test machine and produced briquettes

The prepared mixture of sawdust, bagasse and thermoplastic was fed into the mold, then a flat cover was inserted to ensure uniform compaction. Since a thermoplastic binder was employed, no water was added during the mixing process. The filled mold was then placed in a computer-controlled electro-hydraulic universal testing machine, where densification was performed by applying compaction pressures ranging from 5 to 15 MPa. Once the desired pressure level was achieved, it was maintained for a fixed holding time 30 second to promote effective densification process[45].Then the mold was unloaded and the briquette was carefully removed to avoid structural damage. Finally, the produced briquettes were dried to stabilize their moisture content prior to characterization. A convective dryer was used at a temperature of 75 °C for 24 hours to remove residual moisture. After drying, the briquettes were and became ready for characterization.

3.4 Experimental Design and Optimization Method

3.4.1 Design of Experiments and Response Surface Methodology

There are multiple interacting variables involved in the production of biomass briquettes that affect their mechanical and fuel properties. To study the effects of these variables a Design of Experiments (DOE) approach was used because it allows simultaneous variation of independent variables helpful to evaluate both individual and interaction effect while reducing numbers of runs.

In this study, Design Expert software version-13 was used to perform experiments and statistical analysis. To model the relationship between the independent variables (pressure, binder ratio and sawdust proportion) and the responses or the dependent variables **(**compressive strength and density), Response Surface Methodology (RSM) was selected within the software. RSM is a technique that is used to develop a model from experimental data to analyze the linear, quadratic and interaction effects of variables.

3.4.2 Experimental Design: Variables and Central Composite Design

In this study the independent variables of interest were compaction pressure, binder ratio (thermos plastic waste) and sawdust to bagasse proportion. The selection is based on literature review, preliminary trail and practical feasibility. The selected variables account for the main contribution of the physicochemical performance of the briquettes. Moreover, compaction pressure affects the densification process, structural integrity and mechanical strength. Similarly, the biomass blend affects ash content, fiber content and the combustion behavior of the briquettes, whereas the thermos-plastic binder ratio governs energy content, inter-particle adhesion and strength of the briquettes.

The independent variables were varied carefully within the ranges and coded at three levels (high, center and low), corresponding to the minimum, low, center, high, and maximum values used in the Central Composite Design (CCD)**.** Coding of variables was performed in Design-Expert software Version-13 to standardize factor levels and enhance the reliability of regression modeling. The actual levels of the independent variables are summarized in Table 3.1**.**

Table 3.1 : Independent variables with their actual levels used in the CCD *

Factor	Symbol	Unit	Axial low	Center point	Axial high
Compaction pressure	A	Mpa	5	10	15
Binder ratio	B	%	5	15	25
Sawdust proportion	C	%	25	50	75

*The ranges for the three factors; compacting pressure, binder ratio and sawdust proportion were taken from previous studies [46], [47].

The three factors considered in this study compaction pressure, binder ratio, and sawdust proportion were selected based on their significant influence on briquette density, mechanical strength, and combustion properties as reported in previous studies[46][47]. The experimental ranges (5–15 MPa for compaction pressure, 5–25% for binder ratio, and 25–75% for sawdust proportion) were chosen to cover the practical limits reported in the literature while allowing sufficient variation to capture the effects of each parameter and identify optimal conditions for briquette production.

Density and compressive strength are selected as main response variables because they are directly related to the briquettes fuel property, mechanical strength and handling durability. Central composite design was used in the design of expert software to generate experimental matrix consisting of 20 including factorial points, axial points and six replicates of center points. The aims of replicating the central points are to estimate experimental error and assess reproducibility. The matrix for all the 20 experimental run is represented in Table 3.2 with their actual factor levels.

Table 3.2: Full experimental matrix for 20 central composite design runs

Run	Factor 1 A:Pressure MPa	Factor 2 B:Binder ratio %	Factor 3 Sawdust C:proportion %
1	10	15	50
2	10	15	50
3	15	5	75
4	5	15	50
5	15	5	25
6	10	15	50
7	5	25	75
8	5	25	25
9	10	15	75
10	10	15	50
11	5	5	75
12	10	15	50
13	10	15	50
14	15	25	25
15	10	15	25
16	10	5	50
17	15	25	75
18	10	25	50
19	15	15	50
20	5	5	25

3.4.3 Model Development and Validation

The experimental data obtained based on CCD runs was used to develop second order model that explains the relationship between the dependent variables: density, compressive strength and the independent variables: pressure, sawdust proportion and binder ratio. The general formula of the second order polynomial regression model will have the following form,

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X^2 + \sum_{i=1}^{k} \sum_{j=i+1}^{k} \beta_{ij} X_i X_j \quad (3.1)$$

Where Y represents the response or the dependent variable, X_i and X_j are the independent variables, $\beta_{i\,,}\beta_j,\ \beta_{ij}.\, and\ \beta_0$ are the regression coefficients for linear, quadratic and interaction effects respectively.

Analysis of variance (ANOVA) was used to evaluate the model adequacy and statistical significance at 95% confidence level in which terms of the model with p- values less than 0.05 were considered as significant. Model fit and predictive accuracy were evaluated based on the value of R^2, adjusted R^2, and predicted R^2 and the lack of fit test to check the adequacy of the model.

3.4.4 Optimization of Process Parameters

After the model is developed and validated, optimization of the briquette production process was done using design of expert software version-13. Optimization of the responses, density and compressive strength was done simultaneously using desirability function approach. The values of the independent variables, compaction pressure, binder ratio, and sawdust proportion were kept at the range used in the CCD design then the aim of the responses were to maximize their value. The software predicted the optimal combination of factor levels that would maximize the selected responses, providing estimated values for both the independent variables and the corresponding responses. In addition, graphical outputs such as Ramp plots and 3D response surfaces were generated to visualize the effects of the factors and to confirm the location of the optimum. To validate the software-optimized conditions, briquette samples were prepared at the predicted optimal settings, and their experimentally measured properties were compared with the predicted values.

3.5 Characterization of Physicochemical and Fuel Properties of Briquettes

Density and compressive strength were selected as the primary response parameters due to their direct relevance to briquette handling, storage, and structural integrity. Proximate analysis, ultimate analysis, and calorific value were additionally determined to evaluate the fuel quality and energy potential of the produced briquettes. Other properties such as durability and combustion behavior were not considered in this study due to experimental constraints and were beyond the scope of the present work.

3.5.1 Physical properties characterization

Density of the samples

The mass of the briquettes was measured in the laboratory using a digital balance. Their volumes were calculated from direct measurements of height and diameter, as the briquettes are cylindrical in shape. The density was then determined using the following equation.

$$\rho_b = \frac{M_b}{V_b} \tag{3.2}$$

Where, ρ_b is density of briquette, M_b is mass of the briquette and V_b is volume of the briquette and the cylindrical volume was calculated using the area; A and the height of the briquette; h

$$V = A * h \text{ and } A = \pi * (R^2 - r^2)$$

(3.3)

$$V = \pi * (R^2 - r^2)\, h \tag{3.4}$$

Where, R; radius of the exterior circle and r; the radius of an interior circle of cylindrical mold.

Compressive Strength

The compressive strength of the briquette samples was determined using a computer-controlled hydraulic universal testing machine, according to ASTM and as employed in recent studies on biomass briquettes[48]. Before testing, the briquettes were ensured they were dry and physically not damaged. Their height and diameter were measured using ruler then the sample was put vertically between the parallel compressions plates of the machine and exposed to a gradually increasing axial load at a constant crosshead speed of 5mm/min up to failure occurred. The maximum force that the briquette withstood was recorded and divided by the cross-sectional area of the briquette to get compressive strength.

$$\sigma_c = \frac{F_{max}}{A_C} \tag{3.5}$$

Where, σ_c *is copressive strength* F_{max} is maximum force and A_c is cross sectional area of the briquette

3.5.2 Proximate Analysis

The proximate analysis, percentage volatile matter content, percentage ash content, moisture content, and percentage content of fixed carbon of the briquettes was conducted following the standard procedure of the ASTM international (American society for Testing and Materials).

Moisture Content

The moisture content of the sample from the biomass briquette was done using the following procedure[49]. For the raw materials and for the briquette 5 g of sample was weighed and taken and placed into oven at 105 °C. Thereafter, the sample was dried and weighed until the constant weight was obtained. Then the moisture content was calculated by the equation below.

$$\text{MC}(\%) = \frac{W_1 - W_2}{W_1} * 100 \tag{3.6}$$

Where, MC (%) is percentage moisture content W1; the initial weight of the sample before drying and W2; the weight of sample after drying.

Volatile Matter Determination

The volatile matter content was determined according to ASTM standards [38], 5 grams of each sample were placed in crucibles and heated in a furnace set at 950 °C. After 7 minutes, the crucibles were removed, allowed to cool, and then weighed. This procedure was carried out for all biomass and briquette samples. The volatile matter (%) was then calculated using the following formula:

$$VM(\%) = \frac{W_i - W_f}{W_i} * 100 \quad (3.7)$$

Where: VM(%), is the percentage of volatile matter W_i is the initial weight of the sample (g) and W_f is the final weight of the sample (g).

Ash Content Determination

Similarly the ash content of the samples were determined according to the ASTM Standard by the gravimetric method using a furnace [8]. From the dried biomass briquette samples 5 g is taken into crucibles and placed in a furnace set to 600°C for 4 h, then removed, cooled and weighed. Then the percentage of ash was calculated as follows,

$$AC(\%) = \frac{W_a}{W_s} * 100 \quad (3.8)$$

Where, Wa is the weight of ash, Ws is the weight of sample.

Fixed Carbon Content

Fixed carbon content, was determined by difference from the results of the volatile matter, moisture content and as follows:

$$(\%)FC = 100 - (\%)V_m - (\%)A_C - (\%)M_C \quad (3.9)$$

Where: FC; is the fixed carbon, A_C is ash content and V_M; is the volatile matter content.

3.5.3 Elemental Composition Analysis

The elemental composition of the optimized briquette sample (carbon, nitrogen, and sulfur) was determined through certified laboratory analysis conducted at the Geology Department Laboratory, Mekelle University. The analysis was performed on the optimized briquette produced under a compaction pressure of 15 MPa with 16 wt% thermoplastic binder and 51 wt% sawdust proportion. The certified analytical results provided by the laboratory are presented in Appendix D. Hydrogen content was not directly measured due to instrumental limitations; therefore, it was estimated using an empirical correlation based on proximate analysis parameters, including fixed carbon, volatile matter, ash content, and moisture content, as shown in Equation (3.10). This empirical estimation approach is commonly applied when direct hydrogen determination is not available.

$$H = \left(0.36PFC + 0.086(VM - 0.1PAC) - (0.0035PMC^2)(1 - 0.02PMC)\right) \tag{3.10}$$

Where, PFC is percentage fixed carbon, PAC is percentage ash content, PVM is percentage volatile matter and PMC is percentage moisture content.

The oxygen content was calculated by difference using Equation (3.11):

$$\%O = 100 - \%C - \%H - \%N - \%S \tag{3.11}$$

3.5.4 Calorific Value

Calorific value was determined in the Messebo Cement Factory using a device called adiabatic bomb calorimeter (IKA-Calorimeter C4000 Adiabatic). This technique measures the heat release, through the determination of the temperature difference before and after the complete combustion process of samples introduced into the container submerged in a water bath. The steps followed were: First, the selected and optimized briquette samples were milled into powder form. Then, a sample of 0.5 g was weighed on an electronic beam balance. Next, the powder sample was inserted in the capsule, and the capsule was pressed to compact the material. Following, the capsule was carefully placed into the holder. And the bomb was lowered in the calorimeter, and the cover was closed and filled with oxygen at 30 bars. Finally, the experiment ended when the sample was fully burned by measuring the temperature rise and the gross calorific value is calculated the following formula,

$$\mathrm{GCV(kca/kg)} = \frac{\mathrm{C}*\Delta\mathrm{T}}{M} \tag{3.12}$$

Where C is calibrated heat capacity of bomb calorimeter, ΔT is measured temperature rise during briquette combustion and M is the mass of the briquette sample.

4 RESULT AND DISCUSSION

To evaluate the mechanical performance and energy potential of the briquettes produced their physical and fuel properties were systematically analyzed. The main responses of interest were density and compressive strength and were measured for all the experimental runs to assess the structural integrity and durability of the briquettes. Additionally calorific value, proximate analysis and ultimate analysis were evaluated for selected and optimized samples which reflect their fuel characteristics.

Central composite design was used to examine the effect of the independent variables, compaction pressure, sawdust proportion, and thermoplastic binder on the physiochemical properties of the briquettes. Furthermore, regression models were developed for density and compressive strength, which were the main responses, and ANOVA, coefficients of determination (R^2, adjusted R^2, and predicted R^2), and lack-of-fit tests were used to evaluate model adequacy. Finally, Optimization of the process variables was done following the desirability function approach, and experimental validation was performed at the predicted optimum conditions.

The discussion is organized as follows: first, the effects of process variables on density and compressive strength are presented along with statistical analysis and response surface interpretations. This is followed by optimization of the process parameters. Finally, the physicochemical and fuel properties of the selected and optimized briquettes are presented to confirm their energy potential and suitability as alternative fuel.

4.1 Density and Compressive Strength Analysis of Briquettes

The primary response, density and compressive strength were determined for all 20 experimental runs generated from the central composite design (CCD) and the result found is tabulated in table 4.1 below.

Table 4.1: Summary of density and compressive strength of briquettes

Run	Factor 1 A: Pressure MPa	Factor 2 B:Binder ratio %	Factor 3 Sawdust C: proportion %	Response 1 Compressive strength MPa	Response 2 Density g/cm^3
1	10	15	50	2.64	0.843
2	10	15	50	2.44	0.773
3	15	5	75	2.16	0.638
4	5	15	50	2.04	0.53
5	15	5	25	2.09	0.594
6	10	15	50	2.16	0.871
7	5	25	75	1.72	0.491
8	5	25	25	1.62	0.456
9	10	15	75	2.38	0.702
10	10	15	50	2.58	0.802
11	5	5	75	1.56	0.44
12	10	15	50	2.62	0.734
13	10	15	50	2.68	0.897
14	15	25	25	2.28	0.668
15	10	15	25	2.43	0.669
16	10	5	50	2.2	0.564
17	15	25	75	2.29	0.705
18	10	25	50	2.32	0.742
19	15	15	50	3.32	0.997
20	5	5	25	1.44	0.417

4.1.1 Density Analysis

The density values obtained from the experiments ranged from 0.4 to 0.9 g/cm³, indicating a strong dependence on the selected process variables. To quantify these effects and establish a predictive relationship, a quadratic regression model was developed and statistically evaluated using surface response methodology.

ANOVA for Density Model

Table 4.2: ANOVA results of Density Model from Design of Expert-13

Source	Sum of Squares	DF	Mean Square	F-value	p-value	
Model	0.4431	9	0.0492	8.68	0.0011	significant
A-pressure	0.1608	1	0.1608	28.33	0.0003	
B-binder ratio	0.0167	1	0.0167	2.95	0.1167	
C-sawdust proportion	0.0030	1	0.0030	0.5213	0.4868	
AB	0.0003	1	0.0003	0.0573	0.8157	
AC	0.0001	1	0.0001	0.0117	0.9162	
BC	$3.125E^{-06}$	1	$3.125E^{-06}$	0.0006	0.9817	
A^2	0.0016	1	0.0016	0.2813	0.6075	
B^2	0.0498	1	0.0498	8.78	0.0142	
C^2	0.0287	1	0.0287	5.05	0.0484	
Residual	0.0567	10	0.0057			
Lack of Fit	0.0378	5	0.0076	1.99	0.2343	not significant
Pure Error	0.0190	5	0.0038			
Cor Total	0.4999	19				

Based on the ANOVA results of the density model (Table 4.2), the F value of the model is 8.68 and the P value is 0.0011 that shows the model is statistically significant and the selected process variables, pressure binder percentage and sawdust proportion, sufficiently explain the variation in the density of the briquettes. From the linear terms, compaction pressure (A) has more effect on density ($F = 28.33$, $p = 0.0003$), reflecting its dominant role in the densification process. The results show that increasing pressure increases inter-particle bonding and particle rearrangement, which raises the briquette density. On the other hand, the linear effect of sawdust proportion (C) and binder ratio (B) is not statistically significant ($p > 0.05$), which means varying these factors has no significant direct impact by itself in the studied range. However, their nonlinear or quadratic term with ($p < 0.05$) which is significant. This implies that there are binder and sawdust levels beyond which density drops, most likely because too much binder results in poor compaction or too much sawdust increases void spaces. Additionally, the lack-of-fit test ($p = 0.2343$), was not significant, which means the constructed model fits the experimental data well.

Fit Statistics for Density

Table 4.3: Fit statistics for Density model

Parameter	Value	Parameter	Value
Std. Dev.	0.0753	R^2	0.9041
Mean	0.6766	Adjusted R^2	0.8865
C.V. %	11.13	Predicted R^2	0.7843
		Adeq. Precision	10.1096

According to the fit statistics shown in Table 4.3 the variation in briquette density was sufficiently described by the quadratic model. Over 90% of the observed variability is explained by the model, based the coefficient of determination **(**$R^2 = 0.9041$**)** and the model's dependability is confirmed by the modified R^2 (0.8865), which takes the number of predictors into consideration. The model's ability to forecast density for untested situations within the examined factor ranges is demonstrated by the projected R2 (0.7843), which exhibits good agreement with experimental values. Additionally, a suitable signal-to-noise ratio is shown by the appropriate precision value (10.1096), indicating that the model has enough discriminating ability for optimization.

Final Regression Model for Density

$$\text{Density}\left(\frac{g}{cm^3}\right) = +0.8070 + 0.1268A + 0.0409B + 0.0172C + 0.0064AB + 0.0029AC + 0.0006BC - 0.0241A^2 - 0.1346B^2 - 0.1021C^2 \quad 4.1$$

Where, ρ is the Density of the briquettes $\left(\frac{g}{cm^3}\right)$, A is compaction pressure (MPa), B is binder ratio (%) and C is sawdust proportion (%).

The relationship between compaction pressure, binder ratio and sawdust proportion is described by the above quadratic regression model in coded factors. The linear, quadratic and interaction terms represent both the individual and combined effect of the factors. The positive coefficient of the linear terms implies increasing compaction pressure, binder ratio and sawdust proportion results increasing density. Whereas the negative coefficient of the quadratic terms implies that each factor has an optimum value beyond which density does not increase further. Some of the interaction terms are small but included in the regression model to include the potential combined effect. Within the studied range this model gives a tool which is reliable and predictive for estimating the density of the briquette that will be used for further diagnostics, optimization and process improvement.

Model Diagnostics for Density

The accuracy and reliability of the quadratic regression model to predict density were evaluated by performing model diagnostics. The predicted density closely follows the 45° reference line as shown in the actual against predicted plot (Figure 4.1), demonstrating good level of consistency between the experimental data and model predictions. Most of the data points lied near the reference line across the entire density values (0.4–0.9 g/cm³) having minor deviation at higher density that indicates the model is reliably represent the trend of the experimental data.

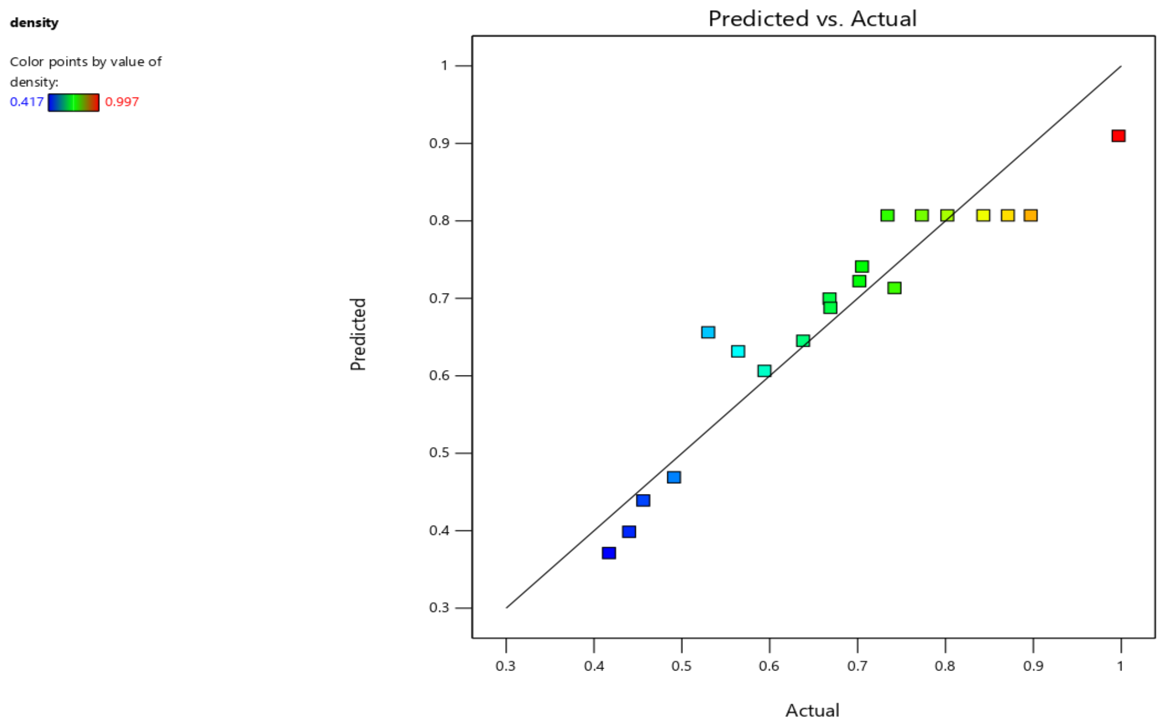

Figure 4.1: Actual against predicted plot of density

Effect of Compaction Pressure, Binder Ratio, and Their Interaction on Briquette Density

The result indicated that the density of the briquettes ranged from 0.417 g/cm³ to 0.997 g/cm³ and implies the compaction pressure and binder ratio have strong effect on density. The maximum density which is 0.997g/cm³ was observed at a compaction pressure of 15MPa, a binder ratio of 15% and sawdust proportion of 50%, on the other hand the lower density which is 0.417 g/cm³ was obtained at a lower compaction pressure of 5MPa, lower binder ration of 5% and 25% of sawdust proportion. These results show compaction pressure and binder ratio play a key role in briquette density.

Figure 4.2 shows the interaction plot of compaction pressure and binder ratio on density and clear increasing trend is observed with increasing pressure across all binder levels. For instance, at 5% binder content for instance at a binder content of 5% density showed an increment from 0.48–0.56 g/cm³ at 5–10 MPa to around 0.73 g/cm³ at 15 MPa. Similarly, at binder levels 25%, density increased from 0.49–0.55 g/cm³ at low pressure to about 0.82 g/cm³ at 15 MPa. This pattern shows that increasing pressure gives good particle rearrangement, reduces internal void space and improves mechanical interlocking of the biomass particles.

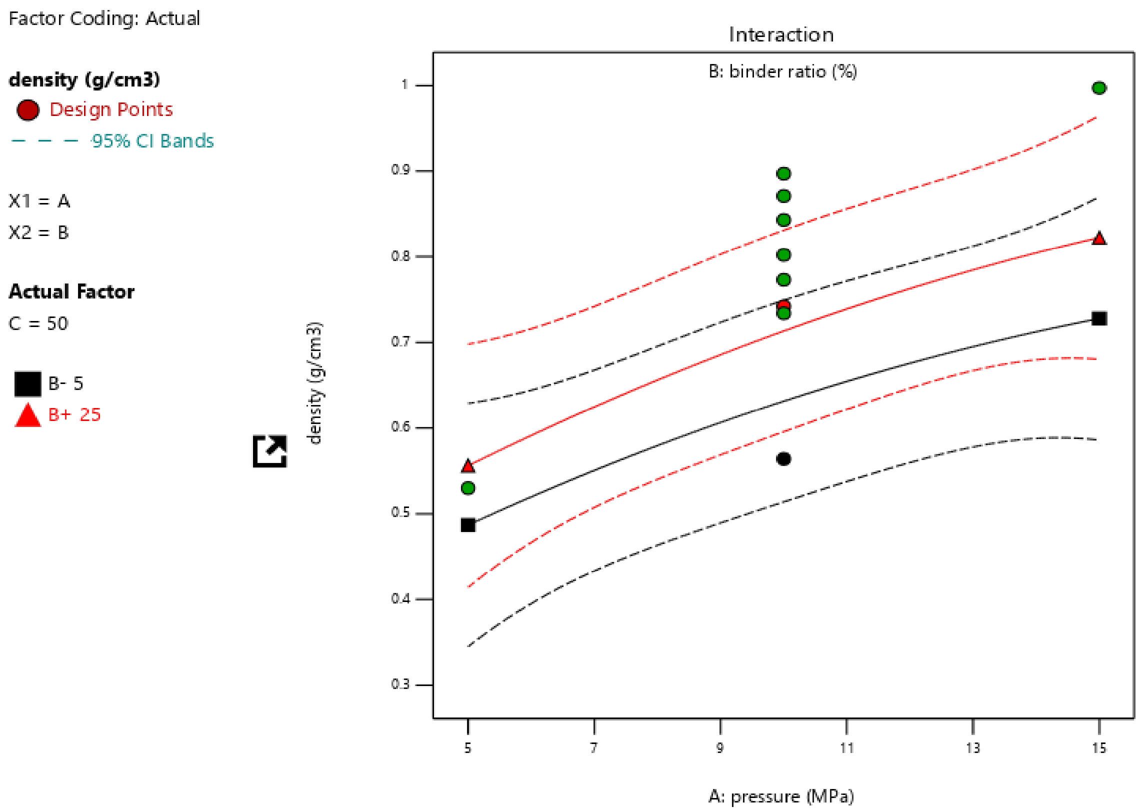

Figure 4.2: Effect of Compaction Pressure and Binder Ratio on Briquette Density

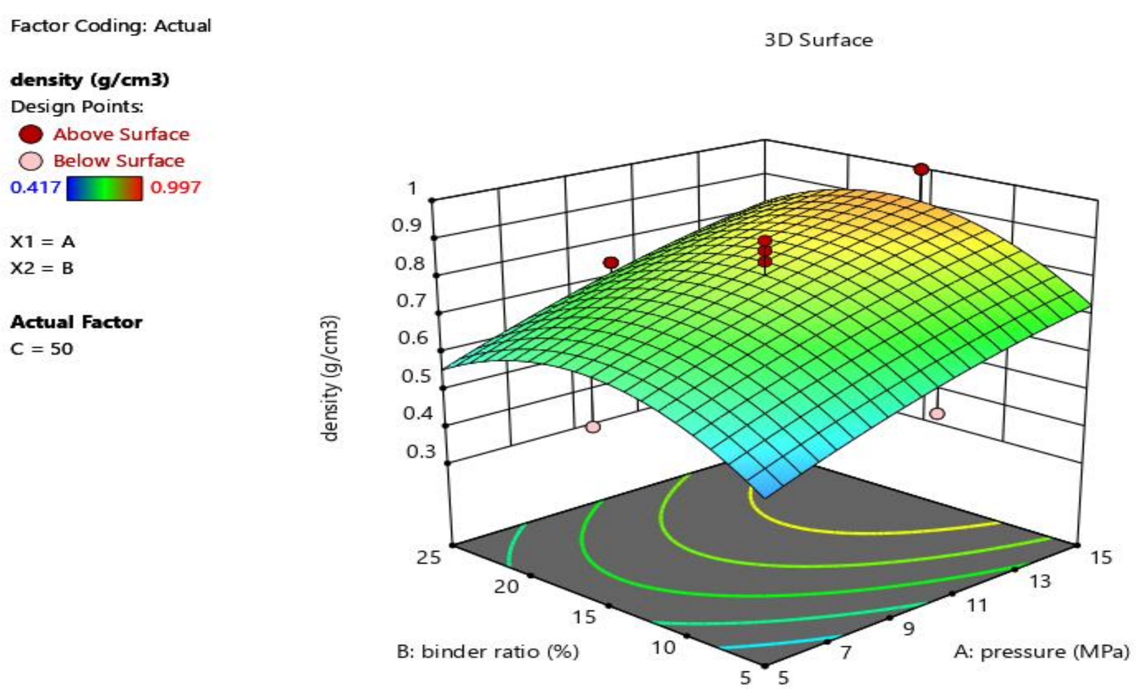

Figure 4.3: Effect of Compaction Pressure and Binder Ratio on Briquette Density, 3D plots

The effect of binder ratio on density is also observed. At comparable pressure levels, higher binder contents generally produced higher densities, particularly at moderate to high pressures. At 10 MPa, density values increased from approximately 0.56–0.64 g/cm³ at low binder content to above 0.74–0.87 g/cm³ at higher binder levels. This behavior indicates that the thermoplastic binder improves particle bonding and promotes consolidation by filling inter-particle voids and enhancing cohesion within the briquette matrix. However, the improvement in density was more pronounced at elevated pressures, suggesting a significant interaction between compaction pressure and binder ratio.

The interaction lines are non-parallel and diverging which confirms that the influence of binder ratio on density is pressure dependent. At lower pressures (5 MPa), increasing binder content resulted in only modest density improvement due to insufficient compaction energy to fully activate binder flow and particle deformation. In contrast, at higher pressures (13–15 MPa), the presence of sufficient binder enabled substantial density gains. Thermoplastic softening and flow under high compressive stress are responsible for this behavior, which improved particle packing and made it easier for solid bridges to develop between biomass particles. Due to insufficient bonding and potential elastic recovery upon pressure release, raising pressure alone without a suitable binder produced limited densification.

While increasing binder content generally improved densification, the result data shows that the highest density was obtained at intermediate binder content of 15% not at the highest binder ratio. Further adding of the binder resulted in lowering of the density this effect may be caused due to the lower intrinsic density of the thermoplastic phase compared with the biomass or increasing of lubrication effects during compaction, which limits friction and limit effective load transfer within the compact.

From a practical perspective, the experimental result indicates production of high-density briquette requires the combined optimization of both binder content and compaction pressure but not independent adjustment of single factors. The highest densities which are approximately 0.9–1.0 g/cm³ were observed at high pressure pressures (13–15 MPa) combined with moderate binder ratios (around 15%), demonstrating the interactive contribution of applied pressure and binder-facilitated particle bonding.

These findings aligned with reports from previous briquetting studies which showed increasing compaction pressure improves particle packing and the plastic waste binder increases density by softening, flow, and solid bridge formation during compression. For instance, [50]reported a maximum briquette density of 1100 kg/m^3**,** [17]observed density values ranging from 580 to 1170 kg/m^3**.** The density values found in this study, 0.417–0.997 g/cm^3, are in a good agreement to these literature reports.

4.1.2 Compressive Strength Analysis

In current study, to assess the mechanical performance of briquettes produced from sawdust using thermoplastic waste as a binder compressive strength was evaluated as one of the main responses. The experimentally measured compressive strength values for the total of 20 experimental run generated using central composite design ranged from 1.44 MPa to 3.32 MPa, showing a wide variation in mechanical behavior across the process investigated conditions. To develop reliable relationships between the process variables and compressive strength, the experimental data was modeled to a quadratic response surface model. Analysis of variance ANOVA, fit statistics and diagnostics analysis were used to evaluate the statistical significance, adequacy, and predictive capability of the model.

ANOVA for the Compressive Strength Model

As summarized in Table 4.4, The ANOVA results indicate that the overall model is statistically significant, with an F-value of 8.19 and a p-value of 0.0014, implying that the selected process variables sufficiently explain the variation in compressive strength within the investigated experimental range.

Table 4.4: ANOVA result for the compressive strength model

Source	Sum of Squares	DF	Mean Square	F-value	p-value	
Model	3.27	9	0.3638	8.19	0.0014	significant
A-pressure	1.41	1	1.41	31.81	0.0002	
B-binder ratio	0.0608	1	0.0608	1.37	0.2691	
C-sawdust proportion	0.0063	1	0.0063	0.1406	0.7155	
AB	0.0001	1	0.0001	0.0011	0.9739	
AC	0.0025	1	0.0025	0.0551	0.8191	
BC	0.0008	1	0.0008	0.0180	0.8959	
A^2	0.0003	1	0.0003	0.0074	0.9333	
B^2	0.4602	1	0.4602	10.35	0.0092	
C^2	0.1918	1	0.1918	4.32	0.0645	
Residual	0.4445	10	0.0444			
Lack of Fit	0.2549	5	0.0510	1.34	0.3767	not significant
Pure Error	0.1896	5	0.0379			
Cor Total	3.72	19				

From the linear terms compaction pressure (A) showed strong and significant effect on compressive strength ($p = 0.0002$) indicating that pressure is the dominant factor affecting the mechanical strength of the briquettes. On the other hand, the linear effect of the binder ratio (B) and sawdust proportion (C) is not significant ($p > 0.05$) this tells us that their individual effect on compressive strength is not significant when considered independently.

According to the quadratic terms binder ratio B^2 indicates statistically significant effect on compressive strength ($p = 0.0092$) which shows nonlinear relationship between binder ratio and compressive strength and suggests that there is an optimum binder content beyond which compressive strength decreases. While the C^2 (sawdust proportion squared) was insignificant ($p = 0.0645$**),** and A^2 (pressure squared) was not significant ($p = 0.9333$**),** indicating that pressure mainly influences compressive strength in a linear manner over the investigated range.

The p-value of the lack-of-fit test is 0.3767, which is greater than 0.05, indicating that the lack of fit is not significant relative to the pure error. This confirms that the developed quadratic model adequately represents the experimental data and that no systematic variation remains unexplained by the model. Overall, the ANOVA results demonstrate that the quadratic response surface model is statistically sound and suitable for describing and predicting the compressive strength of briquettes as a function of compaction pressure, binder ratio, and sawdust proportion.

Fit Statistics for the Compressive Strength Model

Fit statistics which include, the coefficient of determination (R^2), adjusted R^2, predicted R^2, coefficient of variation (C.V. %), and adequate precision was employed to assess statistical adequacy and predictive capability of the model for compressive strength. And the result is summarized in Table 4.5.

Table 4.5: Fit Statistics for the Compressive Strength Model

Parameter	**Value**	**Parameter**	**value**
Std. Dev.	0.2108	R^2	0.9104
Mean	2.25	Adjusted R^2	0.8805
C.V. %	9.38	Predicted R^2	0.7729
		Adequate Precision	10.4525

The coefficient of determination ($R^2 = 0.9104$) means the model explained approximately 91.0% of the total variability in compressive strength, showing a strong correspondence between the experimental and predicted values. The adjusted R^2 (0.8805) is clothe to the coefficient of determination ($R^2 = 0.9104$) and the predicted is R^2 (0.7729). Good precision and repeatability of the experimental data are shown by coefficient of variation (C.V. = 9.38%). Additionally, an adequate precision of 10.4525 is observed which implies adequate signal to noise ratio.

Final Regression Model for Compressive Strength

Second order regression model was developed to relate the compressive strength with individual factors (binder ratio, compaction pressure and sawdust to bagasse ratio). The final model in terms of coded factors is given in equation 4.2 below.

$$\text{Compressive strength} = +2.58 + 0.3760A + 0.0780B + 0.0250C - 0.0025AB - 0.0175AC - 0.0100BC + 0.0109A^2 - 0.4091B^2 - 0.2641C^2 \quad (4.2)$$

Where, A is compaction pressure, B is binder ratio, and C is sawdust proportion.

The linear coefficient of compaction pressure (A) is positive and tells that increasing pressure brings increasing in compressive strength and is consistent with ANOVA result that identified ($p = 0.0002$) meaning that pressure is most influential factor. This behavior is attributed to enhance particle rearrangement, deformation, and improved bonding under higher compaction forces, resulting in stronger and more consolidated briquettes. And the positive linear coefficients of binder ratio and sawdust proportion are relatively small meaning that their individual effect on compressive strength is less compared to pressure. This value agreed to the ANOVA results in which binder ratio and sawdust proportion had statistically insignificant linear effect ($p > 0.05$). However, their influence becomes important through quadratic terms.

The quadratic coefficient of both factors (binder ratio (B^2) and sawdust proportion (C^2)) that implies there is an optimum level beyond which further increasing of the optimum values of both factors lead to reduction in compressive strength. This could be due to the fact that excess binder acts as soft or lubricating phase and higher sawdust proportions reducing effective particle interlocking. Overall, the regression equation confirms that compressive strength is primarily governed by compaction pressure, while binder ratio and sawdust proportion influence the response mainly through their quadratic effects.

Model Diagnostics for Compressive Strength

Standard regression diagnostic tools were employed to examine adequacy of the developed quadratic model to predict compressive strength. Figure 4.4 is the predicted versus actual plot and it indicates that a good agreement between the model predicted and experimentally measured data. This shows that the model has good capability of accurately capturing the correlation between the independent variables and the dependent variable which is compressive strength within the studied experimental range.

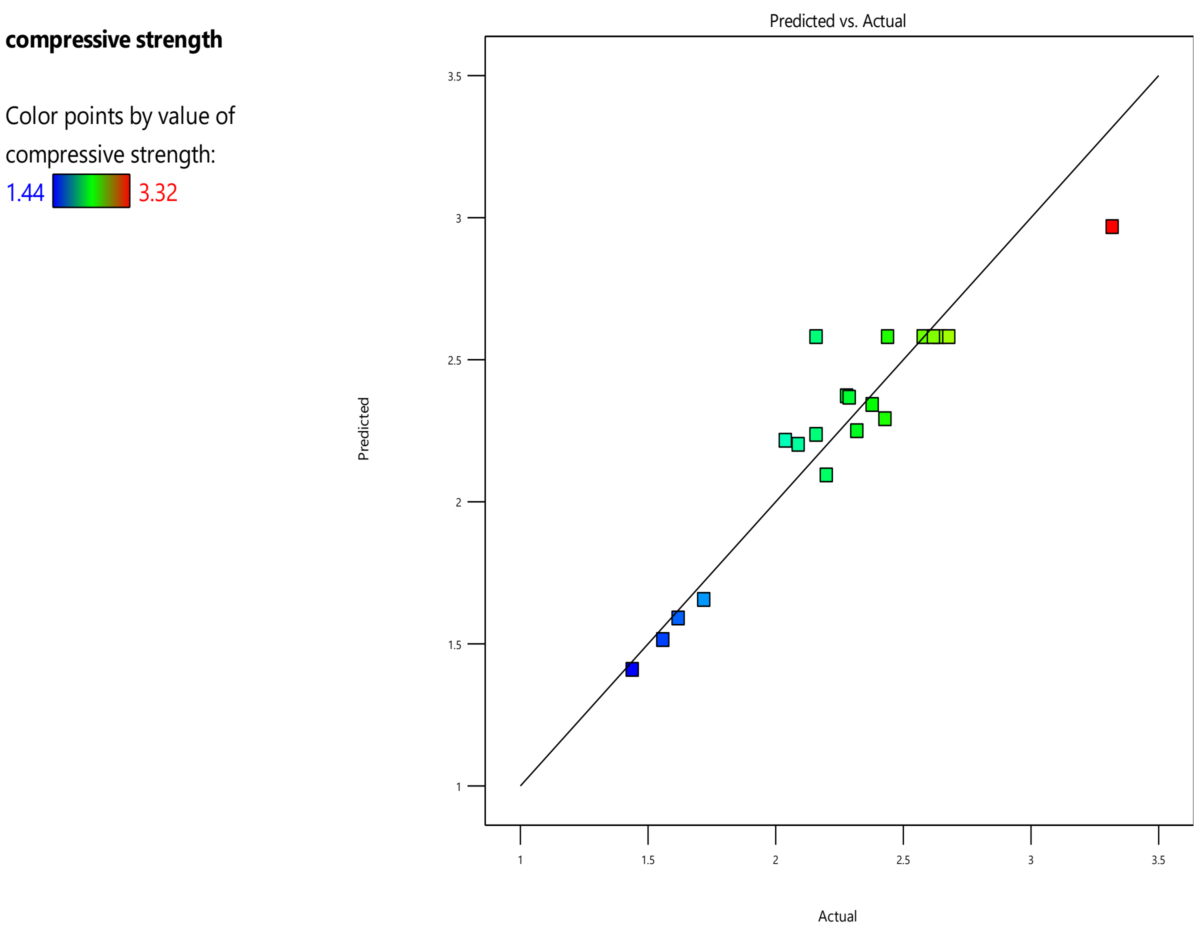

Figure 4.4: Model Diagnostics plots for Compressive Strength

Effect of Compaction Pressure, Binder Ratio, and Their Interaction on Briquette compressive strength

The results of the experiment indicated that the compressive strength of the briquette varied from 1.44 MPa to 3.32 MPa**,** showing that the mechanical performance of the briquettes was significantly affected by compaction pressure, binder ratio, and sawdust proportion. A compressive strength of 3.32 MPa which was the highest of all, was obtained at a compaction pressure of 15 MPa, binder ratio of 15%**,** and sawdust proportion of 50%**,** on the other hand (1.44 MPa) was the lowest strength compressive strength occurred at the pressure **(**5 MPa**)** and binder ratio **(**5%**)** with 25% sawdust**.** These results show that sufficient compaction energy and sufficient binder content are essential for getting strong inter-particle bonding and resistance to compressive failure.

The combined effect of compaction pressure and binder ratio on compressive strength is explained by the interaction plot (Figure 4.5) and shows a general increase in compressive strength with increasing pressure at all binder levels. For instance, at a low binder ratio of 5%, compressive strength increased from approximately 1.44–1.56 MPa at 5 MPa to about 2.09–2.16 MPa at 15 MPa. Similarly, at higher binder contents (25%), compressive strength improved from approximately 1.62–1.72 MPa at low pressure to around 2.28–2.29 MPa at 15 MPa.

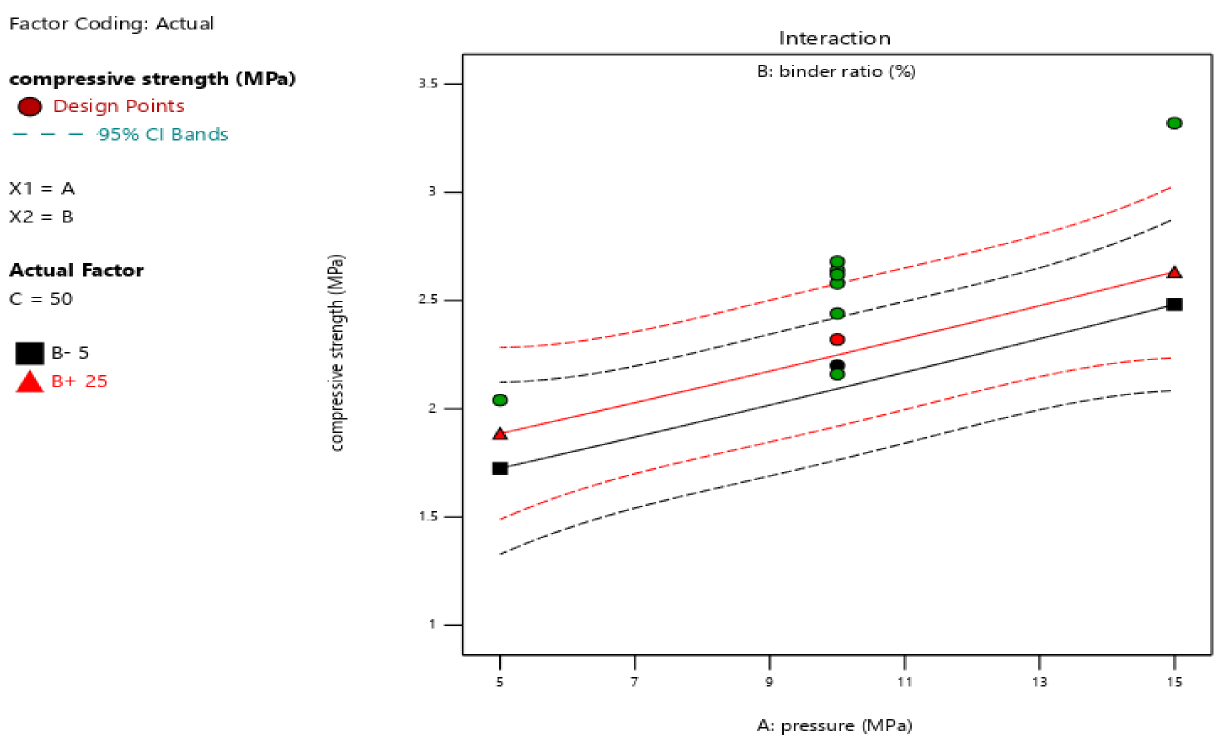

Figure 4.5: Effect of Compaction Pressure and Binder Ratio on Briquette compressive strength

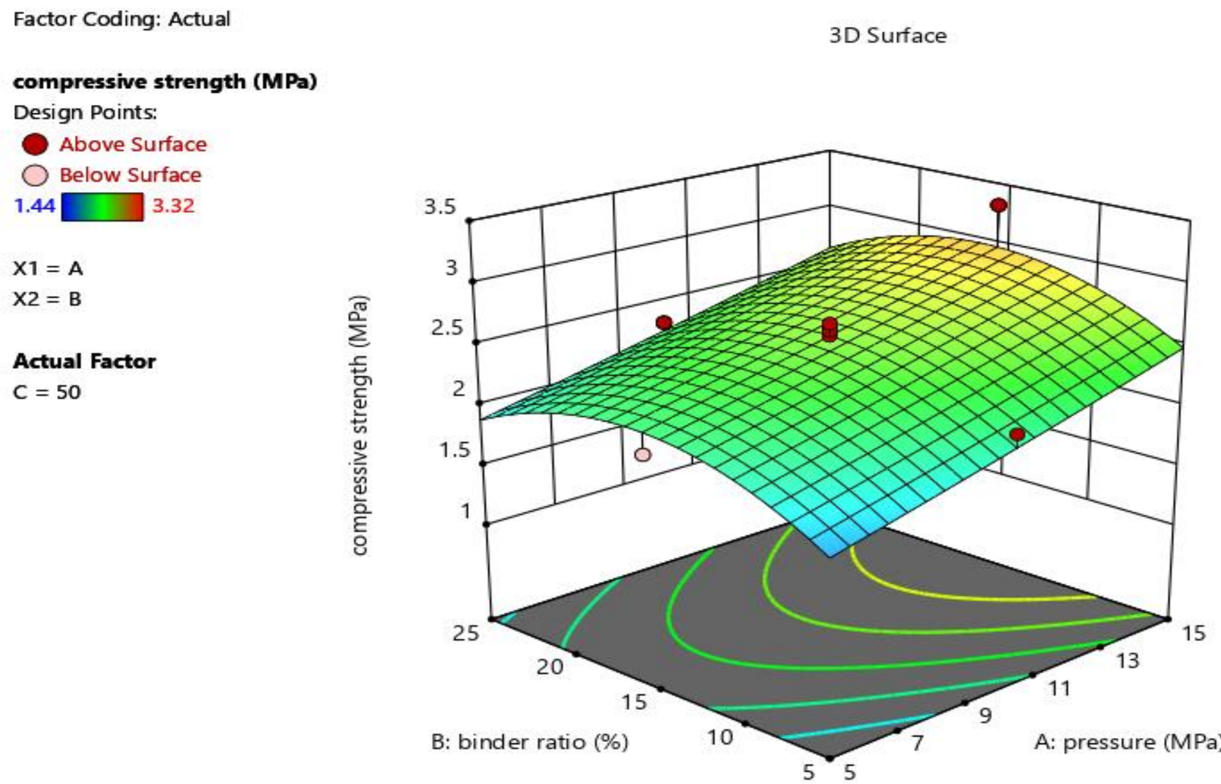

Figure 4.6: Effect of Compaction Pressure and Binder Ratio on Briquette compressive strength 3D plots

Binder ratio has also significant effect on compressive strength. At similar pressure levels, increasing binder content generally increase compressive strength, especially at moderate to high pressures, compressive strength increased from approximately 2.16–2.20 MPa at low binder content to about 2.43–2.62 MPa at moderate binder levels. This behavior implies that the thermoplastic binder improves inter particle stress transmission by creating solid bonds thereby enhancing cohesion within the briquette body; Nevertheless, the increment in compressive strength was more significant at higher pressures, indicating a strong interaction between compaction pressure and binder ratio.

The interaction lines are non-parallel which implies that the effect of binder ratio on compressive strength is pressure dependent. When compaction pressure is low (5MPa) the increase of binder content brought low improvement in compressive strength due to the inadequacy in the applied pressure to initiate binder activation and particle structural reshaping. By contrast, at elevated pressure (13–15 MPa),the applied compaction pressure to facilitate the binder to soften and redistribute leading to enhanced particle bonding and increasing compressive strength. Without adequate binder content increasing pressure alone provided small improvement in compressive strength due to weak inter-particle bond and elastic recovery could happen when the pressure is unloaded.

The points of the experimental data are closely clustered around the fitted interaction curve with narrow 95% confidence band. This shows that good model adequacy and reliable prediction of compressive strength within the investigated factor ranges. The results demonstrate that achieving high compressive strength requires simultaneous optimization of compaction pressure and binder ratio. The highest compressive strength exceeding 3 MPa was observed at high compaction pressure **(**15 MPa**)** combined with a moderate binder ratio (15%**),** highlighting the synergistic effect of mechanical compaction and binder assisted bonding.

These results are similar with previous studies on biomass briquetting, which reported increasing compaction pressure increases mechanical strength by improving particle contact and bonding, and thermoplastic binders play a key role to mechanical strength by softening, flow, and solid bond formation under compression. For example,[51] described that increasing adhesive content in biomass LDPE briquettes improved compressive strength from 4.35 MPa at low adhesive loading to 7.09 MPa at higher adhesive addition. Likewise,[52]reported an increasing of compressive strength from 1.07 MPa for briquettes without LDPE to a maximum of 2.56 MPa at 5% LDPE addition, implying the effectiveness of plastic binders in improving cohesive structure and uniform stress distribution. Relative to the findings of these studies, the compressive strength found in the present work (1.44–3.32 MPa**)** lies within the range.

4.2 Optimization of Process Parameters

The developed models for density and compressive strength were used to optimize the process. All factors were set “in range” to ensure practical feasibility. The responses: density and compressive strength were assigned the goal of maximization. Table 4.6 summarizes the ranges and goals set for each factor and response during the optimization process.

Table 4.6: Constraints for Process Parameters Optimization

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: pressure	in range	5	15	1	1	3
B:binder ratio	in range	5	25	1	1	3
C: sawdust proportion	in range	25	75	1	1	3
compressive strength	maximize	1.44	3.32	1	1	3
density	maximize	0.417	0.997	1	1	3

Numerical optimization was employed to determine the optimal combination of process variables and to establish a trade-off between density and compressive strength using the desirability function approach. In this method, each response is transformed into a dimensionless desirability value ranging from 0 (completely undesirable) to 1 (fully desirable), and the overall desirability is calculated as the geometric mean of the individual responses. The ramp plot in Figure 4.7 illustrates the contribution of each independent variable compaction pressure (A), binder ratio (B), and sawdust proportion (C) to the responses and overall desirability. The red indicators represent the optimized levels of the factors, while the blue indicators correspond to the predicted response values. The optimization results show that the best conditions were achieved at a compaction pressure of 15 MPa, a binder ratio of 16.34%, and a sawdust proportion of 51.49%, resulting in a density of 0.915 g/cm^3 and a compressive strength of 2.97 MPa, with an overall desirability value of 0.835, which was the highest among the evaluated solutions. The ramp plot further reveals that compaction pressure has a strong positive influence on both density and compressive strength due to enhanced particle packing and inter-particle bonding. The binder ratio shows an optimum at a moderate level, where sufficient binder improves cohesion, but excessive binder reduces density due to increased voids. Similarly, the sawdust proportion indicates that a balanced composition is necessary, as excessive sawdust weakens the briquette structure because of its lower binding capability.

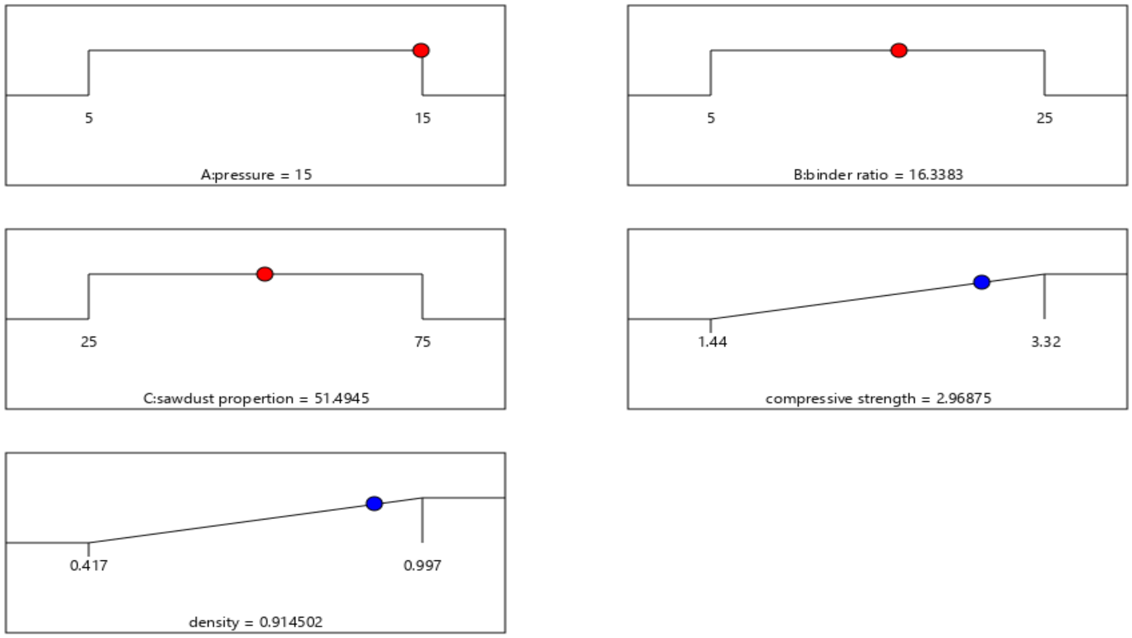

Figure 4.7: Ramp plot of Numerical Representation

These results are in close agreement with previous studies. For example, [16] reported that increasing compaction pressure from 5 MPa to 20 MPa increased briquette density from approximately 0.65 g/cm³ to 1.0 g/cm³, which supports the observed positive relationship between pressure and density in this study. In addition, [32] reported compressive strength values ranging from 1.5 MPa to 3.5 MPa for briquettes produced under moderate pressure and balanced biomass composition, which is comparable to the 2.97 MPa obtained in this study. The slight differences in values can be attributed to variations in raw material characteristics, particle size distribution, and moisture content, which significantly influence bonding mechanisms and final briquette properties. Therefore, the present findings are consistent with established literature and further confirm that optimal briquette performance is achieved through a balanced combination of pressure, binder content, and biomass composition rather than extreme values of any single factor.

4.2.1 Validation of the Optimization Results

Validation experiment was done to evaluate the reliability and predictive capability of models at the optimized process parameters. Three independent experiments were performed at 15 MPa pressure, 16.34% binder ratio, and 51.49% sawdust proportion. And the result of the responses with their deviation from the model predicted response.

Table 4.7: Validation of Briquette Physical Properties

Run	A:compaction pressure, MPa	B:binder ratio, %	C:Sawdust proportion, %	Density, g/cm^3	Density, %E	Compressive strength, MPa	Compressive strength, %E
1	15	16.34	51.49	0.937	2.35	2.914	1.89
2	15	16.34	51.49	0.874	4.69	3.05	2.66
3	15	16.34	51.49	0.869	5.29	2.874	3.30
			Average value	0.893	4.11	2.946	2.62

The three experimental results for density were 0.937 g/cm³, 0.874 g/cm³, and 0.869 g/cm³ giving an average density of 0.893 g/cm³ that is similar with the predicted density of 0.915 g/cm³. Likewise, the compressive strength was 3.05 MPa, 2.914 MPa, and 2.874 MPa, resulting in an average compressive strength of 2.946 MPa that is similar with the predicted value of 2.97 MPa. The error between experimental and predicted values were calculated and found to be within ±5%, which is generally considered acceptable in engineering process optimization.

4.3 Fuel Properties of Briquettes Characterization and Analysis

4.3.1 Proximate Analysis of Raw Materials and Briquette Samples

To evaluate the fuel properties of the raw materials, six selected briquette samples and the opti mized briquette proximate analysis and calorific value were done. The result is illustrated and summarized in Table 4.8 below. The selected representative samples and their corresponding experimental conditions are as follows: B05S25P15 (5% binder, 25% sawdust, 15 MPa), B05S75P05 (5% binder, 75% sawdust, 5 MPa), B15S50P10 (15% binder, 50% sawdust, 10 MPa), B15S50P15 (15% binder, 50% sawdust, 15 MPa), B25S25P15 (25% binder, 25% sawdust, 15 MPa), B25S75P15 (25% binder, 75% sawdust, 15 MPa), and OPT-B16S51P15 (16% binder, 51% sawdust, 15 MPa), which represents the optimized condition

Table 4.8: summary of the proximate composition result of the samples.

S/N	Sample Code	Moisture Content (%)	Volatile Matter (%)	Ash Content (%)	Fixed Carbon (%)
1	B05S25P15	6.58	61.87	4.16	27.39
2	B05S75P05	6.14	60.44	7.38	26.04
3	B15S50P10	5.37	65.42	3.82	24.89
4	B15S50P15	5.10	67.63	3.34	23.93
5	B25S25P15	4.83	72.19	3.17	19.81
6	B25S75P15	4.07	75.66	2.21	18.06
7	OPT-B16S51P15	5.21	69.35	3.46	21.98
8	SD	14.28	68.38	4.97	12.37
9	SCB	9.63	70.81	5.53	14.03
10	TPW	2.29	93.76	2.33	1.62

Moisture Content

In solid biofuels moisture content is one of the most important elements to determine fuel quality as it affects energy release, combustion stability, handling and ignition. If there is high moisture content in the briquettes it requires additional energy to evaporate the water which reduces the energy output. In this study, the raw sawdust shown highest moisture contents 14.28%, and bagasse at 9.63%, while the thermoplastic binder exhibited lowest value that is 2.29%. But when densified and briquetted the moisture content decreased significantly ranging from 4.07% to 6.58%, and the optimized briquette (OPT-B16S51P15) shown a moisture content of 5.2%.

This moisture percentage falls within the preferred range for solid biofuels, which is usually less than 8–10%. For example, recent study on briquettes formulated from agricultural pruning residues stated a briquette moisture content of around 8%,[53]**.** Similar study of investigation into agricultural biomass briquettes reported that final briquette moisture content of approximately 4.45% to 5.33%, enhancing efficient combustion and ensuring structural integrity[54]. The observed reduction in moisture content of this study is consistent with previous studies demonstrating that densification and drying of feedstock decrease moisture thereby, resulting in a briquette with enhanced combustion behavior, ignition and overall heat output.

Volatile Matter

In the present study, the volatile matter of the briquettes was recorded ranging from 61.87% to 75.66%, with the optimized briquette (OPT-B16S51P15) shown as 69.35%. These values imply that the briquettes are high in content of volatile constituents. Which is commonly typical for briquettes produced from non-carbonized biomass and thermoplastic binders. the high VM content is expected to facilitate devolatilization and stabilize flam formation which enhances ignition and maintain combustion[4]. This result strongly agrees with recent literature on biomass briquetting. For instance a study of briquette produced from mixed agricultural residues reported a VM value ranging from 68.5% to 75.8%, which showed good combustion characteristics[38]. Similarly,[55]stated that variable VM percentage (>70%) were due to the difference in composition of the raw materials and binder effects, underscoring that VM is primarily determined by the properties of the feed stock and process parameters. This VM content provides a balance between quick ignitions and sustained burning, making the briquette suitable for domestic and small-scale industrial use.

Ash Content

Lower ash content typically supports cleaner combustion, reduces slagging and fouling, and improves overall energy output. The ash content of the raw biomass feedstock was 4.97% (sawdust), 5.53% (bagasse), and 2.33% (thermoplastic binder). In the final briquettes, ash content ranged from 2.21% to 7.38%, with the optimized sample (OPT-B16S51P15) measuring 3.46%. Notably, sample B25S75P15 (25% binder, 75% sawdust, 15 MPa) exhibited an ash content of 2.21%, slightly lower than the thermoplastic binder itself (2.33%). Since a blend cannot theoretically have less ash than its lowest ash component this deviation likely arises from experimental or measurement variability during proximate analysis. Overall, the decrease in ash content after briquetting demonstrates that densification and binder addition enhanced particle bonding and reduced inorganic residue. These results are consistent with those reported by[59], which found ash contents between 2.5% and 6.8%.

Fixed Carbon

Fixed carbon represents the part of the fuel remaining after the volatile matter is released. Increased fixed carbon percentage generally contributes to greater energy density and good combustion time.

In this study the fixed carbon percentage of the raw biomass was 12.37% for sawdust, 14.03% for bagasse, and 1.62% for thermoplastic binder and the produced briquette shown a fixed carbon content ranging from 12.37% to 27.39%with optimized (OPT B16S51P15) briquette achieving 21.98%. These results are consistent with previous studies reports evaluating the fuel properties of biomass briquette. For instance, a briquette formulated from sugar cane bagasse, rice straw and banana peel reported a fixed carbon percentage of 21.2%[38]. Figure 4.8 illustrates the proximate analysis result (volatile matter, moisture content, ash content, and fixed carbon) of the raw biomass, thermoplastic binder, six selected samples and the optimized briquette samples (OPT-B16S51P15) for a visual comparison.

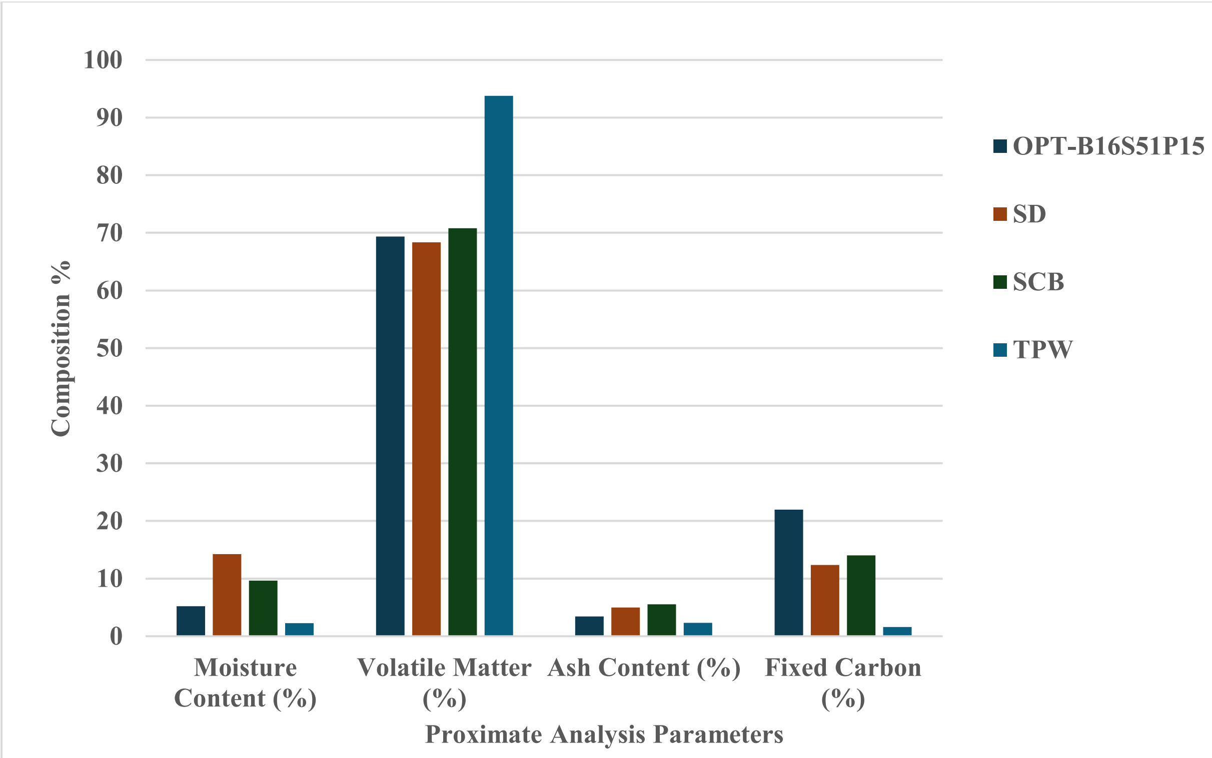

Figure 4.8: Proximate analysis comparison of raw materials and optimized briquette highlighting fuel property changes after briquetting.

As Figure 4.8 shows, the optimized briquette sample exhibits low ash content, relatively high fixed carbon, moderate moisture content and the volatile matter percentage is moderate which is suitable for combustion behavior.

4.3.2 Calorific Value of Briquettes

The gross calorific values result of the six selected briquette samples and that of the optimized one (OPT-B16S51P15) are presented Figure 4.9 below. The obtained result ranged from 3,789.43 kcal/kg (B05S25P15**)** to 5,061.52 kcal/kg (B25S75P15) and the optimized one demonstrated 4,107.83 kcal/kg. The sample with 25% of binder, 75% sawdust and pressed at 15Mpa (B25S75P15) shown the highest calorific value.

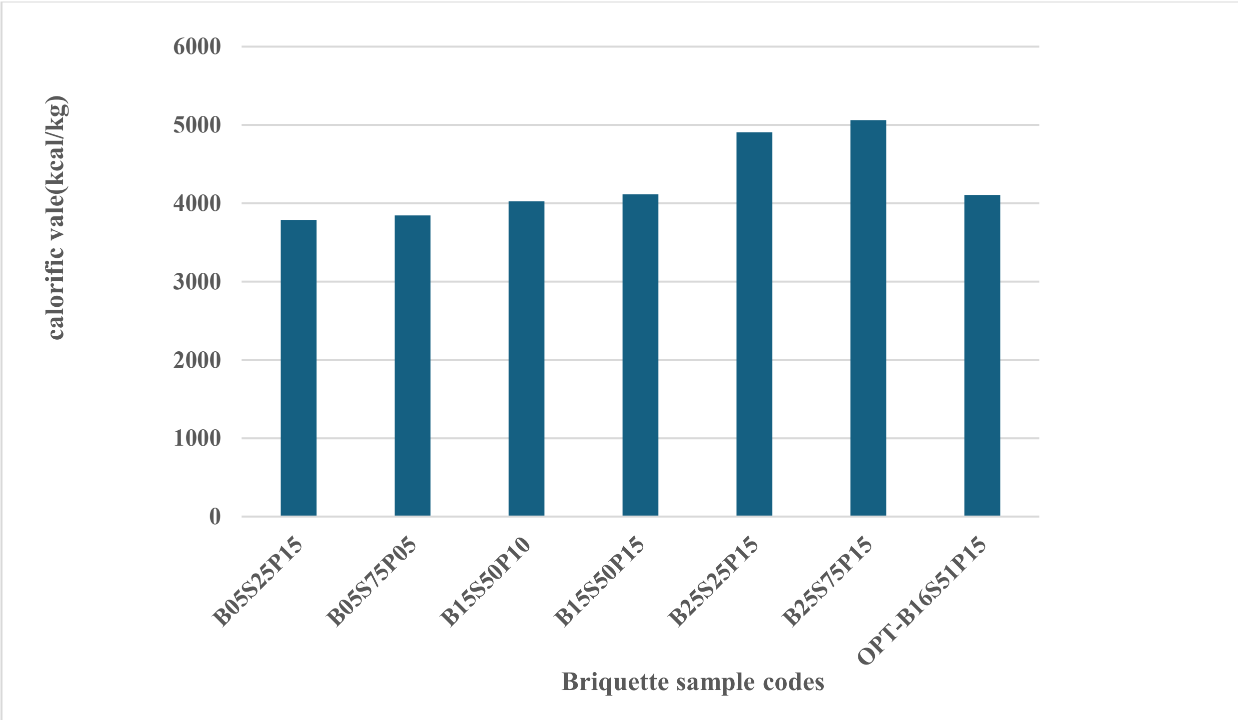

Figure 4.9: The gross calorific values of the six selected briquette samples and the optimized briquette

As illustrated in figure 4.9 above the briquette with higher binder content and balanced sawdust proportion showed higher gross calorific value and the optimized briquette sample exhibited saisfactory combined with good proximate characteristics. The calorific value result of this study agrees with reported on biomass briquettes for instance, [43] reported a calorific value ranged from 24.22–29.09 MJ/kg (5,798–6,946 kcal/kg). Another recent study investigated briquette produced from *mixed biomass briquettes* reveled that lower percentage of moisture and ash, along with higher fixed carbon, which result improved calorific values between 18.0 and 22.0 MJ/kg (4,300–5,250 kcal/kg)[57].

4.3.3 Elemental Composition Analysis of the Optimized Briquette Sample

The elemental composition analysis, carbon, hydrogen, oxygen, sulfur and nitrogen, was done for the optimized briquette sample. The result showed that the briquette is dominantly composed of carbon and oxygen with moderate amounts of hydrogen and very small amounts of nitrogen and sulfur compositions. The carbon content observed in this study was (53.85%) which is in the upper range of biomass briquette study reports. [1] Reported carbon concentration of 40–55% of dry biomass which, strongly agree with result of the present study. The high carbon content observed in the current research can be attributed due to the lingo-cellulosic nature of sawdust combined with the hydrocarbon-rich thermoplastic waste binder. The hydrogen composition was (6.03%) similar with result reported as 5–8% by [58]. The hydrogen concentration found in this study suggests that improved combustion properties of the briquette.

The Oxygen composition observed was (39.97%) agree strongly with literatures that have reported oxygen concentration varying from 35–48% [1]. The sulfur and nitrogen composition of the optimized briquette were shown to be very low 0.017% and 0.13% respectively. This is very advantageous characteristics in the environmental emission point of view because nitrogen and sulfur are the main to the NO_x and SO_x formation while burning [59]. The very low amount of nitrogen and sulfur composition reported in the present study implies that burning of the optimized briquette produced is unlikely to have significant risk related to acid gas emission.

4.3.4 Comparison of Key Results of Similar Biomass Briquette Studies

Table 4.7 : Comparison of Briquette Properties from the Present Study and Previous Literature

Reference	Biomass and Binder	Process Conditions Variables	Key Results
This Study	Sawdust and Bagasse; Thermoplastic waste (HDPE),	Particle size 1–3 mm; Sawdust-bagasse ratio 25–75%; Compaction pressure 5–15 Mpa	Moisture: 5.21%, Ash: 3.46%, C: 53.85%, H: 6.03%, N: 0.13%, S: 0.017%, O: 39.97%; CV: 4107 kcal/kg (optimized), max CV: 5061 kcal/kg
[8]	Sugarcane bagasse; Cow dung, waste-paper, molasses	Particle size 0.75–4.8 mm; Binder ratio 5–15%; Manual press	C: 47.49%, H: 5.133%, N: 1.557%, S: 0.374%, O: 45.446%; CV: 39927 kcal/kg (unit likely error)
[6]	Sawdust, Okra stalks, Corn cobs; Thermoplastic (PP)	Pressing temperature: 150–300 °C; Binder ratio: 5–15%	Fixed Carbon: 86.9% (okra stalks, 15% PP, 250 °C); Compressive strength: 10.8 MPa; Briquette durability: 94.9%; Bulk density: 510 kg/m³; CV: 38.9 MJ/kg (~9310 kcal/kg)
[57]	Banana and Avocado waste, Bagasse; Water	Air-dried, carbonized, ground; blended with water; formed into briquettes; sun-dried 5 days	Moisture: 2.66%, Volatile Matter: 39.90%, Fixed Carbon: 54.54%; CV: 29.93 MJ/kg (~7145 kcal/kg); Ignition: 1.39–2 min; Burning time: 29.1–43.41 min; CO: 1.8–14.5 ppm

[58]	Pruning residuals of Ficus nitida;	Optimal moisture content: 8%	Moisture: 8%, Briquette durability: 96.9%, Bulk density: 0.18 g/cm³, Compressive strength: 18.5 MPa; CV: 3250.7 kcal/kg (~17.38 MJ/kg)
[59]	Pineapple peels, Banana peels, Water hyacinth;	Carbonized and uncarbonized briquettes; and bomb calorimeter analysis	Moisture: 3.9–18.65%, Volatile matter: 22–75%; Bulk density: up to 1.089 g/cm³; Compressive strength: up to 53.22 N/mm²; CV: 16.22–25.08 MJ/kg (~3870–5980 kcal/kg); Boiling time: 26–41 min

The present study produced briquettes from sawdust and bagasse with a thermoplastic binder, achieving the highest density and calorific value among the reviewed studies, while exhibiting lower compressive strength. The high density results from optimized compaction pressure, small particle size, and sawdust bagasse blending, which improves particle packing and reduces void spaces. The fibrous bagasse provides natural reinforcement, enhancing mechanical interlocking. The lower compressive strength is likely due to bonding limitations of the thermoplastic binder, which prioritizes energy density over inter-particle adhesion, unlike conventional binders such as cow dung or molasses. The high calorific value is attributed to the inherent energy content of the plastic binder combined with optimized biomass blending. Overall, the comparison highlights a trade-off between density, mechanical strength, and energy output: thermoplastic-biomass briquettes maximize energy density but may require further optimization for mechanical durability. These findings demonstrate the potential of sawdust bagasse thermoplastic blends for energy-focused applications, particularly in heating and cooking, while suggesting directions for improving structural performance.

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The present study investigated the production and optimization of biomass briquettes produced from sawdust–bagasse blends utilizing thermoplastic waste particularly HDPE as a binder. The effects of binder ratio, compaction pressure and sawdust to bagasse proportion on density, compressive strength, calorific value and proximate analysis of formulated briquettes were studied in this research. Furthermore, the experiment was designed, and optimization was done using Design of Experiments (DOE), Response Surface Methodology (RSM), and Central Composite Design (CCD) that gives the optimal combination process parameter that results in balanced mechanical durability and fuel performance.

The result of experiment indicated that density and compressive strength of the briquettes are significantly affected by compaction pressure, binder percentage, and sawdust to bagasse blending ratio. If compaction pressure is increased the particle bonding will be improved and the internal void is reduced which enhances densification and structural integrity. Additionally, binder content played key role in improving inter-particle cohesion although excessive binder addition reduces direct biomass to biomass contact, weakening particle interlocking and structural cohesion. Optimization using RSM identified the optimal production parameters as a compaction pressure of 15 MPa, binder content of 16.34%, and sawdust proportion of 51.49%. Under these optimized conditions, the briquettes achieved a density of 0.9145 g/cm^3 and a compressive strength of 2.968 MPa, demonstrating sufficient durability for handling, transportation, and storage. While the maximum experimental density (0.997 g/cm^3) and compressive strength (3.32 MPa) were observed at different conditions, the optimized formulation provided a balanced combination of structural strength and fuel performance suitable for practical applications.

Proximate analysis results showed favorable combustion properties for the optimized briquettes, including a low moisture content of 5.21%, volatile matter content of 69.35%, and low ash content of 3.46%, indicating good ignitability, stable combustion, and reduced inorganic residue formation. The calorific value of briquettes shown a variation depending on binder and biomass composition. Although the maximum calorific value obtained in the study was 5061 kcal/kg under different experimental conditions, the optimized briquette exhibited a calorific value of 4107 kcal/kg, confirming its suitability as a solid biofuel while maintaining adequate mechanical durability. Elemental analysis of the optimized briquette revealed a carbon content of 53.85%, hydrogen content of 6.03%, and oxygen content of 39.97%, with very low sulfur (0.017%) and nitrogen (0.13%) levels. These results suggest a reduced potential for harmful emissions during combustion compared with conventional fossil fuels. Although direct emission measurements were not conducted, the elemental composition indicates the potential for relatively cleaner combustion behavior.

This study contributes novel findings by demonstrating the feasibility of producing optimized briquettes using a combined sawdust–bagasse feedstock with thermoplastic waste as a primary structural binder. Unlike conventional briquetting approaches that rely on starch or clay binders, the present work establishes the effectiveness of thermoplastic waste in enhancing mechanical durability while maintaining acceptable fuel performance. Furthermore, the application of RSM and CCD for process optimization under moderate compaction pressures (10–15 MPa) provides a systematic and resource-efficient methodology applicable to small- and medium-scale briquetting systems in resource-limited settings.

Despite the promising outcomes, this study has several limitations. Experiments were conducted at laboratory scale, and measurements such as direct combustion emissions, long-term storage durability, ash fusion behavior, and industrial boiler compatibility were not performed. Additionally, the work focused on specific thermoplastic waste and locally available biomass, which may limit generalizability. These limitations highlight areas for future research and practical application, as discussed in the recommendations section. Overall, the results demonstrate that briquettes produced from sawdust–bagasse blends with thermoplastic waste binders can be effectively optimized to achieve satisfactory mechanical strength, acceptable energy content, and low pollutant potential. The integration of agricultural residues with plastic waste offers a sustainable approach to solid fuel production while contributing to waste reduction and environmental management. The optimized briquettes developed in this study provide a promising alternative energy source for household and institutional thermal applications, supporting sustainable energy utilization in developing regions

5.2 Recommendations

Based on the outcome of this study the following recommendations are proposed:

- This study used thermoplastic waste particularly HDPE waste as a binder and no emissions analysis was done so, future studies should investigate emissions analysis during briquette combustion.
- Further research should be done focusing on investigation detailed economic feasibility and life cycle assessment to evaluate feasibility, scalability and energy efficiency.
- Small- and medium-scale enterprises, households, institutional kitchens, and energy-intensive industries are recommended to integrate the optimized briquette formulation as a supplemental fuel to promote sustainable energy utilization and effective waste management.
- Manufacturers are recommended to implement the optimized production parameters established in this study specifically a compaction pressure of 15MPa, binder content of 16% and sawdust proportion of 51% which gives a briquette with good fuel properties and good mechanical durability.

REFERENCES

[1] S. Lanka, “Briquettes Production as an Alternative Fuel,” Nature Environment and Pollution Technology, vol. 20, no. 4, pp. 239–244, 2021, doi: 10.46488/NEPT.2021.v20i04.029.

[2] G. Yadeta *et al.*, “Synthesis and Characterization of Briquette from Carbonized Pinus Patula Saw Dust as Alternative Energy Source,” no. 1, pp. 55–63, 2024, doi: 10.47540/ijias.v4i1.1332.

[3] M. Mengist, B. Woldeyes, and N. Gabbiye, “Production and characterization of sawdust briquettes for firewood substitution,” in *Proc. ICAST 2020, LNICST 384*, M. A. Delele et al., Eds., Springer Nature, Switzerland, 2021, pp. 3–26, doi: 10.1007/978-3-030-80621-7_1.

[4] H. M. P. Marreiro, R. S. Peruchi, R. M. B. P. Lopes, S. L. F. Andersen, S. A. Eliziário, and P. R. Junior, “Empirical Studies on Biomass Briquette Production :,” *Energies*, vol. 14, p. 8320, 2021.

[5] M. Maposa, M. Chigondo, C. Rashama, and D. Nyadenga, “Biomass Carbonization , Briquetting and Briquette Characteriza- tion : A Review Biyokütle Karbonizasyonu , Briketleme ve Briket Karakterizas- yonu : Bir İnceleme,” vol. 3, no. 1, 2025.

[6] R. S. A. Faidallah, M. A. M. Abdeen, A. Awny, and C. Mark, “Journal of Soil Sciences and Agricultural Engineering Utilization of Thermoplastic as a Binder for Producing High Quality Charred Biomass Briquettes from Agricultural Residues,” vol. 14, no. 3, pp. 81–88, 2023, doi: 10.21608/jssae.2023.194435.1149.

[7] O. F. Obi, R. Pecenka, and M. J. Clifford, “A Review of Biomass Briquette Binders and Quality Parameters,” *Energies*, vol. 15, no. 7, pp. 1–22, 2022, doi: 10.3390/en15072426.

[8] A. Gebrekidan, M. Goitom, G. Berhe, and M. Berhe, “Production and characterization of briquettes from sugarcane bagasse of Wonji Sugar Factory , Oromia , Ethiopia,” *Mater. Renew. Sustain. Energy*, no. 0123456789, 2023, doi: 10.1007/s40243-023-00248-1.

[9] G. Gebrehiwot, D. Weldegebriel, G. Haileslassi, R. Kahsay, and F. Berhane, “International Journal of Renewable Energy and its Commercialization Production and Characterization of Biomass Briquette from Sawdust and Cow Dung Admixture for Domestic Cooking Applications in Northern Ethiopia,” *Ijrec*, no. December 2019, pp. 49–57, 2019, [Online]. Available: www.journalspub.com

[10] “Combatting plastic pollution for sustainable development : A snapshot of UNDP ’ s work in 12 countries,” pp. 1–74.

[11] E. D. Ezeokolie, T. U. Maduoma, E. M. Akpotabor, O. Akanni, A. A. Garbati, A. A. Odeh, P. M. Chukwu, F. N. Achoronye, and J. N. Esonwune, “Production and optimization of briquette (solid fuels) from waste biomass using industrial starch as binder,” *European Journal of Sustainable Development Research*, vol. 8, no. 4, p. em0270, 2024, doi: 10.29333/ejosdr/15138.

[12] T. Kebede, D. T. Berhe, and Y. Zergaw, “Combustion characteristics of briquette fuel produced from biomass residues and binding materials,” *J. Energy*, vol. 2022, Article ID 4222205, 10 pages, 2022, doi: 10.1155/2022/4222205.

[13] Haile, T. Kebede, A. M. Gebrekidan, and B. Woldeyes, “Production and characterization of briquettes from carbonized *Cupressus lusitanica* sawdust with different organic binders,” *Int. J. Recent Sci. Res.*, vol. 11, no. 12(A), pp. 40189–40194, Dec. 2020, doi: 10.24327/IJRSR.

[14] W. Anggono, G. J. Gotama, C. Pronk, and I. Christian, “Characteristics of biomass briquettes from coffee husk as sustainable fuel,” vol. 03002, 2023.

[15] T. Kebede, D. T. Berhe, and Y. Zergaw, “Combustion Characteristics of Briquette Fuel Produced from Biomass Residues and Binding Materials,” vol. 2022, 2022, doi: 10.1155/2022/4222205.

[16] B. R. Segun, A. O. Olorunnisola, T. E. Omoniyi, and M. A. Onilude, “Research Highlights on Characterization of Briquettes Produced from Gmelina arborea Sawdust and Different Binders,” vol. 9449, pp. 52–62, 2024.

[17] T. Olugbade, O. Ojo, and T. Mohammed, “Influence of Binders on Combustion Properties of Biomass Briquettes: A Recent Review,” *Bioenergy Res.*, vol. 12, no. 2, pp. 241–259, 2019, doi: 10.1007/s12155-019-09973-w.

[18] S. Y. Kpalo, M. F. Zainuddin, L. A. Manaf, and A. M. Roslan, “A review of technical and economic aspects of biomass briquetting,” *Sustain.*, vol. 12, no. 11, 2020, doi: 10.3390/su12114609.

[19] M. Lubwama and V. A. Yiga, “Development of groundnut shells and bagasse briquettes as sustainable fuel sources for domestic cooking applications in Uganda,” *Renew. Energy*, vol. 111, pp. 532–542, 2017, doi: 10.1016/j.renene.2017.04.041.

[20] M. A. Garrido, J. A. Conesa, and M. D. Garcia, “Characterization and production of fuel briquettes made from biomass and plastic wastes,” *Energies*, vol. 10, no. 7, 2017, doi: 10.3390/en10070850.

[21] F. Zannikos, S. Kalligeros, G. Anastopoulos, and E. Lois, “Converting Biomass and Waste Plastic to Solid Fuel Briquettes,” vol. 2013, 2013, doi: 10.1155/2013/360368.

[22] P. E. Akhator and L. Bazuaye, “Characterization of Fuel Briquettes Produced from Pet Plastics and Sawdust,” vol. 5, no. 2, pp. 47–57, 2023.

[23] P. E. Akhator, L. Bazuaye, A. Ewere, and O. Oshiokhai, “Heliyon Production and characterisation of solid waste-derived fuel briquettes from mixed wood wastes and waste pet bottles,” *Heliyon*, vol. 9, no. 11, p. e21432, 2023, doi: 10.1016/j.heliyon.2023.e21432.

[24] M. Aliyu, I. S. Mohammed, M. Usman, S. Musa, and I. J. Igbetua, “Production of composite briquettes (orange peels and corn cobs) and determination of its fuel properties,” vol. 22, no. 2, pp. 133–144, 2020.

[25] A. C. De Conti, G. T. Nakashima, M. Paulo, P. Granado, E. Ricardo, and D. Padilla, “Binderless Briquetting of Mixed Cassava Rhizome , Sugarcane Bagasse , and Sugarcane Straw for Producing Solid Biofuel with High Durability,” 2021.

[26] N. A. Ab Jalil, N. A. Mokhtaruddin, C. H. Chia, I. K. Ahmad, M. J. Saad, and M. Sarif, “Physical and Chemical Characteristics of Agricultural-Plastic Wastes for Feasibility of Solid Fuel Briquette Production,” *Sustain.*, vol. 14, no. 23, pp. 1–13, 2022, doi: 10.3390/su142315751.

[27] I. M. A. Nugraha, I. G. Made, N. Desnanjaya, and F. Luthfiani, “Energy and economic prospects from the utilization of sawdust waste as biomass briquettes in East Nusa Tenggara,” vol. 15, no. 1, pp. 540–547, 2024, doi: 10.11591/ijpeds.v15.i1.pp540-547.

[28] M. Temmerman, “Briquette production manual”.

[29] R. P. Dewi and R. Isnanto, “Analysis of fixed carbon and volatile matter briquettes of pine sawdust and coconut shell,” vol. 14, no. 3, pp. 901–907, 2023, doi: 10.21776/jrm.v14i3.1421.

[30] J. O. Adekunle, J. S. Ibrahim, and E. I. Kucha, “Proximate and Ultimate Analyses of Biocoal Briquettes of Nigerian ’ s Ogboyaga and Okaba Sub-bituminous Coal,” vol. 7, no. 1, pp. 114–123, 2015, doi: 10.9734/BJAST/2015/15154.

[31] D. W. Hagos, M. G. Weldehans, G. G. Tesfay, T. N. Reda, D. W. Hagos, and M. G. Weldehans, “Textile & Leather Review Conversion of Tannery Solid Wastes into Fuel Briquettes Using Wastepaper as a Binder Conversion of Tannery Solid Wastes into Fuel Briquettes Using Wastepaper as a Binder,” no. November, pp. 701–717, 2023.

[32] P. D. Grover and S. K. Mishra, “Regional wood energy development programme in asia gcp / ras / 154 / net biomass briquetting : technology and practices,” no. 46, 1996.

[33] H. A. Ajimotokan, A. O. Ehindero, K. S. Ajao, A. A. Adeleke, and P. P. Ikubanni, “Combustion Characteristics of Fuel Briquettes made from Charcoal Particles and Sawdust Agglomerates,” *Sci. African*, p. e00202, 2019, doi: 10.1016/j.sciaf.2019.e00202.

[34] M. A. W. O. A. A. C. C. Enweremadu, “Influence of feedstock mixtures on the fuel characteristics of blended cornhusk , cassava peels , and sawdust briquettes,” *Biomass Convers. Biorefinery*, vol. 13, no. 17, pp. 16211–16226, 2023, doi: 10.1007/s13399-023-04039-6.

[35] G. N. Shelke, “Feasibility Study on Utilization of Biomass Briquette in a Conventional Downdraft Gasifier,” vol. 16, pp. 157–166, 2016.

[36] W. Okwara, D. Nyaanga, P. Kabok, and J. Nyaanga, “Effect of Process Techniques on Three Feedstocks Mix on Briquette Performance Properties,” vol. 7, no. 1, pp. 1–8, 2022, doi: 10.11648/j.jeece.20220701.11.

[37] E. Science, “Study of bio-briquette formulation from mixture palm oil empty fruit bunches and palm oil shells Study of bio-briquette formulation from mixture palm oil empty fruit bunches and palm oil shells”, doi: 10.1088/1755-1315/443/1/012079.

[38] Y. K. Dalimunthe, S. Kasmungin, L. Satiawati, T. Madani, and T. Ananda, "Analysis of the Quality of Mixed Coconut Shell Waste Briquettes with Various Biomass Additives as Alternative Fuels (Analisis Kualitas Campuran Briket Limbah Tempurung Kelapa dengan Berbagai Aditif Biomassa Sebagai Bahan Bakar Alternatif)," vol. 4, no. 2, pp. 2–7, 2021.

[39] P. Sawdust, "Experimental Study on the Mechanical Properties of Biomass Briquettes from a Mixture of Rice Husk and," 2020.

[40] S. F. Elsisi, M. N. Omar, M. Gomaa, and E. A. Elsaeidy, "Production the briquettes from mixture of agricultural residues and evaluation its physical, mechanical and combustion properties," vol. 40, no. October, pp. 393–418, 2023, doi: 10.21608/mjae.2023.219214.1107.

[41] O. Araque, N. Arzola, and L. Gallego, "Mechanical Behavior of Briquettes Made from a Mixture of Sawdust and Rice Husks for Commercialization," *Resources*, vol. 11, no. 3, 2022, doi: 10.3390/resources11030032.

[42] L. Ifa *et al.*, "Heliyon Techno-economic analysis of bio-briquette from cashew nut shell waste," *Heliyon*, vol. 6, no. 9, p. e05009, 2020, doi: 10.1016/j.heliyon.2020.e05009.

[43] R. Ibrahim, M. Aiduan, L. Borrion, and J. A. Stegemann, "Life Cycle Assessment Model for Biomass Fuel Briquetting," *Waste and Biomass Valorization*, vol. 13, no. 4, pp. 2461–2476, 2022, doi: 10.1007/s12649-021-01596-7.

[44] D. A. L. Silva, T. T. Matheus, and F. Freire, "A systematic review and life cycle assessment of biomass pellets and briquettes production in Latin America," vol. 157, no. November 2021, 2022.

[45] C. Study, "Life cycle assessment of biomass waste briquettes as renewable energy," vol. 11, no. 1, pp. 207–224, 2025, doi: 10.22034/gjesm.2025.01.13.

[46] S. R. Anggita, R. F. Devarasalya, and I. Istikomah, "Utilization of Waste from LDPE , Coconut Husk , and Coconut Shell with Tapioca Adhesive as Bio-briquettes," vol. 15, no. 2, pp. 81–90, 2023.

[47] S. T. Mekonone and D. Girmay, "South African Journal of Chemical Engineering Parameter optimization of biochar pressing into a briquette for energy use," *South African J. Chem. Eng.*, vol. 54, no. August, pp. 156–166, 2025, doi: 10.1016/j.sajce.2025.07.016.

[48] A. D. Seboka, J. Morken, M. S. Adaramola, G. A. Ewunie, and L. Feng, "Bioresource Technology Optimization of briquetting parameters and their effects on thermochemical fuel properties of biowaste briquettes," *Bioresour. Technol.*, vol. 439, no. 1432, p. 133277, 2026, doi: 10.1016/j.biortech.2025.133277.

[49] S. E. Ibitoye, T. C. Jen, R. M. Mahamood, and E. T. Akinlabi, "Densification of agro - residues for sustainable energy generation : an overview," *Bioresour. Bioprocess.*, 2021, doi: 10.1186/s40643-021-00427-w.

[50] Y. K. Dalimunthe and I. D. Aditya, "Mechanical Properties , Calorific Value , Proximate , and Thermal Analysis of Briquettes Made from Palm Oil Shell and LDPE with Varying

Amounts of Adhesive," vol. 153, no. October, pp. 1739–1749, 2024.

[51] T. G. Girmay, "Mekelle university," 2024.

[52] C. Demirel and D. Herak, "Compressive Property of Biomass Briquettes Made of Hazelnut Shell and Peanut Shell Compressive Property of Biomass Briquettes Made of Hazelnut Shell and Peanut Shell," 2024, doi: 10.1088/1742-6596/2734/1/012002.

[53] B. Teka, G. Mulu, B. Desta, and F. Abebaw, "Production and characterization of charcoal briquettes from sesame stalks as an alternative energy source," *Mater. Renew. Sustain. Energy*, vol. 14, no. 1, pp. 1–10, 2025, doi: 10.1007/s40243-024-00286-3.

[54] B. Song and P. Hall, "Densification of Biomass and Waste Plastic Blends as a Solid Fuel : Hazards , Advantages , and Perspectives," vol. 8, no. April, pp. 1–7, 2020, doi: 10.3389/fenrg.2020.00058.

[55] Y. K. Dalimunthe, W. Sutrisno, and I. D. Aditya, "Characteristics and Emission Tests of Briquettes Made from Palm Oil Shell Waste with Varation of LDPE Plastic as Alternative Fuel," vol. 38, no. 08, pp. 1968–1983, 2025.

[56] A. M. K. A. Aal, O. H. M. Ibrahim, and A. Al-farga, "Impact of Biomass Moisture Content on the Physical Properties of Briquettes Produced from Recycled Ficus nitida Pruning Residuals," 2023.

[57] O. Access, "briquettes from candlenut shells and kesambi twigs," vol. 7, no. September, pp. 253–264, 2024.

[58] E. Z. Gebremariyam, E. D. Demeke, and W. M. Mengistu, "Briquette production from industrial and fruit wastes as a clean fuel for versatile applications," pp. 1–15, 2025.

[59] A. P. Wulandari *et al.*, "Formulation and Characterization of Bio-Briquettes and Bio-Pellets from Ramie (Boehmeria nivea) Biomass as Renewable Fuel," 2024.

[60] T. Mibulo, D. Nsubuga, I. Kabenge, and K. D. Wydra, "Characterization of briquettes developed from banana peels , pineapple peels and water hyacinth," *Energy. Sustain. Soc.*, pp. 1–14, 2023, doi: 10.1186/s13705-023-00414-3.

[61] K. Roman and W. Rzodkiewicz, "Analysis of Forest Biomass Wood Briquette Structure According to Different Tests of Density," 2023.

[62] M. Wu, K. Wei, J. Jiang, B. Bin, and X. Shengbo, "Advancing green sustainability : A comprehensive review of biomass briquette integration for coal - based energy frameworks," *Int. J. Coal Sci. Technol.*, vol. 0, 2025, doi: 10.1007/s40789-025-00779-0.

APPENDIXES

Appendix-A: Density and Compressive Strength Determination

Density and Compressive Strength Calculation

	Factor 1	Factor 2	Factor 3	Response 1				Response 2		
Run	A: Pres-sure	B: Binder ratio	C: Sawdust proportion	Density calculation				Compressive strength calculation		
	(MPa)	%	%	h, cm	m, gm	V(cm^3)	ρ (g/cm^3)	Force (N)	A (mm^2)	Compressive strength(Mpa)
1	10	15	50	8.94	67.4	79.95	0.843	2360	894	2.64
2	10	15	50	11.05	66.2	85.64	0.773	1891	775	2.44
3	15	5	75	10.43	68.6	107.52	0.638	2227	1031	2.16
4	5	15	50	9.33	64.9	122.45	0.530	2676	1312	2.04
5	15	5	25	8.52	66.7	112.29	0.594	2755	1318	2.09
6	10	15	50	10.16	67.5	77.50	0.871	1648	763	2.16
7	5	25	75	8.92	64.2	130.75	0.491	2522	1466	1.72
8	5	25	25	10.65	68.9	151.10	0.456	2299	1419	1.62
9	10	15	75	8.86	66.4	94.59	0.702	2542	1068	2.38
10	10	15	50	9.74	68.5	85.41	0.802	2263	877	2.58
11	5	5	75	10.59	64.8	147.27	0.440	2170	1391	1.56
12	10	15	50	11.17	68.6	93.46	0.734	2193	837	2.62
13	10	15	50	7.38	66.2	73.80	0.897	2680	1000	2.68
14	15	25	25	11.81	69.3	103.74	0.668	2004	879	2.28
15	10	15	25	9.96	63.7	95.22	0.669	2323	956	2.43
16	10	5	50	10.03	68.7	121.81	0.564	1878	1215	2.20
17	15	25	75	11.38	65.8	93.33	0.705	2075	820	2.29
18	10	25	50	10.31	68.4	92.18	0.742	2968	894	2.32
19	15	15	50	10.86	67.6	67.80	0.997	1365	625	3.32
20	5	5	25	12.17	64.8	155.40	0.417	2360	948	1.44

Final Equation of Density in Terms of Actual Factors

$$
\begin{aligned}
Density \quad &= -0.317370 + 0.041570 * pressure + 0.043067\text{binder ratio} \\
&+ 0.016755\text{sawdust proportion} + 0.000128\text{pressure} * \text{binder ratio} \\
&+ 0.000023\text{pressure} * \text{sawdust proportion} + 2.50000E^{-06}\text{binder ratio} \\
&* \text{sawdust proportion} - 0.000964 pressure^2 - 0.001346 binder\ ratio^2 \\
&- 0.000163 sawdust\ proportion^2
\end{aligned}
$$

The equation in terms of actual factors can be used to make predictions about the response for given levels of each factor. Here, the levels should be specified in the original units for each factor.

Final Equation of Compressive Strength in Terms of Actual Factors

$$
\begin{aligned}
&compressive\ strength \\
&\quad = -0.380045 + 0.074223 * pressure + 0.133027\text{binder ratio} \\
&\quad + 0.045255\text{sawdust proportion} - 0.000050\text{pressujre} * \text{binder ratio} \\
&\quad - 0.000140\text{pressurje} * \text{sawdust proportion} - 0.000040\text{binder ratio} \\
&\quad * \text{sawdust proportion} + 0.000436 pressure^2 - 0.004091 binder\ ratio^2 \\
&\quad - 0.000423 sawdust\ proportion^2
\end{aligned}
$$

The equation in terms of actual factors can be used to make predictions about the response for given levels of each factor. Here, the levels should be specified in the original units for each factor.

Appendix-B: Analysis Results Letters

OF/MCF/070
Issue 1
Page 1of 1

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Date: 08/01/2026
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REF.No: MCF/2458/3.6/26

መሰቦ MESSEBO

TO: Mekelle University
Ethiopian Institute of technology-Mekelle
Faculty of Chemical Engineering

Subject: The Calorifc Value and Proximate analysis of briquette Analysis Confirmation.

According to the request (Ref.No: FoChEg/078/2018 Dated 25/04/2018) to cooperate **Samuel Teklemariam Gaim** to conduct the calorific value and proximate analysis of **briquette** in our laboratory. Hence, the analysis result of **briquette** according to our laboratory Calorific Value (bomb calori) and proximate analysis Procedure (ASTM) is tabulated below.

The Calorific Value and proximate analysis of Samples Results.

S/No	Sample Code	Calorific Value(kcal/kg)	Inherent moisture (%)	Volatility (%)	Ash (%)	Fixed Carbon (%)	Remark
01	B05S25P15	3789.43	6.58	61.87	4.16	27.39	
02	B05S75P05	3845.21	6.14	60.44	7.38	26.04	
03	B15S50P10	4022.39	5.37	65.42	3.82	24.89	
04	B15S50P15	4114.72	5.10	67.63	3.34	23.93	
05	B25S25P15	4904.38	4.83	72.19	3.17	19.81	
06	B25S75P15	5061.52	4.07	75.66	2.21	18.06	
07	OPT-B16s51P15	4107.83	5.21	69.35	3.46	21.98	
08	SD	---	14.28	68.38	4.97	12.37	
09	SCB	---	9.63	70.81	5.53	14.03	
10	TPW	--=	2.29	93.76	2.33	1.62	

With best regards,

Quality control & Optimaization Manager

ጥራትን በተግባር
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Mekelle, Ethiopia
E-mail: earthscience@mu.edu.et\

ቁጥር/Ref. No: Es/01/2018
ቀን/Date: 01/05/2018 E.C

Geo chemistry Laboratory Analytical Result Submission form

Source of Sample	Biomass Briquette	Method used
Contract Number	0005/218	
Sample ID. NO	OPT-B16S51P15	
DATE OF COLLECTION	20/12/2025	
DATE RECEIVED	04/01/2026	
LAB.ID,NO	00122/2018	
Carbon (%)	53.85	Titration method
Hydrogen (%)	6.03	----
Nitrogen (%)	0.13	KJAL- digestion method
Sulfur (%)	0.017	UV
Oxygen (%)	39.973	----

Checked by: Abadi Romha
Signature ____________
Date: 09/01/2026

Approved by: Fetihangest W/mariyam (PhD)
Faculty of Mining & Geosciences Head
Signature ____________
Date 09/05/2026

Faculty of Mining & Geosciences
College of Natural & Computational Sciences

Appendix-C: Briquette Production Processes Photos

Raw sawdust and sugar cane bagasse

Crushing

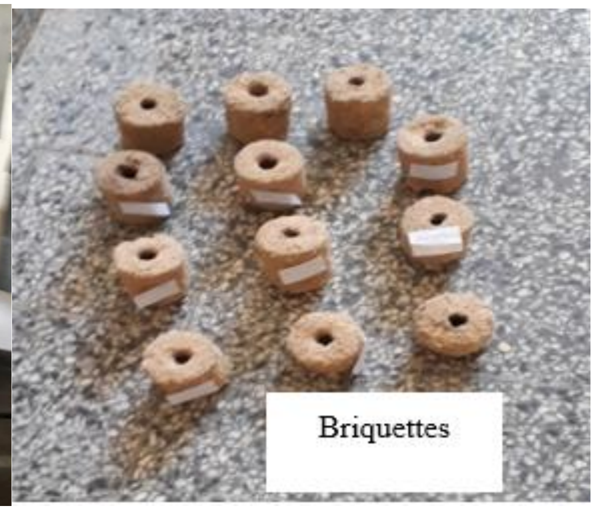
Sieving

Sieved sawdust and sugar cane bagasse

Shredded thermoplastic

Melting and mixing of the thermoplastic


Densification using mold and UTM

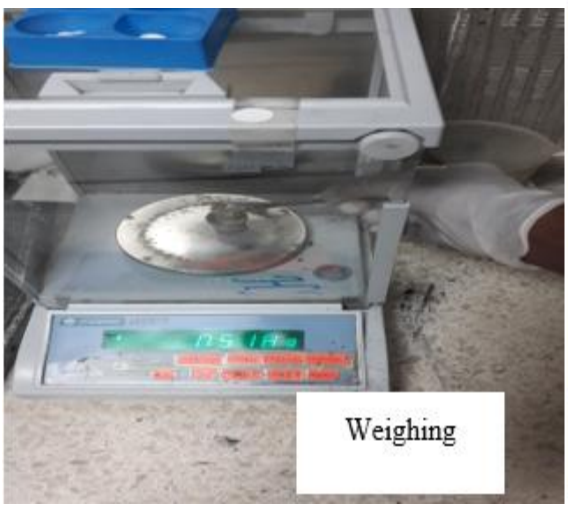

Briquettes


Compressive strength testing

Appendix-D: Proximate Analysis and Calorific Value Determination Photos


Oven drying


Milling


Weighing


Furnace


Bomb Calorimeter