ADDIS ABABA UNIVERSITY
COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES
CENTER FOR ENVIRONMENTAL SCIENCE

BRIQUETTE PRODUCTION FROM FRUIT WASTES AS A CLEAN FUEL FOR VERSATILE APPLICATION

MASTER THESIS

ELDANA ZELEKE

A THESIS SUBMITTED TO CENTER FOR ENVIRONMENTAL SCIENCE IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER SCIENCE IN ENVIRONMENTAL SCIENCE

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SUPERVISOR

DR. YEDILFANA SETARGE (ASSOCIATE PROFESSOR)

ADDIS ABABA UNIVERSITY

ADDIS ABABA, ETHIOPIA

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Center for Environmental Science

I hereby certify that Eldana Zeleke's thesis titled *"Briquette Production from Fruit Wastes as A Clean Fuel for Versatile Application,"* which was submitted to the Center for Environmental Science as part of the requirements for a Master of Science degree in Environmental Science. Complies with the university's regulations and meets the accepted standards for originality and quality.

Signed by Examining Committee

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Advisor: - Dr. Yedelfana Setarge signature --------------------Date --------------

Chair Center for Environmental Science Postgraduate Program Coordinator

Declaration

I declare that the research reported in this M.Sc. thesis is original and has been completed independently by myself (Eldana Zeleke), under the supervision of Dr. Yedelfana Setarge (Associate Professor) this M.Sc. thesis has not been submitted for the award of any other degree or professional qualification. Where other sources are quoted and full references are given

Eldana Zeleke

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Abstract

The study investigates the potential of utilizing briquettes made from banana and avocado fruit wastes mixed with bagasse as a sustainable fuel source for developing regions like Ethiopia. Despite advancements in renewable energy technologies, fossil fuels continue to dominate the global energy landscape, contributing to climate change, health, and socioeconomic issues. The primary objective of the study is to evaluate the potential of using briquettes made from banana and avocado fruit wastes mixed with bagasse as a fuel source. Fruit waste biomass samples were collected from juice houses in Addis Ababa, and bagasse was obtained from the Wonji sugar factory. The samples were air-dried, carbonized, and then analyzed for proximate content, calorific value, and emissions. The carbonized and ground samples were blended to increase briquette strength and heat value. The mixtures were prepared using fruit waste and water. The slurry was manually constricted into a briquette press, and after sun drying for 5 days, the briquettes were ready for heating and cooking. The results showed promising fuel properties, with low moisture content (2.66%), high volatile matter (up to 39.90%), ash concentration (15.57% to 35.78%), and fixed carbon content (54.54%). The briquettes exhibited high calorific values, with Sample 18 (40% avocado, 0% banana, and 60% bagasse) having a calorific value of 29.93 MJ/kg. The ignition times ranged from 1.39 to 2 minutes, and burning times varied from 29.1 to 43.41 minutes, demonstrating consistent energy release suitable for prolonged heating or cooking applications. The analysis of emissions reveals that certain compositions emitted higher levels of hydrocarbons, nitrogen oxides, and carbon monoxide, emphasizing the need to optimize the production process and combustion settings to reduce environmental impact and comply with emission regulations.

Keywords: Fruit waste, Briquettes, Sustainable energy, Solid waste management, Emission analysis, Ethiopia.

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List of Abbreviations and Acronyms

COP	Conference of Party
GHG	Green House Gas
ppm	Parts Per million
SDG	Sustainable Development Goal
UNDP	United Nations Development Program
UN	United Nations

Chapter one

1. Introduction

1.1. Background

The increasing global energy demand, driven by population growth and industrialization, has become a focal point in contemporary discourse (Adams *et al*., 2018). Energy, crucial for economic stability, security, and political dynamics on a global scale, demands strategic resource management to mitigate environmental impacts (Nejat *et al*., 2013). Despite the rapid advancement of renewable energy technologies, fossil fuels dominate the global energy landscape (Adams *et al*., 2018). This reliance, however, exacerbates climate change due to greenhouse gas emissions, intensifying the urgency for a transition to sustainable energy systems (Robinson, 2020; Jorgenson *et al*., 2019).

Furthermore, the discrepancy in energy availability continues to exist, particularly in developing regions where traditional biomass fuels are the predominant energy source. This results in negative consequences on health as well as issues in the socioeconomic sphere (Khan & Singh, 2017). This paradox is shown by Ethiopia, which is endowed with a large number of renewable energy resources; nonetheless, the country's energy industry is still underdeveloped despite the abundance of these resources (Z. Wang, 2018). According to World Bank data, wood, cow dung, and agricultural residues are used as traditional biomass energy sources in the majority of the Ethiopian population of which 83.2% live in rural areas, where modern energy services are rarely available. Fifty percent of the urban households rely on traditional biomass for cooking. And nearly all do in rural areas (except for 0.2% of households use kerosene and 1.2% is charcoal (Demeke, 2022; Kumar et al., 2021; Tessama *et al*., 2013). The consequences of insufficient access to energy transcend beyond the confines of individual families and impact the overall economic development and well-being of society (Hailu & Kumsa, 2020; Tesema, 2014).

Ethiopia, endowed with abundant renewable energy resources, exemplifies this paradox, as its energy sector remains underdeveloped despite ample (Z. Wang, 2018). The repercussions of inadequate energy access extend beyond individual households, affecting broader economic development and societal well-being (Hailu & Kumsa, 2020).

Furthermore, patterns of energy consumption mirror the development of socioeconomic conditions, with a trend toward renewable sources reflecting concerns about energy security and environmental consciousness (Ramachandra *et al.,* 2004). Biomass, as a renewable energy source, stands out for its potential to mitigate greenhouse gas emissions while addressing waste management challenges According to Chang *et al*., (2003) biomass is a renewable energy source that stands out due to its ability to reduce emissions of greenhouse gases while also serving as a solution to problems associated with waste management. However, throughout Sub-Saharan Africa, particularly Ethiopia, the inefficient use of biomass contributes to the worsening of environmental degradation and the continuation of energy poverty (Damte & Koch, 2004; (Hailu & Kumsa, 2020).

Biomass briquetting emerges as a viable approach to enhance energy density, improve transportability, and decrease biomass residue pollution (K. Demirbas & Sahin-Demirbas, 2009; Li & Liu, 2000). This is in light of the issues that have been presented. Briquetting is a technology that has developed into an industrially significant application, enabling a sustainable approach to the usage of biomass (Grover & Mishra, 1996: Kaliyan & Vance Morey, 2009). Briquetting was initially developed in response to fuel shortages that occurred during the war.

Therefore, this study aims to assess the fuel potential of briquette made from fruit wastes mixed with bagasse as well as its implication for sustainable energy production and solid waste management in Addis Ababa.

1.2. Statement of the problem

A significant proportion of mono-saccharides and disaccharides will be present in the trash if it mostly consists of entire fruit, as is the situation with banana wastes, where 5 to 30% of harvested bananas are abandoned as waste due to export limitations (Kesler, 1985). Due to their potential for disposal in landfills or waterways, these plant wastes and byproducts from the food processing industry, along with leftover fruit and plant products, all contribute to environmental dangers (Wadhwa & Bakshi, 2013), resulting in increasing instances of organic contamination and stream obstruction. Climatologists due to the pollution that they cause from greenhouse gases consequently discourage the excessive use of fossil fuels. Because greenhouse gases contribute to global warming and climate change, the greatest harm they inflict directly affects agriculture, horticulture, and forestry (El Saeidy, 2004).

Due to the current rate of generation, grid development, and population increase, it is anticipated that more than half a billion people would lack access to electricity by 2040 (Z. Wang, 2018). Globally, about one in five individuals do not have access to power. For cooking and other daily activities, many people still use charcoal, wood, crop waste, and other solid fuels. As a result, they frequently have health problems that shorten their lives, particularly those of women and children (Khan & Singh, 2017). Ethiopia is heavily dependent on traditional biomass, which is causing several environmental and socioeconomic issues. These issues include deforestation, soil erosion, water pollution, indoor air pollution, and, most significantly, deforestation, which is affecting the country's limited forest resources (Asresu, 2017).

1.3. Objectives of the study

1.3.1. General Objective

The overall objective of the study is to assess the fuel potential of briquette made from various fruit wastes mixed with bagasse as well as its implication for sustainable energy production and solid waste management in Addis Ababa.

1.3.2. Specific objectives

- To characterize the sample’s proximate analysis of fruit wastes and bagasse
- To produce fuel briquettes from leftover fruit waste and bagasse.
- To Measure briquette emission’s (GHGs).

1.4. Significance of the study

There are various positive impacts that briquetting can have on the environment, society, and economy. Initially, briquettes can be produced in a diverse range of dimensions, characteristics, and configurations to precisely accommodate stoves and burners. Furthermore, the aforementioned technique enhances the net calorific value of biomass to its volume. Briquettes are additionally convenient to manipulate, transport, and store. Furthermore, briquetting effectively addresses the problem of residue disposal and consistently yields fuel of superior quality. The extended duration of combustion exhibited by briquettes diminishes the necessity for and reliance on wood fuel, hence mitigating the consumption of fuel wood and logging activities. Moreover, this approach facilitates the appropriate disposal of residual materials, hence enhancing sanitation. Moreover, briquetting can produce both cash and employment opportunities. Briquettes may be produced from readily available biomass residue, which makes them highly favored in poor nations where biomass serves as the predominant energy source. Consequently, briquettes are regarded as a highly important contemporary biomass technology because of their extensive environmental, social, and economic advantages. In Ethiopia, the effective utilization of underutilized biomass resources can be achieved by the broad application of biomass upgrading technology. This initiative is expected to have a positive impact on home energy supply, environmental protection, sanitary conditions, and greenhouse gas emissions reduction.

Chapter Two

2. Literature review

2.1. Sustainable Development Goals and Energy

To maintain human existence and advance the general economic, social, and environmental facets of human growth, access to energy is required. The burning of fossil fuels and deforestation are widely regarded as two of the main causes of anthropogenic climate change. An alternative renewable and carbon-free raw material for the creation of energy is plant biomass (J. Tumuluru et al., 2010).

Sustainable development and the seventh Sustainable Development Goal (SDG), which promotes universal access to affordable and clean energy, are facilitated by sustainable energy (United Nations Development Program) (Uitto, 2016). Additionally, to reduce greenhouse gases (GHG), which renewable energy greatly contributes to, all nations must abide by the decisions made at the UN Conference of Parties (COP 21) on climate change in Paris in the year 2015 (Hermwille *et al.*, 2017). Energy is essential for reducing poverty and achieving the first Sustainable Development Goal, which is to eliminate the number of people living on less than $1.90 per day by 2030 (Freistein, 2016). By creating employment opportunities for those who produce biogas, briquettes, and charcoal. Since the Industrial Revolution, energy has helped people in many low- and high-income countries raise their standards of living. Because they can lessen the long-term harm that greenhouse gas emissions do to the environment and ecosystems, renewable energy sources are favored (Spang *et al.*, 2014).

Losses and waste are the portions of fruits, vegetables, and other food products that are not used or consumed due to the morphological qualities of the product, improper handling procedures, or simply thrown away for a variety of reasons. The by-products of processed horticultural goods also create a large amount of waste. FVWs come in different amounts and types depending on the product as well as morphological components like leaves, roots, tubers, skin, pulp, seeds, stones, pomace, and so on (Panouillé *et al.*, 2007). Numerous fruits and vegetables produce at least 25%

to 30% of trash that is thrown away (Ajila *et al.*, 2010). Fruit and vegetable losses and waste include the indirect waste of important resources such as land, water, fertilizers, chemicals, energy, and labor in addition to the waste of food commodities. These enormous amounts of lost and discarded food contribute greatly to environmental issues as well since they decay in landfills and release harmful greenhouse gases (Vilariño *et al.*, 2017). Fruit and vegetable processing facilities frequently emit the most waste into the environment, followed by domestic rubbish (Gowe, 2015).

In the modern world, the food sector produces a lot of trash. An estimated 1.3 billion tons of food are wasted annually in the world, which is one-third of the entire amount of food produced, according to recent data by FAO. Fruits and vegetables account for the biggest quantity of loss, amounting to 0.5 billion tons. Fruit and vegetable losses are significant in developing nations at the agricultural stage but are primarily explained by the processing stage, which accounts for 25% of losses (Colin, 1990).

2.2. Biomass Densification

A group of technologies is used in biomass densification to turn biomass into fuel. Briquetting is another name for the technology, which enhances the way materials can be handled when being transported, stored, etc.(Dr. Pham Khanh Toan & Sinh, 2000)**.**

Briquettes are fuels that convert energy by direct burning and are used for home, industrial, and commercial heating and cooking. Due to their physical makeup, they work best in fixed bed chambers. Although pellets can be employed in reactors with various geometries and feeding systems, they have the same applicability (Khlifi *et al.*, 2020; Okwu & Samuel, 2018).

Briquette manufacture frequently goes hand in hand with second-generation biofuels, encouraging the recycling of agricultural and forestry waste. Most pieces utilized waste materials like straw, wood, bark, leaves, stems, and sawdust. Waste from wood cutting (Raslavičius, 2012) and from species.

Because it is heavy, damp, and dispersed, biomass in its original form is challenging to successfully employ as a fuel in large-scale applications. The process of biomass densification entails turning plant waste into fuel. These techniques, which improve the handling properties of the materials for transport, storage, etc., are also known as pelleting, briquetting, or agglomeration. Many nations have used pelleting and briquetting for a long time (J. Tumuluru *et al*., 2010). Depending on the system being employed, process variables (such as temperature and pressure), feedstock characteristics (such as moisture content and particle size/distribution), and biochemical composition variables, the precise amount of energy needed for biomass densification will vary (e.g., presence of starch, protein, fat, and lignocellulose composition) (Reed *et al*. 1980).

Similar to briquetting, palletization creates smaller densified products called pellets using smaller dies (about 30 mm). The ring dies and the flat die is two different types of pellet presses. The rollers rotate in both ring- and flat-die machines while the die is kept still. There are other spinning die pellet mills on the market where the rollers remain during the manufacturing process.

2.3. Types of Briquetting

The briquetting technologies can be broken down into three categories based on compaction: high-pressure compaction, medium-pressure compaction with a heating element, and low-pressure compaction with a binder (Grover & Mishra, 1996). There are now two high-pressure technologies in use for briquetting: piston presses and screw extrusion machines. A screw press produces briquettes that have a concentric hole, which has better combustion properties since it has a bigger specific area than a piston press, which produces entirely solid briquettes. The screw press briquettes are uniform and resist easy disintegration. These can take the place of coal in most applications including in boilers because of their high combustion rate. From loose biomass with a bulk density of 100 to 200 kg/m^3, briquettes can be made with a density of 1200 kg/m^3. In comparison to the raw materials from which the briquettes are manufactured, a higher density gives the briquette a higher heat value and causes the briquettes to burn more slowly (Kaliyan & Vance Morey, 2009).

2.4. Manufacturing Methods and Devices

Biomass is normally densified to improve the heating value, to reduce the required storage space, and to ease transportation. Biomass typically is mixed with a binder to enhance the adhesion properties of the briquette mixture and then processed with a briquetting device. At present, there are several briquetting technologies available worldwide, and these can be classified as follows: piston press, screw press, hydraulic press, and roller press.

2.4.1. Piston Press Technology

Piston press technology is the simplest and most widely used briquetting device. It consists of a ram (piston) and a die. Biomass feedstock is fed into the chamber, and a reciprocating ram is used to compress the biomass at a high pressure against the die. When the compressed feedstock passes through the die, the briquette retains the shape of the die. Usually, circular briquettes are produced by this method. The device can accommodate biomass with a moisture content of up to 22% (Chin & Siddiqui, 2000; Dinesha *et al*., 2019) they used a piston and die press for preparing briquettes using biomass materials like rice husk and sawdust. The biomass was compressed to a pressure of 5–7MPa (Chou *et al*., 2009; Dinesha *et al*., 2019) they used a manually operated hot press with a maximum capacity of 100kgfcm2 at a temperature of 200C to prepare briquettes from rice straw and rice bran (Dinesha *et al*., 2019; Rahaman & Salam, 2017).

2.4.2. Screw Press

A screw press consists of a screw extruder and a die. The raw material is fed into the feedstock hopper. The screw extruder is conical in shape and has a minimum diameter at the die region. The raw material selected for briquetting needs to be free from foreign particles such as metallic pieces, stones, etc. The material flows into the conical compression zone through a screw extruder and is compressed to a high pressure. The advantages of this method are that no binding materials are required, and the produced briquettes are of high quality. Filler materials of small size can be directly used. However, this method has several limitations: moisture content should be less than 12% and the biomass size should be less than 4mm. High wear rate on the screw and high power requirements are other drawbacks of this method (Prasityousil & Muenjina, 2013). It used an extruder-type machine to prepare briquettes from municipal wastes and sawdust (Bhattacharya *et al.,* 2002*)* they used a similar type of arrangement to prepare biomass briquettes. They used a single extrusion die screw press with a heating arrangement. The operating temperature of the device, which has a capacity of 90 kg-1 and is driven by a 20 HP motor, was fixed at 30^0C.

2.4.3. Hydraulic Press

With hydraulic press technology, the electric energy of the motor is converted to mechanical energy through a high-pressure hydraulic oil system. Biomass feedstock is fed into the hopper and compressed due to the hydraulic oil pressures. The main advantage of this method is that it can operate satisfactorily when the moisture content is high. Limitations include leakage of oil, and slower motion of the ram compared to other systems. (Davies & Davies, 2013; Dinesha *et al*., 2019) used water hyacinth as a filler material with phytoplankton scum as a binder and prepared briquettes using a hydraulic-powered press. They used a 30mm in1 speed for the piston by actuating through a hydraulic pump. The pressure was maintained at 20kPa for 45 s. The die size was selected to be 14.3cm in height and 4.7 cm in diameter. (Bolufawi & Bamgboye, 2014; Dinesha *et al*., 2019) used a hydraulic operated press with a cylindrical die of 56mm diameter at a pressure of 10.5MPa for preparing briquettes from Guinea corn residue.

2.4.4. Roller Press

A roller press type briquetting device. It consists of small dies of 30mm diameter and produces small-sized briquettes known as pellets. A thick disc having several holes drilled circumferentially is used as a die. The biomass material is passed through the set of rollers into the die and hence acquires the die shape. Two types of dies are used: flat and ring types. (Dinesh*a et al*., 2019; Kaliyan & Morey, 2010) used a pilot scale roller press for manufacturing briquettes in the form of pellets from switch grass and corn starch. The compression pressure was maintained at 150MPa, and no binding agents were used during the preparation.

2.5. Applications of Briquettes

Briquettes can be used in a wide variety of residential and small-scale industrial applications. They are frequently utilized as a development intervention to swap out solid fuels like firewood, charcoal, and others. Briquettes fill this void for the following uses: Heating domestic cooking and water heating; Heating production processes such as tobacco curing, fruits, tea drying, poultry rearing, etc.; Firing ceramics and clay wares such as improved cook stoves, pottery, bricks, etc.; Fuel for gasifiers to generate electricity; Powering boilers to generate steam. This is due to the current fuel shortage and ever-rising prices (Oladeji, 2015).

2.5.1. Energy demand for cooking

Ethiopia relies heavily on traditional biomass for its energy needs, including firewood, agricultural waste, dung, and charcoal. Over 92% of the nation's total energy consumption is met by traditional biomass, with the remaining 4% coming from hydro, geothermal, and petroleum products. In the 1980s, the briquetting technique was developed. Low-pressure piston equipment installed by private persons served as Ethiopia's first briquetting facility. 60 % of the basic material is sawdust, with the remaining 40% being coffee and cottonseed husk. The briquettes are primarily marketed to middle-class hotels in Addis Ababa that have built quite sophisticated wood-burning stoves (Asresu, 2017).

For use in homes, businesses, and industries, biomass is the main energy source. The household sector dominates Ethiopia's energy market, making up over 93% of the country's total energy usage. Ninety-nine percent of the total amount of biomass consumed is used for home purposes, with the remaining one percent going to commercial and public functions. 96% of the population relies on firewood, agricultural leftovers, dung, and traditional charcoal to meet their energy demands for domestic cooking, both in rural and urban regions (Asresu, 2017).

2.6. Comparison between Pelleting and Briquetting

Because the biomass resources do not always need to be pre-processed or uniformly mashed up, briquette processing is more efficient than pelleting. Briquetting has the additional benefit of being put up on-site. Costs associated with disposal can be reduced by briquetting waste byproducts and utilizing them locally for electricity instead of shipping them elsewhere or to a landfill. In general, briquettes require less horsepower. Briquette production provides lower maintenance and procurement expenses than pellet production from an investment standpoint. Even though they are utilized in some larger, commercial applications, pellets have traditionally been seen as more of a domestic fuel. Pellets are more advantageous than briquettes if transportation is a primary consideration because they have more pounds per foot. This is especially true if the briquettes are bigger since the extra space between them when stacked allows for more air to pass through (J. Tumuluru et al., 2010).

2.7. Heavy Metal analysis and determination

Heavy metal contamination in food products is a significant environmental and public health concern due to the potential toxic effects on humans and animals (Sobti *et al*., 2019). This analysis examines heavy metal concentrations in avocados, bananas, and bagasse based on a previous study. The metals of interest typically include lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and other trace metals that may accumulate in these food products (Rahman & Singh, 2019).

Avocados are known for their nutritional benefits, but they can also absorb heavy metals from the soil and environment in which they are grown. The previous study found that the concentration of lead (Pb) in avocado samples was generally low, ranging from 0.01 to 0.03 mg/kg, which is below the maximum allowable limit set by the FAO/WHO (0.1 mg/kg) (Ezez & Belew, 2023). Cadmium (Cd) levels were also low, typically less than 0.01 mg/kg, again within safe consumption limits (FAO/WHO limit: 0.05 mg/kg). Other metals, such as arsenic (As) and mercury (Hg), were either undetectable or present in trace amounts, far below the health risk thresholds (Zhao *et al*., 2023).

Bananas are widely consumed fruits, and their heavy metal content is a point of concern, especially in regions with industrial or agricultural activities that may contaminate the soil (Gupta *et al*., 2018). The study reported that lead (Pb) levels in banana samples ranged from 0.02 to 0.05 mg/kg, with a few samples approaching the upper limit of the FAO/WHO guideline (0.05 mg/kg). Cadmium (Cd) concentrations varied from 0.005 to 0.015 mg/kg, which are also within permissible limits (FAO/WHO limit: 0.05 mg/kg) (Habte *et al*., 2017). Mercury (Hg) and arsenic (As) levels were generally low, with occasional samples showing slightly higher values, but still within acceptable ranges for human consumption (Al Sayegh Petkovšek *et al*., 2012).

Bagasse, the fibrous residue remaining after sugarcane juice extraction, is often used in animal feed and as a biofuel (Alokika et al., 2021). The heavy metal content in bagasse can reflect soil contamination and agricultural practices. The study indicated that lead (Pb) concentrations in bagasse were higher compared to avocados and bananas, ranging from 0.05 to 0.10 mg/kg, sometimes exceeding the FAO/WHO safety threshold (0.1 mg/kg). Cadmium (Cd) levels were also notable, with some samples reaching up to 0.03 mg/kg, though still below the 0.05 mg/kg limit (Satarug *et al*., 2017). Arsenic (As) and mercury (Hg) were generally found at trace levels, but certain samples showed concentrations near the upper safety limits, highlighting the need for regular monitoring and soil management practices to mitigate heavy metal uptake *(O'Connor et al*., 2019).

The heavy metal analysis in avocados, bananas, and bagasse from the previous study indicates that, while most samples fall within safe consumption limits set by FAO/WHO guidelines, there are occasional instances where metal concentrations approach or exceed these thresholds. Regular monitoring and improved agricultural practices are essential to ensure the safety and quality of these food products. Consumers and producers should remain vigilant about potential sources of contamination, particularly in regions with higher environmental exposure to heavy metals.

2.8. Briquetting Experience in Ethiopia

Ethiopia relies heavily on traditional biomass for its energy needs, including firewood, agricultural waste, dung, and charcoal. Over 92% of the nation's total energy consumption is met by traditional biomass, with the remaining 4% coming from hydro, geothermal, and petroleum products. In the 1980s, the briquetting technique was developed. Low-pressure piston equipment installed by private persons served as Ethiopia's first briquetting facility. 60% of the basic material is sawdust, with the remaining 40% being coffee and cotton seed husk. The briquettes are primarily marketed to middle-class hotels in Addis Ababa that have built quite sophisticated wood-burning stoves (Asresu, 2017).

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2.9. Binders in Biomass Briquetting

Biomass generally contains naturally occurring structural binders or stabilizing agents, such as lignin and proteins that are released and activated when biomass is densified at relatively high levels of temperature and pressure (Mani *et al*., 2006; Obi *et al*., 2022; Oyelaran *et al*., 2015). This improves the structural particle bonding in biomass briquettes. However, in some cases, the biomass may not contain a significant amount of natural binder (lignin) or due to the densification conditions, additional binders may be required to achieve the desired briquette hardness and durability. Briquette binders can be broadly divided into organic and inorganic binders. It could further be divided into organic, inorganic, and compound binders based on their composition

(Montiano *et al*., 2015; Obi *et al*., 2022). The choice of binders among the various types is largely dependent on several factors, including the desired bonding strength, low emissions, the effect on combustion performance of the briquette, environmental friendliness, and sustainability and economic availability. While binders are used to improve bonding between biomass particles during densification, the actual mechanism of the bonding process is complex and yet to be fully comprehended (Anukam *et al*., 2021).

Previous studies have propagated several theories to explain particle bonding in biomass densification including attraction forces between biomass particles, adhesion and cohesion forces, solid bridges and mechanical interlocking bonds, interfacial forces, and capillary pressure (Ibitoye *et al*., 2021; Samuelsson *et al*., 2012). These theories have been approached from both mechanical and chemical points of view thus explaining the influence of biomass structural and chemical substances on the bonding process during densification. In a recent study, Anukam, Berghel, Henrikson, Frodeson, and Ståhl (Anukam *et al*., 2021) provide a detailed review of the current state of knowledge on bonding mechanisms in biomass during the densification process.

2.9.1. Classification of Briquette Binder

A. Organic binders

Organic binders generally have good binding properties, including high impact and abrasion strength, and high water resistance. However, at high temperatures, they decompose easily having poor thermal stability and mechanical strength (Han *et al*., 2014). They are mostly characterized by extensive availability, low price, high heating value, and low ignition temperature. There are four main types of organic binders and they include biomass (agricultural wastes, forestry biomass, etc.), tar pitch and petroleum bitumen (coal tar pitch, tar residues, etc.), lignosulphonate, and polymer binders (resins, polyvinyl, and starch). (Miao *et al*., 2019)noted that organic binders could further be divided into hydrophobic binders (e.g., asphalt, and coal tar) and hydrophilic binders (e.g., biomass) based on their reaction to water. The poor thermal stability of organic binders has contributed to limiting their commercial application in biomass briquetting (Obi *et al*., 2022). Organic binder example Water hyacinth, starch, lignin, and guar gum.

B. Inorganic binders

Inorganic binders have strong adhesion, non-pollution with sulfur capture characteristics, low cost, and good hydrophilicity, however, their combustion efficiency is lower due to their limited calorific values, and the ash content is often high (Shu *et al.*, 2012). Examples are clay, bentonite, ammonium nitrate, etc. Inorganic binder could be classified into three main types, industrial (bentonite clay, cement, sodium silicate, and magnesium chloride), civilian (limestone, and clay), and environmental protection (desulfurization agents, e.g., iron oxide, magnesium oxide, and calcium oxide) inorganic binders (G. Zhang *et al.*, 2018). However, the use of inorganic binders in recent literature for biomass briquetting appears to be limited (Afsal *et al.*, 2020; Chukwuneke *et al.*, 2021). Inorganic binder's example Limestone, calcium oxide, clay, cement, bentonite, and iron oxide.

C. Compound binders

Compound binders comprise the combination of two or more binders to take advantage of the multiple binding benefits offered by the different binders, thus yielding briquettes with high mechanical strength and thermal stability. Examples are starch and bentonite, and carbide lime (Buravchuk & Gur'yanova, 2018; Deshannavar *et al.*, 2018). Compound binder example Bentonite and starch, resin and starch, pitch.

Table 1 is an overview of the binder types and their characteristics (G. Zhang et al., 2018)

Binder Classification	**Examples**	**Advantages**	**Disadvantages**
Organic	Water hyacinth, starch, molasses, lignin, and guar gum.	High heating value, widely available, low price, and high mechanical strength.	Low ignition temperature, emission pollutants, low thermal stability, and low water-proofing.
Inorganic	Limestone, calcium oxide, clay, cement, bentonite, and iron oxide.	High bonding strength, wide availability, good thermal stability, sulfur retention, and hydrophilicity.	High ash content, low heat and high price.
Compound	Bentonite and starch, resin and starch, pitch, and molasses.	Good thermal stability, high bonding strength, high water resistance, and high mechanical properties.	Mostly high price and high ash content.

2.9.2. Common Biomass Briquette Binders

As earlier stated, binders are added to the biomass densification process in other to improve the compressive strength, abrasion resistance, and, in some cases, the energy content of briquettes (Richard Oliver (dalam Zeithml., 2021). Different types of raw materials require different binder types due to their underlying material bonding mechanisms (G. Zhang *et al*., 2018).

I, Glycerol

Crude glycerin, a by-product in biodiesel production, has been successfully used as a binding agent in biomass briquetting with significant positive effects on the briquette properties (Helwani *et al*., 2020; Petricoski *et al*., 2020; Wongwuttanasatian & Sakkampang, 2016). Although crude glycerin can be purified into valuable chemicals for use in the pharmaceutical, food, and cosmetics industries, the purification process is rather expensive and inefficient due to a wide variety of impurities it often contains (Obi *et al*., 2022). The glycerin market on the other hand is well saturated and its disposal at landfills is environmentally unsustainable (Ayoub & Abdullah, 2012; Hartini *et al*., 2020).

II, Starch

Starch is a white powder mostly extracted from various crops, including cereals, rhizomes, and roots, in the form of semi-crystalline granules that are unique to the individual crop source (Bertoft, 2017). The application of heat and water to starch brings about the formation of intermolecular hydrogen bonds between the two major polysaccharide components in starch—amylose and amylopectin. This is achieved through the disruption of the granular structure of the starch molecules leading to swelling, hydration, and solubilization (Ai & Jane, 2017). These results in a viscous solution called starch paste that gels as it cools. The transition from granules to starch paste is accompanied by increased viscosity which increases the paste's resistance to deformation showing significant binding strength (Khlifi *et al*., 2020). The high-energy content of starch in addition to its chemical and structural properties makes it an excellent binding agent in biomass densification and remains the most common biomass briquette binder in the literature (Chungcharoen & Srisang, 2020; Lubwama et al., 2020; Obi *et al*., 2022; Okwu & Samuel, 2018). However, its use in commercial briquetting has been limited due to its high cost, low coking, and water-proof properties (G. Zhang *et al*., 2018).

III, Algae

Algae are a group of photosynthetic, heterotrophic single-celled organisms inhabiting fresh- and seawater ecosystems, and can easily be cultivated; its production rate is about 50 times faster than most terrestrial biomass (Haykiri-Acma *et al*., 2013). Algae has potential applications in biomass binding due to its high protein and lignin content (Nagarajan *et al*., 2021). The binding capability of algae has been linked to the combination of two constituents of algae, chitin, and proteins, which act as natural binding agents (Ververis *et al*., 2007).

Table 2 Comparison of calorific value from worked briquettes

Residue	**Energy Content (MJ/kg)**	**Reference**
Lettuce	0.91	(Akande&Olorunnisola, 2018)
Green beans	1.02	
Cabbage	1.26	
Carrot leaves	3.22	
Cardboard	14.48	(Lohri *et al*., 2015)
Grass/leaves	15.61	
Banana peel	17.10	(de Oliveira Maia *et al*., 2018)
Orange peel	17.61	(Zanella et al., 2016)
Bagasse	18.35	(Brunerová *et al*., 2020)
Avocado peel	24.60	(Demeke, 2022)
Avocado pit with sawdust and cassava as a binder	13.36	(Lukuy *et al*., 2022)
Palmyra palm waste using molasses 5% as a binder	28.90	(Utchariyajit *et al*., 2019)
Banana peel charcoal briquette with 0% clay	25.06	(Mopoung & Udeye, 2017)
Banana peel and bagasse with avocado peel	29.93	This study

As shown the Table 3, the avocado peel has a higher calorific value than others although the whole selected wastes such as avocado peel, banana peel, and bagasse are better than others because have high energy content and the product briquettes mixed with a high calorific value are also high energy content. In addition, as shown the Table 2, the vegetable waste has the lowest calorific value such as lettuce, green beans, cabbage, and carrot leaves.

Chapter Three

3. Materials and Methods

3.1. Sampling

The fruit waste biomass was collected samples from three juice houses at around Arat kilo Addis Ababa between February and April 2023. The fruit peel generated from the fruit is the process of making juice and collected in the sample box as shown in the figure below. The bagasse were collected from the Wonji sugar factory Dodota branch. The branch is located 18 Km from Wonji town and is found in the Oromia region near Adama City 110 kilometers from Addis Ababa. Commencing production in 1954, Wonji Sugar Factory is the oldest and the pioneer in the history of Ethiopia's sugar industry. After being collected, the samples were transported to the Center for Environmental Science Research laboratory where they were stored until processing.

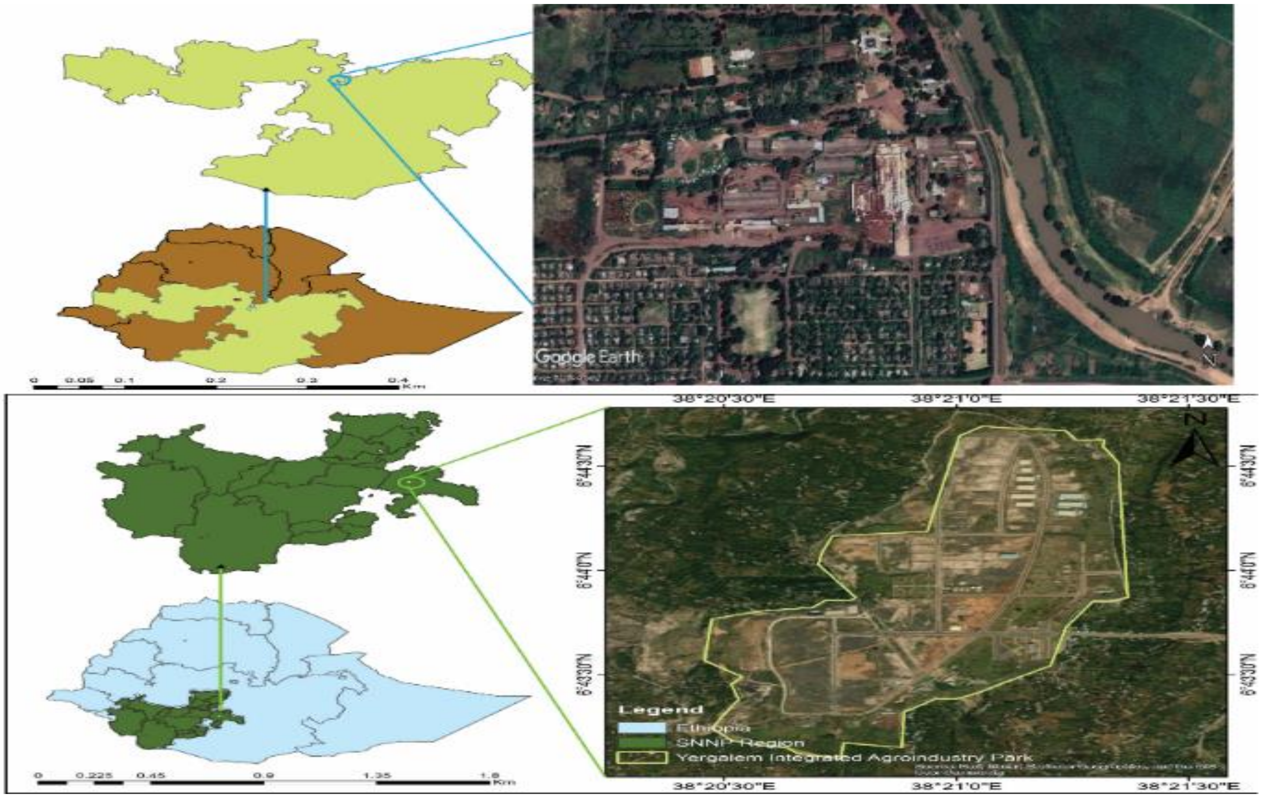


Figure 1 Study area map

Figure 2 Sample collection for fruit waste and bagasse

3.2. Sample preparation

The collected samples of fruit waste (Avocado and Banana) were chopped into pieces no longer than 3 cm, and air-dried for 5 days to a moisture level of about 10%, while the bagasse had been previously dried in the sugar factory. After drying, the samples (avocado, banana, and bagasse) were transported to the alternative energy development and promotion laboratory and workshop center and were carbonized by oxygen-limited in a carbonization kiln for 30 minutes at 500^0C. After carbonization, the samples were ground with a high-grade grinder.

Figure 3 sample drying process

3.3. Sample Characterization (proximate analysis of fruit wastes and bagasse)

3.3.1. Moisture content (MC)

Moisture content is a measurement of the quantity of water or water vapor contained in a sample of fruit waste and bagasse. A parameter can be used to describe the wetness of a sample. Measuring the sundry weight and oven-dry weight of the fruit waste and bagasse allowed for the determination of their moisture content. An estimate of the moisture content of the waste materials was provided by the percentage difference between these two weights. The moisture content (dry basis) of the samples was determined using the oven-dry method developed by (Onukak et al., 2017). One of the key factors affecting briquette quality is moisture content. Briquettes' lower moisture content suggests that they have a higher heat value. On the other hand, if the briquette has a higher moisture content, it will be more difficult to burn, producing less energy and more smoke.

By weighing 2 g of each dried sample in a crucible with an electronic balance and depositing it in an oven set at 110℃ for 4 hours, followed by chilling in a desiccator for 25-30 minutes, the moisture content was calculated using (ASABE, 2003) in triplicate. The desiccator is used to prevent further moisture damage to the samples. The following equation was used to determine the moisture content.

$$MC = \frac{W1-W2}{W1} \times 100\% \qquad (1)$$

Where W1 is the weight of sun deride samples for two weeks, W2 is the weight of oven deride samples at 110^{o}C for 4 hours.

3.3.2. Volatile Matter

The components of carbon, hydrogen, and oxygen that are present in biomass are referred to as volatile matter. When heated, these components are transformed into vapor, which is often a combination of long- and short-chain hydrocarbons. Using (ASTM, 2003) in triplicate, the volatile matter was measured by weighing. Two grams of each sample were placed in a crucible and heated in an oven to a consistent weight. The samples were heated to a temperature of 550°C for 10 minutes, weighed after cooling, and the results were calculated using the formula below:

By using the following formula to determine:

$$Volatile\ Matter\ (VMC\ \%) = \frac{W2-W3}{W2} \times 100\% \qquad (2)$$

Where W2 is the weight of oven dried sample and W3 is the weight of the sample after 10 min in the furnace at 550℃.

3.3.3. Ash Content (AC)

The term "ash" describes the inorganic residue left over following either full oxidation or ignition of the organic materials in a meal sample. The minerals found in the food sample make up the majority of the inorganic residue. As part of the proximate analysis for nutritional evaluation, the ash content is determined. Ash plays a crucial role in both the diffusion of oxygen to a fuel's surface during char combustion as well as the transmission of heat to that surface. Fuels with a low ash concentration are more suited for thermal use than fuels with a high ash level because ash is an impurity that will not burn. A fuel with a higher ash concentration typically emits more dust and has a lower combustion volume and efficiency.

By weighing 2 g of the samples into a crucible, heating them at 550 0C for 4 hours in a muffle furnace, and recording the results in triplicate, the ash content was calculated according to (AOAC, 1999). After being removed from the furnace, the crucibles were placed in the desiccators to cool for an hour. Following cooling, the weight was utilized to compute the ash content using the formula below.

$$Ash\ Content\ (AC) = \frac{W3}{W2} \times 100\% \qquad (3)$$

Where W3 is the weight of ash at 500^0C for 4 hours and W2 is the weight of an oven-dried sample.

3.3.4. Fixed Carbon Content

The total amount of carbon needed to produce heat energy from the fuel during the combustion of the biomass briquettes is known as fixed carbon. By deducting the total of the percentage moisture content (PMC), percentage volatile matter (PVM), and percentage ash content (PAC) from 100 percent, the percentage of fixed carbon was computed (ASTM, 2003).

$$FC = 100\% - (MC + VM + AC) \qquad (4)$$

Figure 4 proximate analysis process

Table 3 mixing ratio of the fruit biomass and bagasse

No. run	Avocado (%)	Banana (%)	Bagasse%
1	10	0	90
2	10	20	70
3	10	40	50
4	10	60	30
5	10	80	10
6	10	90	0
7	20	0	80
8	20	20	60
9	20	40	40
10	20	60	20
11	20	80	0
12	20	60	40
13	30	0	70
14	30	20	50
15	30	40	30
16	30	60	10
17	0	0	100
18	40	0	60
19	50	0	50
20	60	0	40
21	70	0	30
22	80	0	20
23	90	0	10
24	100	0	0
25	0	100	0

3.4. Briquetting Procedures (Production of biomass briquette from leftover fruit waste and bagasse)

The carbonized and ground samples were manually blended thoroughly. On a weight percent basis, mixtures were prepared at the following fruit waste. The components were combined with 200 ml water for each. To make round briquettes, a predetermined amount of the slurry was manually constricted briquette machine inside the briquette press with 30mm diameter and 5mm thickness , which consists of an oval-shaped metal mold with a whole perforation at the base. After being sun-dried for 5 days to a moisture level of 10% (on a wet basis), the generated briquettes were ready to be used as a fuel source for heating and cooking.

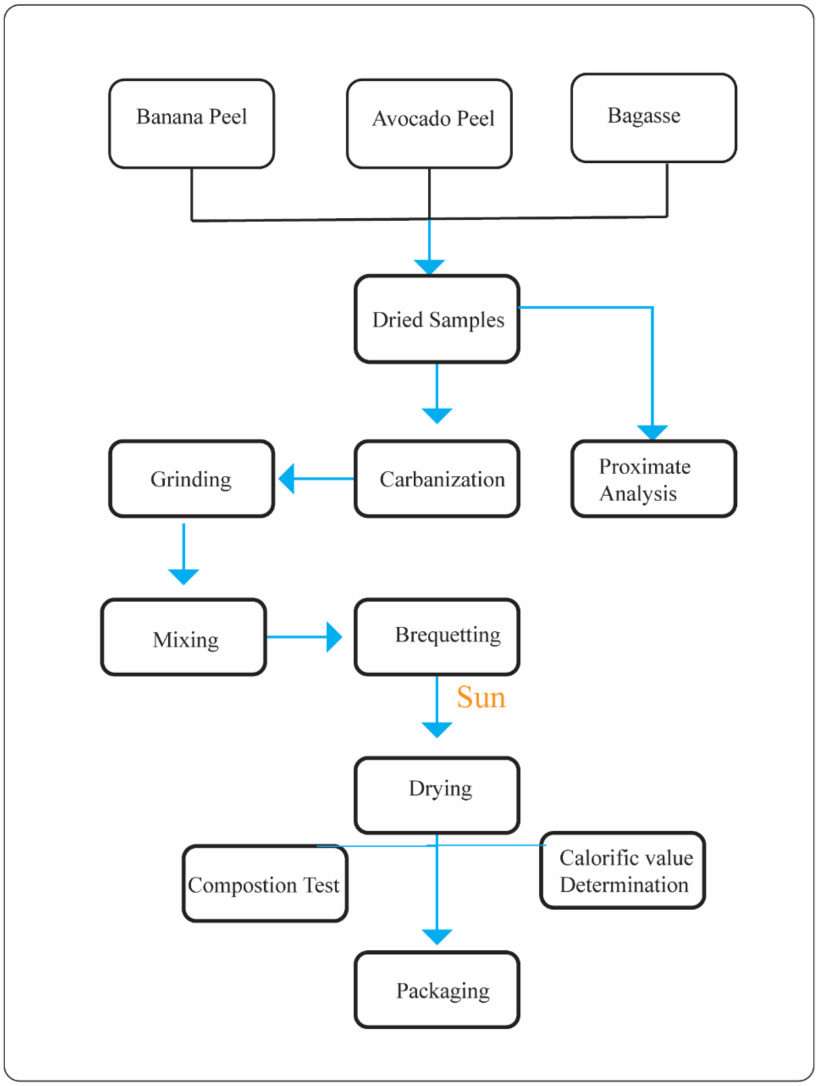


Figure 5 Schematic presentation of the briquetting process

3.5. Calorific value and Bulk density determination of briquette

3.5.1. Calorific value determination

The calorific value of the briquettes was determined by using an automatic bomb calorimeter at the chemical and construction inputs industry research and development center the method employed for determining the calorific value entailed the controlled burning of biomass briquette samples. Every specimen was accurately measured and positioned in a combustion chamber. The briquette was ignited using conventional ignition sources called burner, and the ensuing flame was permitted to burn until full combustion took place. The heat emitted during combustion was quantified using a calorimeter, which documented the alteration in temperature within the system.

The biomass briquette's calorific value was determined by using the following equation calculating the amount of heat emitted per unit mass of the sample.

Gross Calorific value (KJ/Kg) $=(M1+M2Cw)+\frac{T1-T2}{Ms}$ (6)

Where: - M1= Heat capacity of calorimeter obtaind from standard experiment, Kj/^{0}C

M2= Mass of water in copper calorimeter (Kg)

T1=Intial temperature of water (^{0}C)

T2= Final temperature of water (^{0}C)

Ms=Mass of briquette/ raw biomass sample taken (kg)

Cw=specific heat capacity of water

3.5.2. Bulk density determination

The procedure for determining bulk density involved preparing the selected biomass briquette samples, followed by recording their respective masses. Subsequently, every specimen was immersed in a graduated cylinder containing water, and the resultant volume of water displacement was quantified. To determine the bulk density, the formula employed was as follows:

$$Bulk\ density=\frac{mass of briquette}{volume\ of\ breque} \qquad (5)$$

3.6. Combustion test (Greenhouse gas (GHGs) emission test)

3.6.1. Ignition Time (IT)

The biomass briquettes were systematically placed within an electrical stove to evaluate their ignition behavior and combustion characteristics. The selected, biomass briquettes were uniformly ignited. The stopwatch or timer was initiated precisely at the moment when the flame became visibly established on the briquette's surface coating or binder material. The time required for the briquettes to achieve self-sustained smoldering combustion, characterized by the glowing ember propagation through the briquette matrix without external heat input, was recorded.

3.6.2. *Burning time (BT)*

After successfully attaining self-sustained combustion, each briquette was permitted to undergo combustion until full combustion was achieved. The timer was instantly halted upon complete extinguishment of the flame, resulting in the presence of solely embers or ash. This technique guarantees precise measurement of the time it takes for the briquette material to burn, encompassing the period from ignition to full consumption.

3.6.3. *Emission Test (ET)*

The methodology employed for emission testing of biomass briquettes entailed the controlled combustion of the briquettes within a specifically defined chamber, subsequently followed by the collection and examination of released gases and particulate matter. The briquettes were ignited consistently using standard ignition sources, providing consistent combustion conditions. Pollutant concentrations, such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter (PM), were quantified by collecting and analyzing emission samples.

3.7. Data analysis

The data analysis was conducted using Microsoft Excel 2019 and Origin Pro 2022. The initial step was inputting raw data obtained from trials into Excel spreadsheets for the sake of structure and fundamental manipulation. Subsequently, the data were transferred into Origin Pro 2022 software for graphical display. A range of tools and functions were utilized in both software programs to conduct trend analysis, compute descriptive statistics, and produce visual representations, such as graphs and charts, to effectively interpret the findings.

Chapter Four

4. Result and Discussion

In this study, we evaluated the fuel properties of oval-shaped biomass briquettes that were produced by combining fruit waste (avocado and banana) and bagasse. The briquettes have perforations on the right and left sides that help regulate oxygen flow, resulting in minimal smoke and improved burning efficiency. The proximate analysis was conducted to determine various parameters based on dryness, including moisture content, ash content, volatile matter, fixed carbon, calorific value, and combustion performance.

Figure 6. Biomass briquette with the composition of avocado, bagasse, and banana peel

4.1. Analysis of raw biomass

Table 4 Proximate analysis of raw biomass (Mean ± SD)

Types of biomass	**MC%**	**VM%**	**AC%**	**FC%**
Avocado	5.03±0.18	73.39±1.48	4.43±0.03	17.11±1.34
Banana	8.21±2.07	75.90±0.11	5.53±0.03	10.74±1.98
Bagasse	6.60±0.26	71.58±1.79	3.15±0	18.66±2.05

The moisture content varied among the samples on a dry biomass basis. Banana peel had the highest moisture content at 8.21%, followed by bagasse at 6.60%, and avocado peel at 5.03% (Table 5). The higher moisture content in banana peel suggests that removing moisture from this feedstock requires more time and energy compared to avocado peel or bagasse. Conversely, avocado peel had the lowest moisture content, implying that moisture removal would be relatively easier and less energy-intensive.

Regarding volatile matter content, banana peel exhibited the highest value at 75.90% on a dry biomass basis, followed by avocado peel at 73.39% and bagasse at 71.58%. This indicates that briquettes with a higher proportion of banana peels would release more emissions during combustion compared to those made from avocado peel or bagasse(Eyasu Gebeyehu *et al*., 2023). Nevertheless, all three feedstock have had relatively high volatile matter content.

The ash concentration followed a different trend, with banana peel having the highest ash content at 5.53%, followed by avocado peel at 4.43%, and bagasse at 3.15%. Although all three samples had relatively low ash concentrations, the raw materials used for briquette production were of good quality and predominantly organic.

Fixed carbon is the combustible residue left after the volatile matter is distilled off and the moisture and ash content are subtracted. It is primarily carbon but also contains minor quantities of hydrogen, oxygen, nitrogen, and sulfur not driven off with the gases. In a combustion process, fixed carbon represents the combustible residue remaining after the volatile matter is released. A high fixed carbon content in the fuel is generally desirable as it contributes to the energy content.

As shown in Table 5, bagasse had the highest fixed carbon content among the three samples, followed by avocado peel and banana peel. The high fixed carbon content of all three feedstock suggests that they possess a high energy content, making them suitable for use as solid fuels or reductants in various thermal processes(Gururani *et al*., 2022; Surup *et al*., 2020).

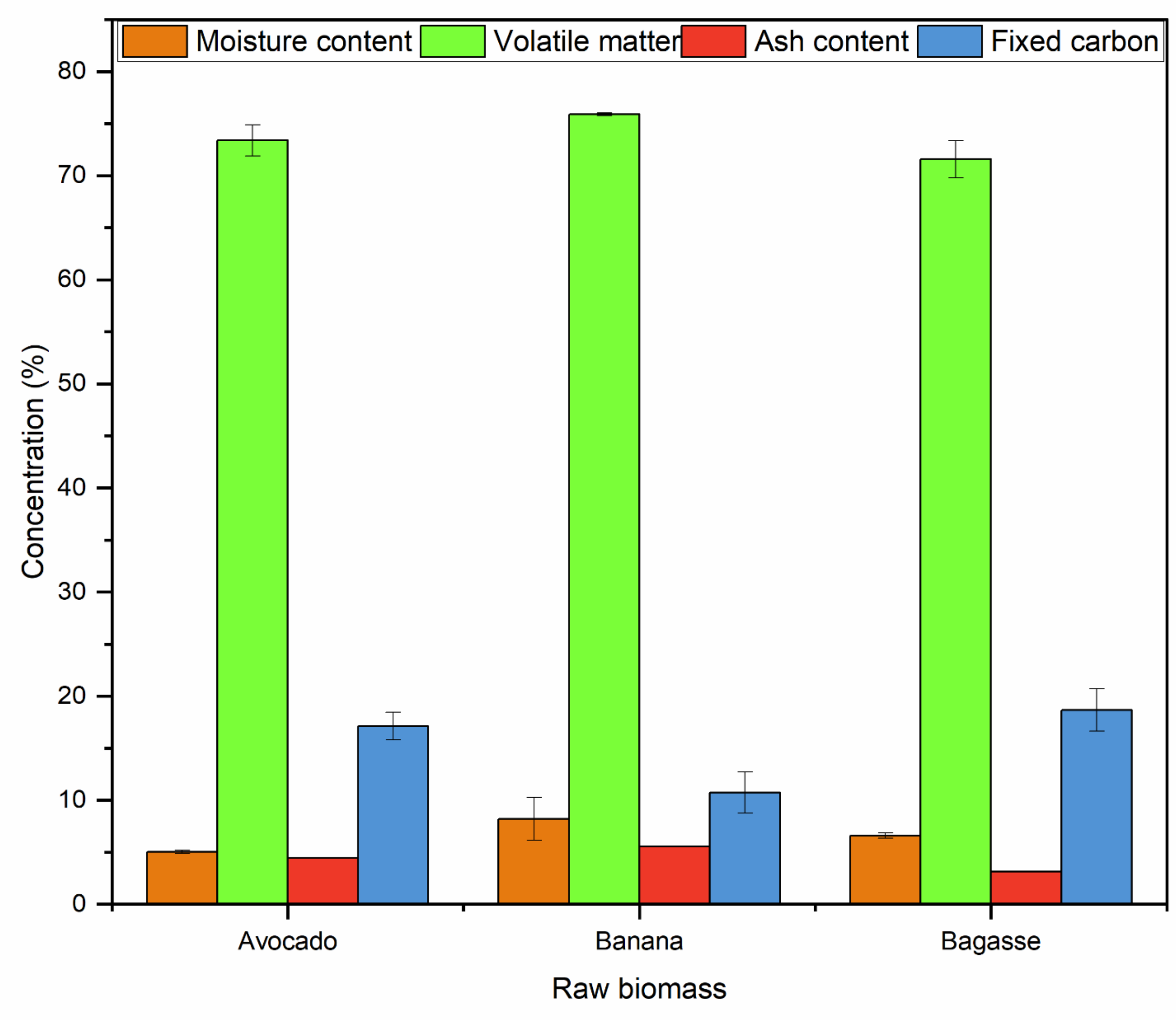


Figure 7 proximate analysis of raw biomass

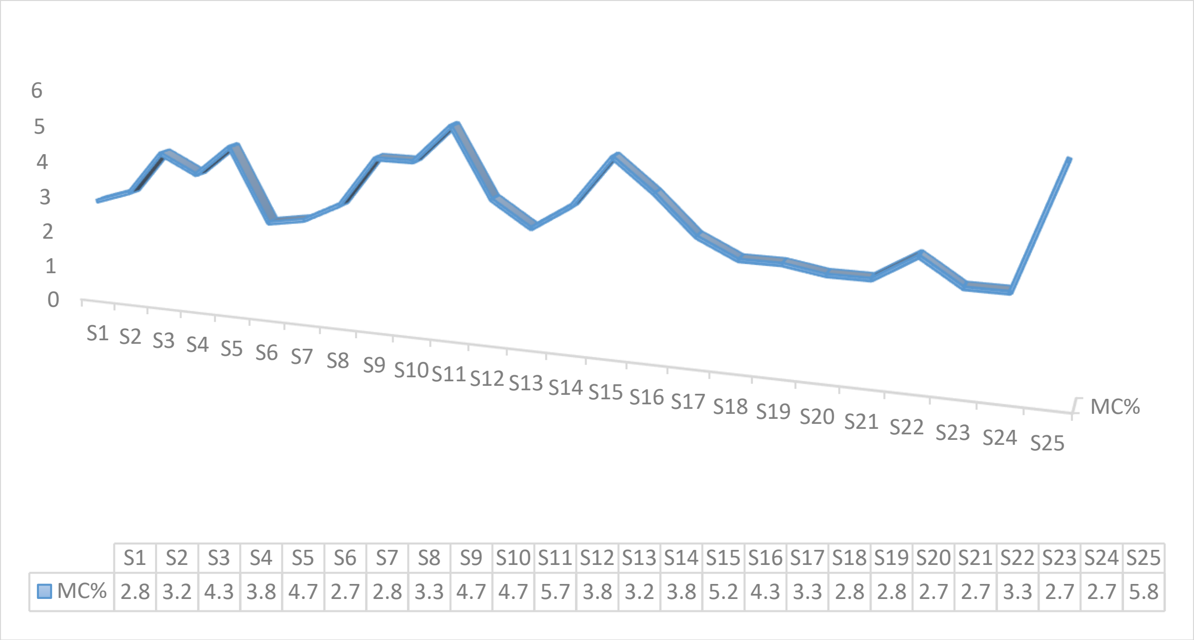
4.2. Proximate analysis

Table 5 Proximate analysis of avocado, banana, and bagasse composition of briquette

No sample	Composition Ratio of A:B: Bg	MC%	VM%	AC%	FC%
S1	10:0:90	2.83 ± .28	37.66 ± 0.47	25.67 ± 0.08	33.83 ± 0.36
S2	10:20:70	3.16±0.26	30.97±0.44	27.70±0.34	38.15±0.54
S3	10:40:50	4.33±0.28	37.62±0.10	28.22±0.08	29.82±0.48
S4	10:60:30	3.83±0.28	36.90±0.42	29.97±0.26	29.28±0.53
S5	10:80:10	4.66±0.28	31.98±0.44	32.34±0.20	31.00±0.38
S6	10:90:0	2.66±0.28	28.07±0.21	35.78±0.19	33.47±0.11
S7	20:0:80	2.83±0.28	28.81±0.44	25.55±0.27	42.80±0.14
S8	20:20:60	3.33±0.28	35.68±0.42	26.20±0.26	34.78±0.12
S9	20:40:40	4.66±0.28	38.10±0.18	30.76±0.21	26.46±0.10
S10	20:60:20	4.66±0.28	29.02±0.26	31.81±0.20	34.51±0.26
S11	20:80:0	5.66±0.28	30.02±0.21	25.96±0.08	38.34±0.15
S12	20:60:40	3.83±0.28	37.43±0.42	25.81±0.25	32.91±0.53
S13	30:0:70	3.16±0.28	34.59±2.79	22.37±0.27	39.87±3.00
S14	30:20:50	3.83±0.28	39.90±0.42	24.25±0.27	35.00±0.13
S15	30:40:30	5.16±0.28	25.82±0.08	25.82±0.08	43.18±0.45
S16	30:60:10	4.33±0.28	38.14±0.42	23.86±0.27	33.65±0.53
S17	0:0:100	3.33±0.28	37.58±0.48	24.13±0.27	34.95±0.37
S18	40:0:60	2.83±0.28	30.18±0.26	20.92±0.27	46.06±0.53
S19	50:0:50	2.83±0.28	35.84±0.26	17.83±0.27	43.49±0.54
S20	60:0:40	2.66±0.28	27.73±0.44	20.20±0.35	49.39±0.37
S21	70:0:30	2.66±0.28	28.93±0.50	17.80±0.32	50.60±0.25
S22	80:0:20	3.33±0.28	29.13±0.21	19.30±0.32	48.22±0.37
S23	90:0:10	2.66±0.28	27.21±0.08	15.57±0.27	54.54±0.37
S24	100:0:0	2.66±0.28	26.70±0.08	17.29±0.32	53.33±0.62
S25	0:100:0	5.83±0.28	24.24±0.53	18.4±0.36	51.52±0.11

4.2.1. Moisture content (MC)

The moisture content of the briquettes of the composition of avocado, banana, and bagasse with different ratios (Table 6). All the ratios of avocado, banana, and bagasse composition of briquettes were below 6%, and lower than the raw biomass of avocado, banana, and bagasse which is an acceptable range. These lower moisture contents are due to the carbonization process that looks before biomass briquette production. The high moisture content of a fuel is disadvantageous because it decreases system capacity and increases operational cost (Mahmudul *et al*., 2017). According to this finding, the biomass briquette moisture ranged from 2.66% to 5.83%, which is within the desirable criteria. Hence, the value of moisture content of the briquettes is lower than in other related studies, which means it releases a higher amount of energy.



	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25
■ MC%	2.8	3.2	4.3	3.8	4.7	2.7	2.8	3.3	4.7	4.7	5.7	3.8	3.2	3.8	5.2	4.3	3.3	2.8	2.8	2.7	2.7	3.3	2.7	2.7	5.8

Figure 8 moisture content of brequettes

4.2.2. Volatile Matter

The volatile matter (VM) content of biomass briquettes significantly influences their combustion properties, such as ignition behavior, flame characteristics, and overall efficiency. The VM percentages in the provided samples range from 24.24% to 39.90%, indicating considerable variability. Samples like S14, with the highest VM at 39.90%, suggest a composition that ignites easily and burns with a longer, more luminous flame due to the higher proportion of volatile compounds that vaporize and combust quickly. Conversely, samples with lower VM, such as S25 at 24.24%, might ignite more slowly and produce less smoke, resulting in a steadier and longer-lasting burn Table 6, and Figure 8. The volatile matter in biomass fuels comprises a complex mixture of condensable and non-condensable gases, including carbon monoxide, hydrocarbons, and other volatile organic compounds (VOCs) (Anca-Couce, 2016). A higher volatile matter content typically indicates a higher reactivity and faster combustion rate, as the volatile gases can readily participate in homogeneous gas-phase reactions (Nussbaumer, 2003).

Banana peel, with its relatively high volatile matter content, is expected to exhibit a highly reactive behavior and faster combustion rate compared to avocado peel and bagasse. The volatile matter content is a crucial parameter that influences the ignition characteristics, combustion kinetics, and emission profiles of biomass fuels. During combustion or gasification processes, the volatile matter is released and undergoes various reactions, contributing to the overall energy conversion efficiency and the formation of gaseous products (Basu, 2013).

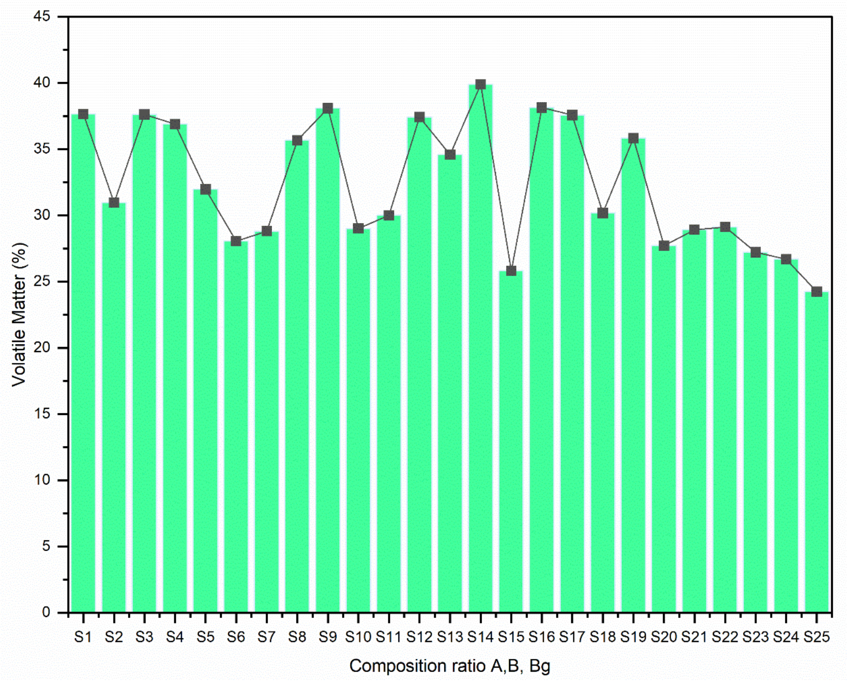


Figure 9 Volatile matter of the briquettes

4.2.3. Ash Content (AC)

The ash content (AC) of biomass briquettes composed of banana, bagasse, and avocado peel varies significantly across the 25 samples, ranging from 15.57% to 35.78%. This variability suggests differences in the composition or processing of the biomass materials. Lower ash content, observed in samples S23 (15.57%), S21 (17.80%), and S19 (17.83%), indicates a higher purity of combustible material, making these samples potentially more efficient as fuel. Conversely, higher ash content, such as in S6 (35.78%), S5 (32.34%), and S10 (31.81%), suggests a higher presence of non-combustible mineral matter, which could result in more residue after combustion and less energy efficiency. A lower ash content in briquettes is desirable as ash can have negative environmental effects, such as generating dust and particulate matter (Kebede *et al*., 2022; Olugbade *et al*., 2019). Additionally, lower ash content enhances combustion efficiency and provides better heating performance at a lower cost.

4.2.4. Fixed Carbon Content

Fixed carbon is the total amount of carbon in biomass that is utilized for generating heat energy during combustion (Kpalo *et al.*, 2020). The results show that the fixed carbon content (FC%) of biomass briquettes made from banana, bagasse, and avocado peel exhibits significant variability, reflecting the diverse composition and potential energy values of the materials. The FC% values range from 26.46 ± 0.10% to 54.54 ± 0.37%, indicating that some briquettes have almost double the fixed carbon content of others Table 6. This wide range suggests differences in the inherent properties of the biomass sources or variations in the briquetting process. The lower FC% values, around 26-35%, likely correspond to materials like banana peel, which may have higher volatile matter content and lower carbonization levels. Briquettes with a greater proportion of fixed carbon have the potential to produce a higher calorific value. This indicates that a greater fixed carbon content in biomass briquettes is preferable as it corresponds to a higher calorific value or heat energy output when burned (Kpalo *et al*., 2020). The variability also shows the importance of optimizing the blend ratios and processing conditions to achieve consistent and desirable fuel characteristics in biomass briquettes (Fadele *et al*., 2021). There is a direct relationship between the amount of fixed carbon in a briquette and its quality. A higher fixed carbon content leads to a higher calorific energy output, which in turn improves the quality of the biomass briquette.

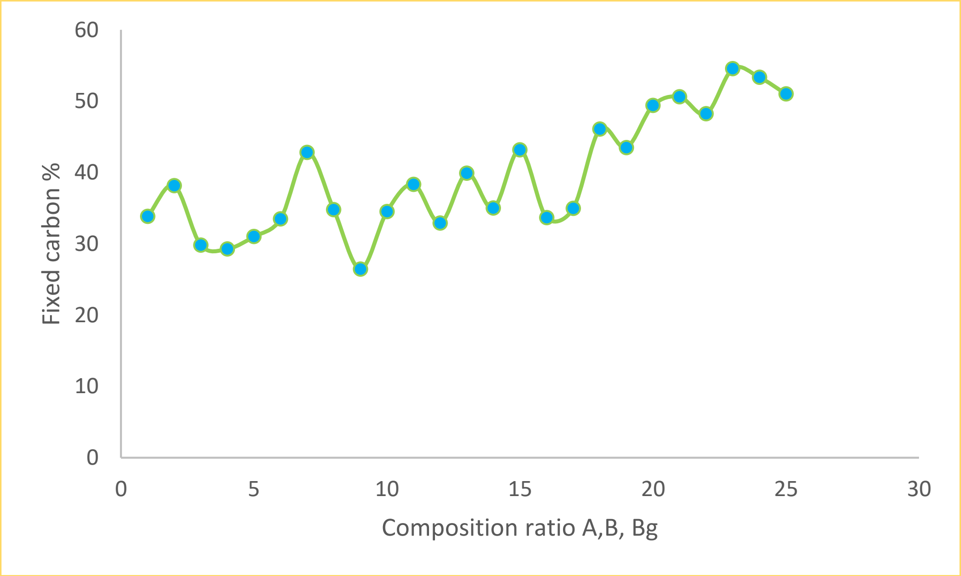


Figure 10 Fixed content of brequatees

4.3. Calorific value determination

The calorific value also referred to as the energy content or heating value, quantifies the energy released during the combustion of a substance. Table 7 indicates by among the three raw biomass avocado peel has a higher calorific value of 27.18MJ/kg indicating that they may be more energy-dense biomass. Compared to the other two biomass types banana has a relatively lower energy content with a calorific value of 15.7KJ/kg. The variation in caloric properties of these biomass sources can affect their ability to release energy when burned (Motghare *et al*., 2016). Avocado peels have higher binding effect in the production of fuel briquettes from bagasse and banana (Demeke *et al*., 2023).

Table 6 Calorific value of raw biomass

Types of Biomass	Calorific Value MJ/kg
Avocado	27.5±0.8
Banana	15.7 ±.4
Bagasse	16.7±.1

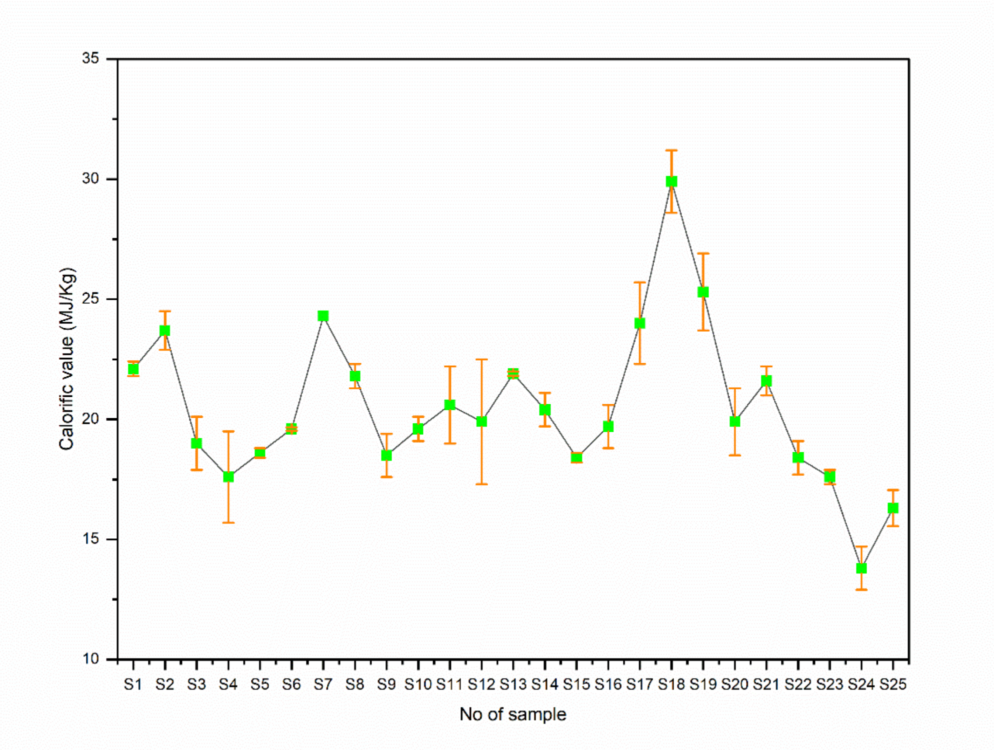


Figure 11 calorific value of produced briquettes

Table 7 calorific value of produced briquettes

No of Sample	Composition Ratio of A:B: Bg	Calorific Value
S1	10:0:90	22.1±0.3
S2	10:20:70	23.7±0.8
S3	10:40:50	19±1.1
S4	10:60:30	17.6±1.9
S5	10:80:10	18.6±0.2
S6	10:90:0	19.6±0.07
S7	20:0:80	24.3±0..3
S8	20:20:60	21.8±0.5
S9	20:40:40	18.5±0.9
S10	20:60:20	19.6±0.5
S11	20:80:0	20.6±1.6
S12	20:60:40	19.9±2.6
S13	30:0:70	21.9±0.09
S14	30:20:50	20.4±0.7
S15	30:40:30	18.4±0.2
S16	30:60:10	19.7±0.9
S17	0:0:100	24±1.7
S18	40:0:60	29.9±1.3
S19	50:0:50	25.3±1.6
S20	60:0:40	19.9±1.4
S21	70:0:30	21.6±0.6
S22	80:0:20	18.4±0.7
S23	90:0:10	17.6±0.3
S24	100:0:0	13.8±0.9
S25	0:100:0	16.3±0.75

As shown in Table 8 the amount of calorific value produced during the combustion of biomass briquette depends on the removal of volatile matter and moisture content. In this study, the biomass briquette 18 (40% avocado, 0% banana, and 60% bagasse, 60) has the highest calorific value, while sample 24 (100% avocado, 0% banana, and 0% bagasse) has the lowest calorific value among the biomass briquettes. According to Sakhiya *et al*., (2021), the greater heating value refers to the total energy released during the combustion of fuel in the open air, which includes the latent heat present in water vapor. This value represents the highest amount of energy that can theoretically be recovered from a specific biomass source. Hence, the calorific values employed in the findings of this study were elevated heating values. The calorific value of briquettes is influenced by many factors. These factors include variations in environmental circumstances, disparities in carbonization temperatures, the utilization of advanced machinery in biomass briquette compression, and the quantity of inorganic matter present in biomass (Ossei-Bremang *et al*., 2024; PARI *et al*., 2023; Sunnu *et al*., 2023). This high heating value is comparable to most biomass energy sources and is sufficient for household cooking and other applications. A higher calorific value means a high heat output which leads to faster cooking. Therefore by adjusting the ratio of avocado, banana, and bagasse in the biomass briquettes, more energy can be generated this heating value is compared with most biomass energy sources and is adequate for household cooking and other intended purposes.

Table 8 comparison of calorific value with other studies

Biomass briquette type	Calorific value (KJ/kg)	References
Maize Cob, Sugarcane Bagasse, and Polythene Composites	28.14	(Awwal *et al*., 2019)
Banana Peel and Banana Bunch	18.1	(de Oliveira Maia *et al*., 2018)
Rice Husk	17.69	(Saeed *et al*., 2021)
water hyacinth (Eichhornia crassipes)-molasses blend	16.6	(Carnaje *et al*., 2018)
Avocado peel	24.60	(Demeke, 2022)
Banana, avocado, and bagasse composite	29.3	These study

4.4. Bulk density

The bulk density of the biomass briquette in our study was 1.26 g/cm^3. This density is an important factor that affects the combustion properties and overall effectiveness of the briquette as a fuel source. A higher bulk density is advantageous as it indicates a more compressed and tightly packed structure, leading to enhanced combustion qualities and greater energy output per unit volume. Antwi-Boasiako & Acheampong (2016) found a positive correlation between the bulk density of biomass briquettes and their calorific value and combustion rate. Briquettes with higher bulk density generally have greater energy content per unit volume, resulting in improved combustion efficiency and heat production. Additionally, increased bulk density can enhance the mechanical strength and durability of the briquettes, reducing their susceptibility to damage during transit and handling (J. S. Tumuluru *et al*., 2015). However, it is important to note that excessively high bulk density can lead to adverse effects, such as increased resistance to airflow during combustion, potentially causing incomplete combustion and increased emissions (J. S. Tumuluru *et al*., 2012). The ideal bulk density for biomass briquettes may vary depending on the specific use, combustion system, and feedstock composition. Experts typically recommend achieving a balance between high bulk density, which improves energy content and combustion characteristics, and enough porosity to allow sufficient airflow during combustion (Mujeebu *et al.*, 2009).

4.5. Combustion test

For the combustion test, six biomass briquettes were selected based on their calorific values. The briquettes with higher calorific values were prioritized for the combustion tests, as the calorific value is a crucial parameter that determines the energy content and heat release potential of a solid fuel.

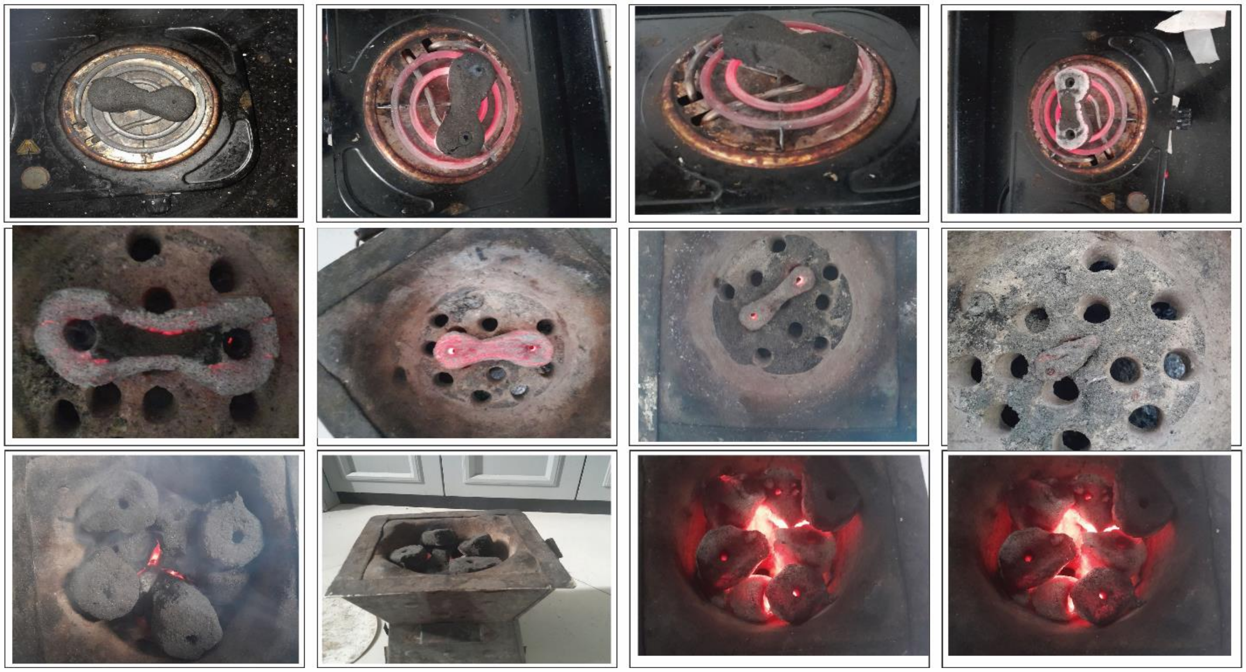


Figure 12 illustrative presentation of combustion test for biomass briquette

4.5.1. Ignition time

The ignition time of the selected biomass briquettes varied between 1.39 and 2 minutes. This suggests that the ratio of raw biomass and the density of the briquettes had a notable impact on their igniting behavior Figure 10. The ignition time, also known as the time it takes a fuel to ignite and begin burning, is affected by several factors, such as the composition and physical characteristics of the biomass briquettes. The observed range of igniting timings (1.39 to 2 minutes) indicates changes in the parameters of the briquettes, such as their bulk density, volatile matter content, and the specific type of biomass feedstock or binder employed. A higher bulk density generally leads to a denser and more compact structure, which might hinder the flow of air and lengthen the time it takes for ignition to occur. Briquettes with a lower bulk density are more likely to ignite quickly because they have improved air permeability.

Biomass materials containing a larger proportion of volatile matter have a greater tendency to ignite easily because they include more highly flammable volatile chemicals, resulting in shorter ignition durations. The choice of binder in briquette production can also affect ignition behavior, as certain binders may have higher combustibility or enhance airflow, hence aiding quicker ignition. Furthermore, the combustibility and ignition duration of biomass feedstock's can be influenced by their diverse chemical compositions and physical qualities (Ndindeng *et al*., 2015; Yaman *et al*., 2000).

This study aligns with the results of other research that examines the igniting characteristics of biomass briquettes. An investigation conducted by (Yaman *et al*., 2000) shows that the ignition duration of briquettes produced from olive residue was shown to rise as the density rose. This indicates that bulk density has a noteworthy influence on ignition behavior. The study conducted by (Ndindeng *et al*., 2015) examined the impact of various binders on the combustion characteristics of briquettes. The researchers discovered differences in ignition times, suggesting that the kind of binder used influenced this aspect.

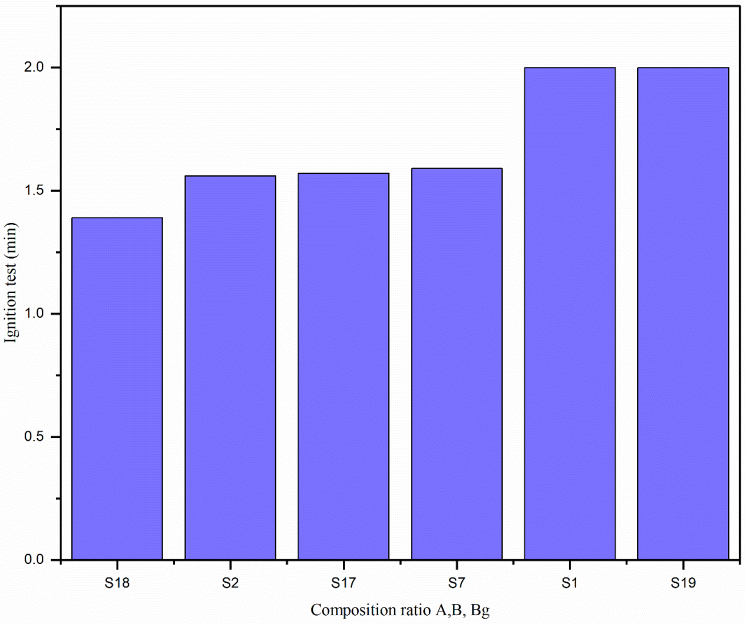


Figure 13 Ignition test of biomass briquette

4.5.2. Burning time

The study examined the burning time of briquettes produced from varying proportions of avocado, banana, and bagasse biomass. The findings indicated that the duration of burning time of biomass briquette was 36, 40, 43, 45, 49, and 46 minutes for S1, S2, S7, S17, S18, and S19, respectively Figure 11. Moreover, it was observed that the presence of larger quantities of avocado, banana, and bagasse in the briquettes resulted in extended burning durations. This discovery implies that the higher amount of biomass in the briquettes led to improved density and increased energy concentration, which in turn resulted in a longer duration of combustion. The longer duration of combustion seen when using briquettes with higher biomass concentration can be attributed to the slow and sustained release of energy resulting from the increased density and energy content of the briquettes (Velusamy *et al*., 2021)). This study consistent with prior studies that has shown how the composition and compaction of biomass affect the way briquettes burn. Moreover, the relation between higher biomass concentration in the briquettes and longer burning periods is consistent with the concepts of energy density and combustion efficiency. Fuels with higher energy density, such as briquettes made from biomass, tend to release energy at a slower rate, resulting in longer burning durations (Bajwa *et al*., 2018).

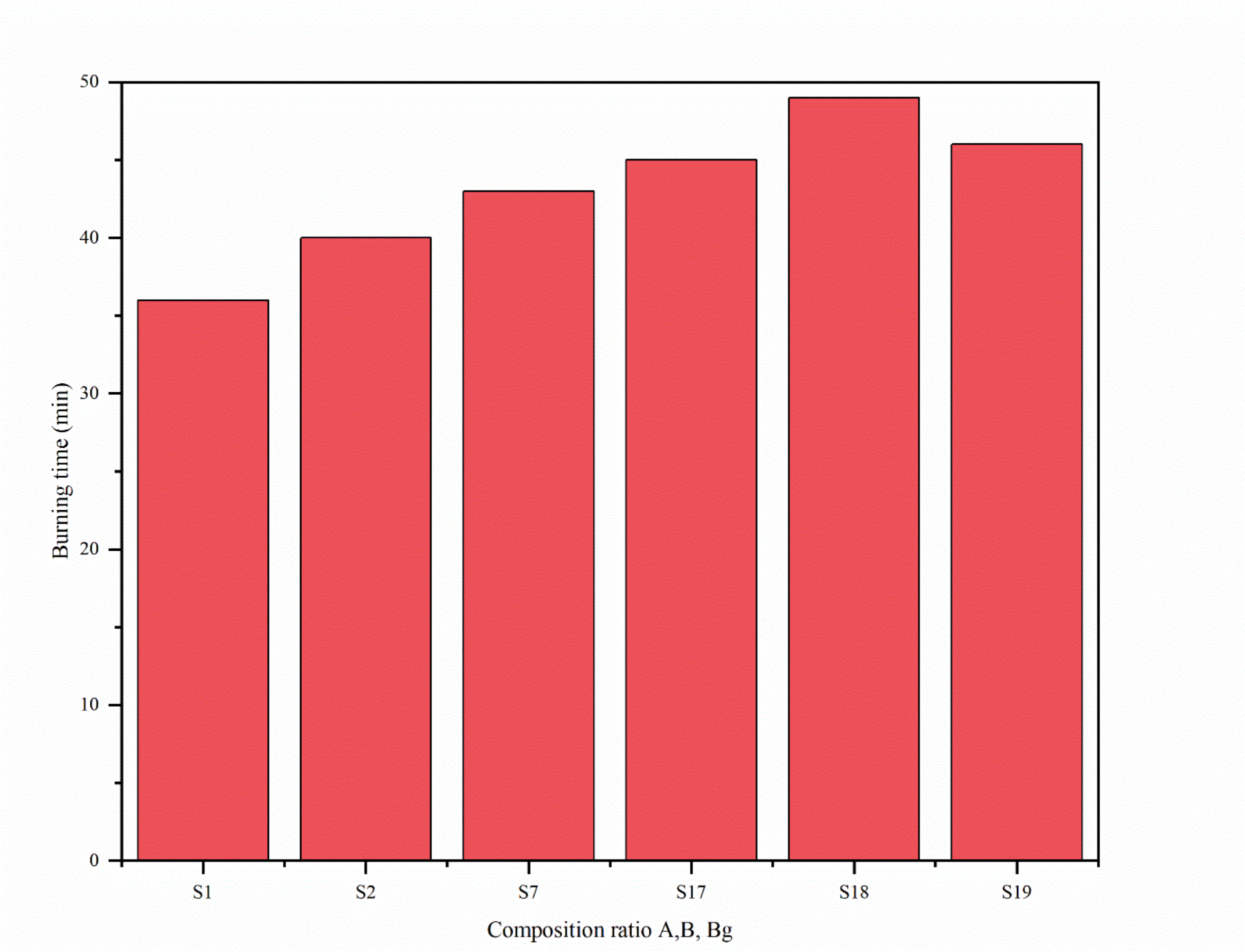


Figure 14 Burning time determination of the selected briquettes

4.5.3. Emission test

The emissions of raw biomass were tested bagasse demonstrates reduced carbon monoxide (CO) emissions, but elevated amounts of nitrogen oxides (NOx), suggesting efficient burning with the potential for increased pollution from nitrogen oxides Table 9. Avocado and banana peels, on the other hand, exhibit elevated amounts of $\%O_2$ and $\%CO_2$, indicating a more thorough process of combustion. However, the high quantities of carbon monoxide (CO) in these peels indicate a less effective combustion process as compared to bagasse. In general, avocado and banana peels exhibit a greater degree of total combustion, as seen by higher amounts of oxygen (O_2) and carbon dioxide (CO_2). However, they are less efficient in terms of carbon monoxide (CO) emissions. Bagasse, although it emits less carbon monoxide, generates higher quantities of nitrogen oxides, which raises environmental issues. It is crucial to optimize combustion conditions to reduce emissions and improve efficiency for various types of biomass. The emissions of the biomass briquette as shown in table, which is made from avocado peel, banana peel, and bagasse, were tested by using a multi-gas analyzer.

Table 9 Emission test of raw biomass

No	Types of biomass	**%O_2**	**Ppm CO**	**%CO_2**	**NO_X**	**NO**
1	Bagasse	19.40	4.82	0.32	8.3	6
2	Avocado	20.85	6.3	0.95	-0.4	1
3	Banana	20.25	7.03	0.90	0.7	2

Table 10 Emission test of biomass briquette

Sample	**%O_2**	**ppm CO**	**ppmCO_2**	**Ppm NO_X**	**Ppm NO**	**PpmNO_2**	**Ppm C_XH_Y**
1	15.52	3.54	0.22	5.5	6	0.5	562
2	16.83	2.63	0.13	4.7	4	0.3	416
3	19.31	2.2	0.28	8.3	6	0.3	782
4	17.78	3.22	0.46	8.5	4	0.5	455
5	16.44	4.20	0.07	7.6	9	-1.4	394
6	16.00	4.96	0.45	7.1	6	-1.9	884
7	18.47	3.09	0.69	7.8	3	-0.2	410
8	19.64	4	0.73	6.7	7	-0.3	464
9	19.79	4.61	0.55	8.1	4	-0.5	687
10	19.79	5.9	0.79	4.8	6	-1.2	553
11	19.46	3.5	0.15	1.3	2	-02	828
12	19.40	4.80	0.34	2.2	3	-0.8	670
13	18.19	5.61	0.56	4.2	6	-1.8	560
14	19.70	4.24	0.89	6.9	8	-1.1	383
15	20.02	3.99	0.32	2.0	3	-1.0	692
16	20.26	3.39	0.90	0.9	2	-1-1	500
17	20.81	2.9	0.96	-1.9	-1	-0.9	203
18	20.04	2.39	0.26	1.8	3	-1.2	343
19	20.25	1.03	0.90	0.7	2	-1.3	477
20	20.28	4.75	0.75	-1.4	0	-1.4	406
21	20.81	3.8	0.96	-1.8	-1	-0.8	192
22	20.81	4.7	0.92	-1.6	-1	-0.6	378
23	19.82	3.50	0.56	-1.2	1	-22	405
24	20.04	3.39	0.26	1.8	3	-1.2	343
25	19.19	5.75	0.39	6.1	9	-2.9	667

The oxygen levels fluctuate between 15.52% and 20.81%. Increased oxygen levels (approaching 21%) generally suggest a more thorough combustion process. Multiple samples (17, 18, 21, 22) indicate oxygen levels of approximately 20.81%, which implies effective combustion. Reduced oxygen levels, as observed in sample 1 (15.52%), may suggest a decrease in the efficiency of burning. The concentration of carbon monoxide (CO) varies between 1.03 ppm and 5 ppm. Reduced carbon monoxide emissions generally indicate a higher level of combustion efficiency. It is worth mentioning that samples 19 and 21 exhibit low levels of CO emissions, specifically 7.03 ppm and 17 ppm, which indicates effective combustion. The EPA National Ambient Air Quality Standards (NAAQS) for CO is 9 ppm over 8 hours and 35 ppm over 1 hour. All samples fall well below the EPA's 1-hour and 8-hour CO limits, indicating acceptable CO emission levels (Demeke *et al*., 2023, EPA, 2024). The concentration of carbon dioxide (%CO_2) ranges from 0.07% to 0.96%. Increased levels of CO_2 suggest improved combustion efficiency, as seen by the high %CO_2 values (0.79% and 0.92%) observed in samples 10 and 22. The carbon dioxide (CO_2) levels vary between 0.07% and 0.96%. Elevated carbon dioxide (CO2) quantities often indicate a higher degree of thorough combustion. Samples exhibiting CO_2 levels exceeding 0.5% (e.g., sample 14 with a concentration of 0.89%) indicate superior combustion efficiency compared to samples with lower CO_2 levels. EPA ambient air quality standard for CO2, the EPA regulates CO2 as a greenhouse gas under the Clean Air Act (EPA Greenhouse Gas Emissions ,2024). The values presented are relatively low, as CO2 concentrations in the atmosphere are typically around 400 ppm. The range of nitrogen oxide (NOx) readings is between 0.7 and 8.5. Biomass burning often results in elevated NOx emissions levels due to nitrogen in the biomass. The range of NO and NO_2 levels (-1.9 to 9) indicates variations in combustion conditions, possibly affected by factors such as temperature and oxygen availability. Hydrocarbons (C_XH_Y) emissions vary from 192 parts per million (ppm) to 884 ppm. Sample 6 exhibits elevated levels of higher hydrocarbons, specifically with a C_XH_Y value of 884 ppm. This indicates incomplete combustion and suggests that the combustion process in sample 6 is less efficient compared to the other samples.

When comparing our current study to previous research, we observe that the oxygen levels in our study (15-21%) are within the optimal combustion limits described in prior studies. The CO levels in our study are comparatively low, suggesting a high level of combustion efficiency. This aligns with previous research that found CO levels ranging from 10 to 20 ppm for efficient combustion of biomass briquettes. The %CO_2 numbers also indicate the effectiveness of combustion. The NOx emissions detected in this study are similar to those reported in other studies (Demeke *et al*., 2023), which generally fall within the range of 5 to 15 for different types of biomass. Sample 6 exhibits high C_XH_Y emissions, which suggests that the combustion process was not fully completed.

Previous research has observed elevated levels of hydrocarbon emissions in situations when combustion is not efficient.

Table 11 Summary of selected biomass briquette parameters

Sample	%MC	%VC	%AC	%FC	Calorific (MJ/kg)	%O$_2$	Ppm CO	%CO$_2$	NO$_X$	NO	NO$_2$	Ppm C$_X$H$_Y$
S1	2.83±0.28	37.66±0.47	25.67±0.08	33.83±0.36	22.11	15.52	3.54	0.22	5.5	6	0.5	562
S2	3.16±0.26	30.97±0.44	27.70±0.34	38.15±0.54	23.73	16.83	2.63	0.13	4.7	4	0.3	416
S7	2.83±0.28	28.81±0.44	25.55±0.27	42.80±0.14	24.37	18.47	3.09	0.69	7.8	3	-0.2	410
S17	3.33±0.28	37.58±0.48	24.13±0.27	34.95±0.37	24.037	20.81	2.9	0.96	-1.9	-1	-0.9	203
S18	2.83±0.28	30.18±0.26	20.92±0.27	46.06±0.53	29.93	20.04	2.39	0.26	1.8	3	-1.3	343
S19	2.83±0.28	35.84±0.26	17.83±0.27	43.49±0.54	25.35	20.25	1.03	0.90	0.7	2	-1.3	477

Analysis of selected six distinct biomass briquettes based on their energy value and burning efficiency (S1, S2, S7, S17, S18, S19) Table 11. The measurements encompass moisture content (%MC), volatile content (%VC), ash content (%AC), fixed carbon (%FC), calorific value (MJ/kg), as well as gaseous emissions such as oxygen (%O$_2$), carbon monoxide (Ppm CO), carbon dioxide (%CO$_2$), nitrogen oxides (NO$_X$, NO, NO$_2$), and hydrocarbons (Ppm C$_X$H$_Y$). The samples show differences in composition, energy content, and emission levels, which are probably influenced by factors like the type of biomass, methods used for pretreatment, and the conditions under which they were operated.

Chapter Five

5. Conclusion and Recommendation

5.1. Conclusion

In this study, we analyzed the fuel potential of biomass briquettes derived from bagasse and fruit waste, specifically banana and avocado peels. The results emphasize the practicality of using them as a sustainable energy source and an effective solution for solid waste management in Addis Ababa. Upon close inspection of the briquettes, it was evident that they possessed desirable fuel properties. These included a low moisture content, a high volatile matter content, and appropriate levels of ash and fixed carbon. These qualities help ensure efficient combustion, resulting in optimal energy release and reduced emissions during burning. The analysis of calorific values revealed that the briquettes possess a significant amount of energy. Sample 18, with its composition of 40% avocado, 0% banana, and 60% bagasse, displayed an impressive calorific value of 29.93 MJ/kg. This value is similar to, and in some instances surpasses, conventional biomass energy sources, suggesting that these briquettes could be a practical substitute fuel for household cooking, heating, and other uses. The combustion experiments provided valuable insights into the ignition characteristics, combustion rates, and duration of the briquettes. The ignition times of the briquettes, which range from 1.39 to 2 minutes, demonstrate the convenience of using them as a readily available fuel source. In addition, the longer burn durations of 29.1 to 43.41 minutes show how energy can be released over a sustained period, which means less frequent fuel replacement and greater convenience for the user. These briquettes effectively address emission concerns and help ensure compliance with set requirements. Moreover, the production of briquettes from fruit waste and bagasse is highly valuable and aligns perfectly with the circular economy's objectives of optimizing resources and reducing waste. Producing briquettes is a great way to protect the environment by preventing open burning or landfilling of these biomass streams. In addition, this helps reduce greenhouse gas emissions and mitigates the harmful impacts of improper waste disposal, fruit waste as a sustainable energy source, and a practical approach to solid waste management in Addis Ababa.

5.2. Recommendation

- ✓ Further study is needed to optimize the composition and production method of briquettes in order to improve fuel qualities and lower emissions.
- ✓ Investigating large-scale manufacturing and commercialization of bagasse briquettes and fruit waste is important to support waste management and sustainable energy solutions.
- ✓ Awareness campaigns and training initiatives should be conducted to educate the public about the advantages and correct usage of biomass briquettes as an alternative energy source.
- ✓ Government regulations and incentives should be created to encourage the acceptance and broad application of biomass briquettes, especially in regions with restricted access to contemporary energy sources.
- ✓ Collaboration between pertinent parties, such as government agencies, research institutions, and private sector organizations, is essential to ensure the successful implementation of biomass briquette production.

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